Where's my Button?
Search Haptics in Seamless Tangible User Interfaces

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Abstract

In recent years automotive interiors have been dominated by the transition from traditional analog button interfaces towards the digitalization of interaction. This led to a reduction of hardware keys, surface-integration of control panels, and fusion of design and interactive surface, ultimately resulting in the implementation of large, mostly flat, and featureless interactive surfaces. This trend towards surface-integration of tangible user interfaces creates an apparent conflict of aesthetics and usability — especially in safety-relevant interactions like automotive. Despite pleasing and modern-looking, featureless surfaces lack the subtle search haptic sensations from analog button interfaces that constitute a high-quality impression and a safe, easy, and potentially eyes-free interaction.

Haptic technologies — passive or active — are increasingly implemented in featureless surfaces to restore the tangibility known from traditional interfaces in order to resolve the conflict of aesthetics and usability. Despite many potentially suitable technologies, the typical approach has primarily been technology-focused. Fundamental psychological, perception, and design aspects of haptic interfaces are often neglected during development. There is no common understanding of bridging the gap between tactually rich, analog and modern, large, flat digital interface surfaces to retain the strong tactile impression of traditional analog button interfaces. This thesis focuses on what "good" search haptics means, discusses user-centered requirements for potential technologies and proposes basic search haptic design principles. The goal is to explore how passive and active haptic technologies must be implemented to design a rich search haptic impression that supports a potentially eyes-free interaction on otherwise flat and seamless surfaces.

The thesis is organized into four parts: *Part 1* gives a general introduction to haptics and describes the fundamentals of haptic perception. Furthermore, it presents an experience-focused categorization methodology of current haptic technologies and a psychologically-driven framework for the haptic design of automotive user interfaces. *Part 2* examines associative and communicative characteristics of passive haptic forms concerning their fitting and benefit for search haptics. *Part 3* explores the design space of active haptic technologies, particularly electrostatic friction modulation, for search haptic interactions. *Part 4* concludes and discusses all research findings concerning how technologies can be utilized for appropriate search haptic design. It derives guidelines for the design of search haptic impulses in automotive interfaces.

Zusammenfassung

Im letzten Jahrzehnt gab es in Fahrzeuginnenräumen einen Wandel von taktil-analogen hin zu fugenlos-digitalen Bedienoberflächen. Dies äußert sich in einer zunehmenden Reduktion von Bedienelementen, gepaart mit einer fugenlosen Integration und Verschmelzung von dekorativen und interaktiven Oberflächen. Trotz einem visuell schlichten Erscheinungsbild und einer damit einhergehenden hochwertig-modernen Anmutung, erzeugt diese Flächenintegration einen Konflikt zwischen Ästhetik und Bedienbarkeit — besonders in sicherheitsrelevanten Bereichen wie Automotive. Dies liegt vor allem daran, dass die subtilen suchhaptischen Eigenschaften analoger Bedienfelder, die zu einem hochwertigen, intuitiven, sicheren und visuell wenig ablenkenden Bedienerlebnis beitragen, durch die flächige Integration verschwinden.

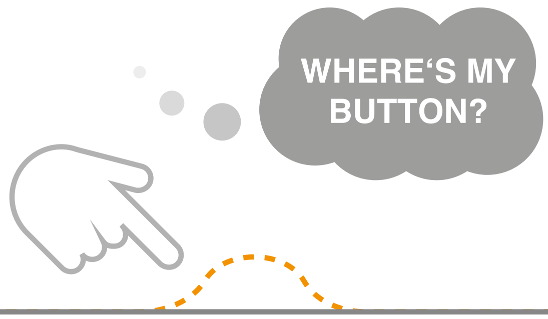
Im Zuge fugenloser Bedienoberflächen wird zunehmend haptisches Feedback — sowohl durch passiv- als auch aktivhaptische Technologien — implementiert, um den haptischen Eindruck mechanischer Tastenfelder zu imitieren. Ziel dabei ist es, den Konflikt zwischen Ästhetik und Bedienbarkeit aufzulösen. Ungeachtet der großen Anzahl geeigneter technologischer Ansätze sind die bisherigen Lösungen stark technologieorientiert. Psychologische und wahrnehmungsbezogene Aspekte haptischer Interfaces werden während der Entwicklung in vielen Fällen nicht ausreichend berücksichtigt. Das liegt unter anderem daran, dass es kein gemeinsames Verständnis darüber gibt, wie die Lücke von analog-mechanischen hin zu digital-fugenlosen Bedienoberflächen geschlossen werden muss, um den hochwertigen suchhaptischen Eindruck traditioneller Bedienelemente zu bewahren. Diese Arbeit befasst sich mit der Frage, was "gute" Suchhaptik bedeutet, diskutiert nutzerzentrierte Anforderungen für entsprechende Technologien und beschreibt grundlegende Richtlinien für das Design von Suchhaptik in Fahrzeugen. Das Ziel ist es zu untersuchen, wie Suchhaptik mit passiv- und aktivhaptischen Technologien gestaltet werden muss, um die Blindbedienbarkeit auf fugenlosen Bedienoberflächen zu unterstützen.

Die Thesis besteht aus vier Teilen: *Teil 1* gibt eine Einführung zum Thema Haptik, sowie deren Bedeutung für User Interaction und den perzeptuell-wahrnehmungspsychologischen Grundlagen haptischer Wahrnehmung. Zusätzlich wird eine experience-basierte Methodik zur Kategorisierung haptischer Technologien und ein wahrnehmungspsychologisch motiviertes Framework für die haptische Gestaltung von Bedienoberflächen in Fahrzeugen beschrieben. *Teil 2* untersucht die assoziativen und kommunikativen Eigenschaften passivhaptischer Formen in Bezug auf deren Eignung und Nutzen für Such- und Auffindehaptik. *Teil 3* exploriert den Gestaltungsraum aktivhaptischer Technologien, insbesondere Electrostatic Friction Modulation, für Such- und Auffindehaptik. *Teil 4* fasst die Forschungsergebnisse zusammen und diskutiert sie im Hinblick auf Gestaltungsprinzipien für Such- und Auffindehaptik, die die Blindbedienbarkeit während der Fahrzeuginteraktion unterstützen.

Part 0

INTRODUCTION

Introduction



With the move towards greater automation, vehicles transform from single-purpose means of transport to multiple-purpose entertainment, communication, and recreation hubs. Driven by technological advancements in interaction technologies, changing requirements towards mobility, and customer expectations — heavily influenced by the fast-paced developments in consumer electronic (CE) devices at the beginning of the 21st century — automotive interior design has undergone a drastic transformation to adapt to the needs expressed by various stakeholders.

While design philosophies vary across automotive manufacturers, there are some common design developments. Design sketches, concept studies, and production cars depict a clear shift from rugged, fixed, and single-purpose button interfaces to flat, clean, and highly integrated flexible interior surfaces. Streamlining interior surfaces, reducing physical hard keys, implementing previously physical functions into graphical user interface (GUI) menus, and fusion of interactive and design surfaces reduce visual complexity by avoiding the rugged impression of traditional button interfaces. Implementing "smart materials" enables seamless integration of interactive and design surfaces by "hiding" technology within decorative and non-functional materials. This allows the design of reduced and monolithic but still multifunctional interior surfaces. Surface-integration also means that carmakers are increasingly trying to maximize screen real estate by implementing large or even multiple screens. While Tesla has been pioneering this trend for years, other carmakers are increasingly consolidating their in-vehicle HMI (human-machine interface) to adapt to these developments. For example, Mercedes' MBUX Hyperscreen (Daimler AG, 2021b, 2021c) inhabits three displays in one large pillar-to-pillar cover glass.

Subsequently, large screens are becoming the center of interaction within automotive interiors due to their multifunctionality and flexibility, making traditional button interfaces obsolete. Physical hard-keys and functionalities are increasingly discarded, transferred to GUI menus, or seamlessly integrated into design surfaces.

The transition from highly functional but single-purpose analog button interfaces to a highly flexible digital interaction space is also heavily influenced by an increasingly experienced-focused perspective in interior design. Smart surface technologies enable a seamless and engineering-driven surface-integration and context-sensitivity of user interfaces and the application of new types of high-quality materials, such as stone, wood, metal, and glass. In the context of an increasingly experience-focused design approach, interfaces do not only need to function flawlessly. They need to be orchestrated in a way that they create a productive, entertaining, and welcoming atmosphere. The vision of most carmakers (but also customers' expectations) is that future cars will not only be seen and used as means of transportation but that the car essentially becomes the extension of one's living room, office, entertainment center, or digital companion (BMW Group, 2023).

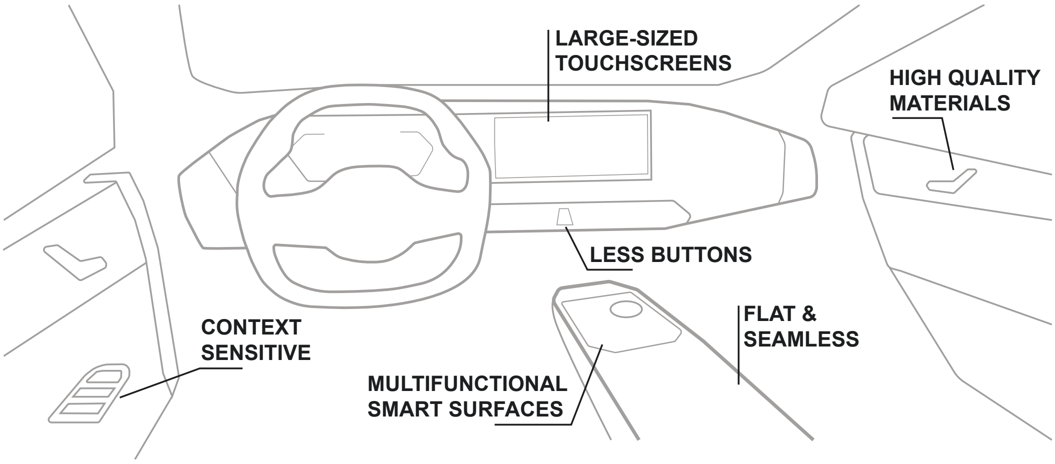


Fig. 1.: Current state automotive interface surfaces are characterized by flat and seamlessly integrated tangible user interfaces with a reduced number of physical buttons and high-quality materials.

The recent design developments (see Figure 1) towards large and flat tangible user interfaces with only a few yet highly integrated physical buttons may undoubtedly be beneficial for several reasons — e.g., easier mechanical integration, cost-savings due to fewer moving parts and higher flexibility in terms of functionality. Ultimately the "flatification" of tangible automotive interfaces results in a conflict between aesthetics and usability (see Figure 2). Driving a car is a visually and cognitively highly demanding task. Flat and featureless surfaces make it difficult for the user to locate functionalities while driving, thus driving attention away from the road. As long as humans are still involved in driving cars, user interfaces not only require a high-quality impression but, even more, an easy-to-use, efficient, potentially eyes-free, and non-distracting interaction. Even though modern seamless surfaces allow for a clean and aesthetically pleasing interior, eyes-free interaction is hardly possible as they lack the haptic qualities of traditional analog interfaces. Traditional button interfaces, which provide subtle haptic cues, offer a rich tactile experience that supports haptic exploration and orientation, thus helping the user to keep their eyes on the road (see Figure 2A).

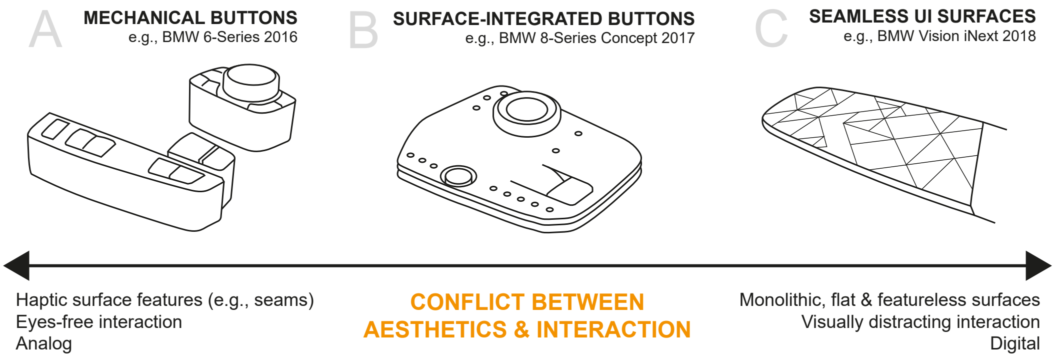


Fig. 2.: The surface-integration of in-car control elements, such as buttons and rotary dials, creates a conflict between aesthetics and interaction.

Restoring tangibility into digitally-focused interactions has been a significant task since touchscreen-based devices took over the consumer market since the launch of the first iPhone in 2007. Ever since *active haptic feedback* has been treated as a way forward to "add" additional layers of functionality and experience in different contexts ranging from consumer electronics to medicine, entertainment, and robotics. This "tangible turn" (Moussette, 2012) in interaction design has also fueled a debate in the automotive community on how to reintroduce the tactually rich experience from analog interfaces properly. In recent years, haptic feedback in flat automotive interface areas has mainly been restricted to the recreation of mere button presses using active actuators. What is still missing is bringing back the search-and-feel qualities of traditional analog interfaces that allow for effortless haptic exploration of interactive elements while driving.

Motivation & Goals

Being a tech- and car-enthusiast, I have always been intrigued by the vision drawn by automotive designers and technology companies since the beginning of the 2010s

— living room-like interiors with less but highly functional interactive surfaces which are seamlessly integrated into real material surfaces. However, as a psychologist, I have always asked myself how users are supposed to deal with the amount of — in most cases visual — information while driving. How are users supposed to keep their eyes and center of attention on the road when all they are left with are blank surfaces for interaction? They cannot help but look if they want to press a button.

Soon the manufacturers seemed to find clever solutions to retain the subtle tactile information from analog interfaces by adding haptic actuators to their technology demonstrators. Since the middle of the 2010s, active haptic technologies have become integral to automotive interaction technologies. Despite an increasing fidelity of haptic technologies, I felt that available solutions (either from OEMs[1] or suppliers) still fall short of their possibilities to support eyes-free interaction as they seemed too engineering-focused. So far, active haptic devices seem to have primarily been focused on imitating passive search haptic experiences from traditional button interfaces (e.g., ridges and mechanical clicks), which leaves the impression that novel haptic technologies are implemented for the sake of innovation. However, haptic feedback is not merely a "nice-to-have add-on" (Carbon, 2016, 2019) but a deeply rooted requirement in in-car interaction. Even though there is an abundance of various mature active haptic technologies (and proof-of-concept studies), knowledge on the design of search haptic experiences to support eyes-free interaction is scarce. Studies have hardly been put into the broader scheme of interaction or lack proper context — especially in the automotive context. While recreating familiar passive haptic impulses might be an initial step, I believe that implementing a user-centered and psychologically-driven design approach — i.e., approaching haptics from a why-what-how- instead of a how-what-why-perspective — might leverage the potential that fully software-defined, context-sensitive and customizable active haptic technologies offer for search haptic interactions.

One main goal of this thesis is to consolidate previous findings concerning search haptics in the automotive context by integrating the rugged scientific landscape into a holistic experience-driven haptic design and technology framework. Based on these theoretical fundamentals, original contributions will explore different aspects of search haptics and examine how different haptic technologies (either active or passive) can and should be utilized to support eyes-free interaction. The goal is to understand search haptic interactions better and facilitate haptic design in featureless tangible automotive user interfaces. One of the main questions will be: "What does good search haptics mean and feel like?"

[1] OEM: original equipment manufacturer

Framing

The field of haptics is mainly dominated by engineering-focused or basic psychophysics inquiries. Yet, being a cognitive psychologist, I believe the answer to the abovementioned questions cannot be purely engineering and technical. Even though haptic feedback involves technology to a non-negligible proportion, this thesis will not be about developing and engineering specific technological prototypes or rendering algorithms to improve the realistic recreation of button clicks and edges. This thesis will implement a psychologically-driven perspective on haptic feedback — following the of *Psychology of Design* in Carbon (2019) — and explore different aspects of effective search haptic design. By implementing a psychological turn that is not only based on a user-driven perspective but also a solid psychological methodology, I want to underscore its importance for effective haptic interface design and describe how this approach might bridge the gap between different professions within the haptics community. Furthermore, this thesis will compile personal experiences, providing a valuable summary for practitioners just starting in the field of haptics.

Haptics is a vast field of application. While the thesis will mainly focus on haptic feedback in an automotive interaction context, some of the findings might apply to other types of haptic technologies and haptic feedback in general.

This thesis, by far, will not provide definite answers to the questions mentioned above but represents the current state of affairs regarding available haptic literature and technologies. This is mainly due to the disruptive nature of the haptic market, as haptic start-ups and technologies are introduced and developed at a high pace. This has been an issue during the dissertation project as technologies that seemed promising concerning interaction were far from production-ready upon the start of this project in October 2017.

I also want to clarify how I will use the word *haptics* throughout this thesis. Besides cutaneous information, haptic perception also includes kinesthetic, thermal, and nociceptive information[2]. Similar to the framing of technologies described in *The Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-Based Haptic Technologies Through Fidelity* (Breitschaft et al., 2022a), this thesis mainly explores devices that rely on the direct contact of a bare finger with a surface, as this is the main case of how interactive interior surfaces are being explored. This thesis will only focus on the cutaneous submodality of haptic perception, which includes different mechanoreceptors to perceive vibration and surface geometries

[2]A more detailed description of what makes the haptic sense is described in Figure 3 (p. 15)

— even though there may be interesting approaches using kinesthetic and thermal cues to convey haptic feedback. In the context of automotive, *haptics* is also often used to refer to the general hedonic appearance of the automotive interior surface. Sometimes it is equated with the perceived level of material quality. The hedonic impression of materials is an important part of user experience and certainly plays a major role in a more functional type of haptics as well (Carbon, 2019). However, this thesis will focus more on functionality-induced haptic feedback terminology during in-vehicle interaction.

Structure

This thesis mainly explores how different haptic approaches can be leveraged to facilitate search haptic design in seamless automotive user interfaces. As already indicated in the beginning, the answer cannot be purely technical. Yet, it cannot be a purely psychological one either. As haptics (the community, technologies, approaches to design, etc.) is a multidisciplinary field, this thesis will explore different aspects of this question. This thesis is divided into four parts to satisfy the influences from the various areas.

Part 1: THE BASICS gives a general introduction to the field of haptics. It covers the question of what haptics means, provides a common understanding of human haptic perception and its opportunities and challenges, covers different areas of haptic applications, and describes user-centered reasoning why haptics enhances product experience. This part stresses the importance of a psychological turn in haptic research and design and reviews current haptic technologies using a novel and psychologically-driven categorization framework. Furthermore, it introduces the special characteristics of the automotive context and streamlines haptic terminology and findings from automotive haptic literature within a common framework of haptic processing in automotive user interfaces.

Part 2: PASSIVE HAPTICS describes how passive haptics has traditionally been implemented for search haptic feedback and covers explorations into search haptic design of passive haptic technologies. Based on a systematic tripartite study series, which investigated form-functionality associations of various haptic forms, this part describes how the aesthetic association principle as a genuinely psychologically-driven design approach may improve haptic interface design and facilitate search haptics.

Part 3: ACTIVE HAPTICS covers how active haptic feedback may be implemented in automotive tangible user interfaces to support eyes-free interaction. Different haptic technologies are assessed based on their appropriateness for search haptic use cases. Electrostatic friction modulation, an auspicious approach for a more feel-focused haptic interaction, is described in more detail. Multiple studies are examining the building blocks of friction haptics. Ultimately, this part describes an in-depth evaluation of an electrostatic friction modulation device using an automotive-related multitask search haptic setting.

Part 4: RÉSUMÉ summarizes findings from the reported studies, literature, and personal experiences and puts them into a broader search haptic perspective. It attempts to provide a conclusion on which factors generally constitute "good" search haptics. Furthermore, it presents guidelines for search haptic design derived from previous findings and experiences. This part also addresses open research questions and provides concluding remarks on haptic design.

Original Contributions

The research body which constitutes this thesis consists of ten original peer-reviewed contributions. Four contributions were part of peer-review journal publications. Six contributions were part of poster presentations at Worldhaptics 2019 and Eurohaptics 2020 and were subsequently published as work-in-progress contributions in the conference proceedings.

This thesis aims to assemble the puzzle pieces and put the findings from all research contributions into a broader context rather than providing a detailed description of each publication. The following sections will describe each contribution in a summarized manner to nourish a coherent understanding. Empirical contributions will be described with respect to Motivation, Method, Results, and Discussion. Methodological and theory-focused contributions will be described with respect to Motivation, Conceptualization, and Discussion. For a detailed description, I encourage to read the full-paper versions, which will be shown below (see also Appendix A).

Journal Publications

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019a). A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. *Frontiers in psychology*, *10*(1470). https://doi.org/10.3389/fpsyg.2019.01470

Breitschaft, S. J., Heijboer, S., Shor, D., Tempelman, E., Vink, P., & Carbon, C.-C. (2022a). The Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-Based Haptic Technologies Through Fidelity [Journal Article]. *IEEE Transactions on Haptics*, *15*(2), 232–245. https://doi.org/10.1109/TOH.2022.3152378

Breitschaft, S. J., & Carbon, C.-C. (2021). Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design. *Frontiers in psychology*, *12*, 2619. https://doi.org/10.3389/fpsyg.2021.646986

Breitschaft, S. J., Pastukhov, A., & Carbon, C.-C. (2022b). Where's My Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces [Journal Article]. *IEEE Transactions on Haptics*, *15*(2), 292–303. https://doi.org/10.1109/TOH.2021.3131058

Conference Contributions

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019b). Using haptic shapes for orientation and identification in automotive user interfaces [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE

Heijboer, S., Breitschaft, S. J., & Carbon, C.-C. (2019a). Characterization of Active Haptic Feedback for User Interface Design and Development [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE

Breitschaft, S. J., & Carbon, C.-C. (2020a). An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.14518.32327

Breitschaft, S. J., & Carbon, C.-C. (2020b). Semantic Differentiation of Haptic Edges rendered on an Electrostatic Friction Modulation Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.34650.98245

Breitschaft, S. J., Heijboer, S., Shor, D., Carbon, C.-C., & Tempelman, E. (2020a). Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.32973.26086

Breitschaft, S. J., Pasthukov, A., & Carbon, C.-C. (2020b). Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.35489.84320

Part 1

THE BASICS

A Tangible Turn

1.1

> *Touch is far more essential than our other senses... It's ten times stronger than verbal or emotional contact.*
>
> — **Saul Schanberg (1991)**

The field of haptics has experienced an unprecedented upward trend during the 2010s. It has evolved into a multifaceted area of research and application — from the first systematic examinations of the sense of touch conducted by Ernst Heinrich Weber through the early days of robotics to the ubiquitous implementation of haptic actuators in consumer electronic devices. Amid digitalization and virtualization of real-world experiences and interactions, which experienced a preliminary climax with the introduction of the first iPhone in 2007, practitioners have started to "re-" discover the haptic sense, an integral building block to create truly immersive and realistic experiences. With the trends towards an almost ubiquitous integration of haptic actuators in everyday devices — a trend that has also been governed by the introduction of Apple's Taptic Engine in 2014 and Core Haptics in 2019 – a gamut of new practitioners with diverging academic and professional backgrounds have entered the field. In recent years, haptic feedback has attracted much interest in the interaction community. Moussette (2012) refers to this as a "tangible turn" in user interaction (UI).

This thesis builds on the multidisciplinary fundamentals of haptic research, technology, and perception. It is influenced and guided by design, technological, and psychological insights. Fundamental knowledge of the perceptual and psychological qualities of how users perceive and explore their surroundings using the sense of touch is essential for novel and expert-level practitioners in the field of haptics-especially for those with an engineering and design background. It helps designers to consider perceptual challenges and capabilities during the design process and, thus, fosters an understanding of how to design compelling haptic interactions. Similar works in the field of haptics usually start with haptic etymology, an in-depth description of mechanoreception, or the analysis of perceptual principles. This thesis

The quote was published in *A natural history of the senses* (Ackerman, 1991).

will start with a condensed introduction to the field of haptics that concentrates on what I feel is relevant for practitioners in the context of user experience and user interaction.

This section will focus on developing a fundamental "haptic" knowledge database, which will give novel and experienced haptic practitioners the proper foundation to understand the role of haptics in user interaction. I will describe what haptics actually is, develop arguments on how haptic feedback can enrich user interaction, provide a brief overview of different areas of application for haptic feedback, explore what makes sense of touch in everyday situations, and describe perceptual and psychological fundamentals, prerequisites and challenges of human haptic perception. Furthermore, I will underscore the value of haptic feedback in the context of interaction. The breadth of the field (from technological principles to physiological basics to perceptual and psychological considerations and philosophical discussion) makes it almost impossible to describe all relevant information in detail. In most cases, this is unnecessary as plenty of resources already provide detailed summaries of specific topics. Table 1 (p. 14) provides an overview of relevant haptic literature that both forms the theoretical foundations of this thesis and serves as a starting point for novice and expert practitioners to get much deeper insights into specific areas of haptics.

1.1.1 What is Haptics?

Haptic perception — also sometimes referred to as somatosensory perception (Birbaumer & Schmidt, 2018a, p.322) — describes the entirety of sensations connected to the sense of touch. It involves information from body-internal and body-external sources and is usually acquired via active exploration. Figure 3 (p. 15) describes the different sources that constitute haptic perception (Birbaumer & Schmidt, 2018a; Reed & Ziat, 2018).

Tactile Perception (also sometimes mechanoreception or the cutaneous sense) involves sensations from external stimuli picked up by different types of mechanoreceptors embedded in different layers of the skin (see Figure 4). Mechanoreceptors are specialized towards specific frequency bandwidths through their perceptual characteristic to sense pressure, touch, vibration, itching stimuli, etc. **Kinesthetic Perception** and **Proprioception** use sensors in muscles, tendons, and joints to feed back information on posture, movement, and force. Even though both descriptions

Tab. 1.: Overview of basic literature resources in the field of haptics.

Area	Author	Title	Summary
Overview	Jones (2018)	*Haptics*	General introduction to the basics of haptic perception and current fields of haptic research
Overview	Grunwald (2008)	*Human Haptic Perception*	Broad overview on history, research, design, and application of haptic perception
Overview	Grunwald (2017)	*Homo hapticus*	A popular scientific description of the ontogenetic evolution of the sense of touch and its importance for personal well-being and social interactions
Physiology	Birbaumer and Schmidt (2018b)	*Biologische Psychologie*	Extensive description of physiological basics of the sense of touch, such as mechanoreception and proprioception (German)
Physiology	Schandry (2016)	*Biologische Psychologie*	Summary of physiological basics of the sense of touch (German)
Physiology	Reed and Ziat (2018)	*Haptic Perception: From the Skin to the Brain*	Summary of physiological and cortical basics of the sense of touch
(Haptic) Perception	Goldstein and Brockmole (2017)	*Sensation and Perception*	Standard reference for all perception scientists with a solid overview of somatosensory perception.
Haptic Perception	Lederman and Klatzky (2009)	*Haptic perception: a tutorial*	A tutorial about the "what" and "where" channels of haptic perception with their respective prerequisites using a psychologically-driven perspective.
Material Properties	Jones et al. (2006)	*Human hand function*	Very broad overview on neurophysiological foundations of human hand functions, tactile & active haptic sensing
Material Properties	Bergmann Tiest (2010)	*Tactual perception of material properties*	Review of haptic material perception, including a discussion of psychophysical functions such as discrimination thresholds
Material Properties	Klatzky et al. (2013)	*Haptic perception of material properties and implications for applications*	Review of material properties perceived via haptic interaction and rendering algorithms used in haptic devices
Interaction Design	Hayward and MacLean (2007)	*Do it yourself haptics: part I*	Introduction to the technical building blocks of haptic interfaces
Interaction Design	MacLean (2008)	*Haptic interaction design for everyday interfaces*	Introduction to haptic interaction design with a profound overview of human haptic capabilities and applications contexts
Interaction Design	MacLean and Hayward (2008)	*Do It Yourself Haptics: Part II [Tutorial]*	Introduction to haptic interaction design based on technical as well as interaction principles
Interaction Design	Vezzoli et al. (2022)	*XR Haptics*	An application-focused guide on how to implement haptics in mixed-reality use cases
Ergonomics in Automotive	Bubb et al. (2015)	*Systemergonomie des Fahrzeugs*	Overview of basic ergonomic principles in the automotive context (German)
History on Haptic Interfaces	Parisi (2018)	*Archaeologies of touch*	A concise and detailed overview of the history of haptic interfacing

are often used synonymous, proprioception is primarily used to refer to the perception of posture. In contrast, kinesthetic perception primarily refers to the perception of body movement (Reed & Ziat, 2018). **Thermoception** i.e., perceiving and processing thermal cues is probably based on free nerve endings. **Nociception** concludes the different sensations that make haptic perception. Highly intensive chemical, mechanical and thermal cues are perceived and processed via nociceptors (which constitute free nerve endings). Noxious don't play any role in automotive touch interfaces. Even though thermal cues are highly relevant in the context of materials' haptic impression and might be interesting for specific interaction purposes (e.g., augmentation of the temperature state of AC controls), they will not be discussed in this thesis.

Lederman and Klatzky (2009) also refer to the *What* and *Where* systems of haptic perception. The *What*-system entails information that allows inferring object proper-

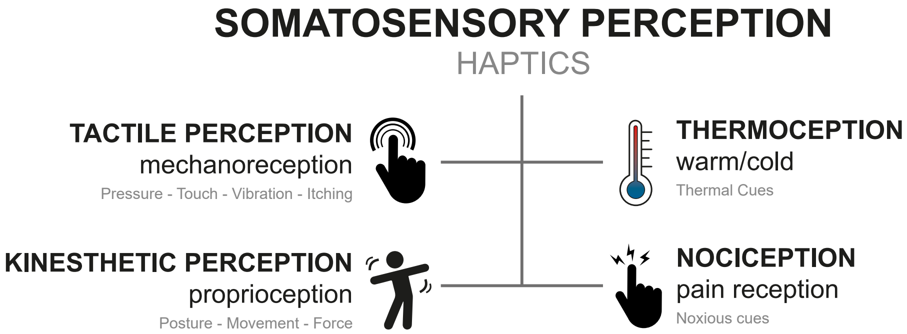


Fig. 3.: Haptic perception constitutes different sensory (sub-)modalities of touch: Mechano-, Thermo-, Noci-, Proprioception & Kinesthetics

ties. It's mainly input from mechano-, thermo-, and nociception. The *Where*-system mainly provides body-internal and body-external spatial information relying on the sense of touch. These are object positions in relation to the human body and each other (sort of a spatial-tactile reference frame), but also the localization of where somebody has been touched on the body.

The terms *haptic* and *tactile* perception appear almost synonymous, considering different kinds of media (websites, literature, consumer electronics, etc.). However, this is not entirely correct. Haptic and tactile perception have fundamentally different prerequisites for interaction with implications on interface design. Haptic perception relies on an actively exploring agent. Kappers and Bergmann Tiest (2015b) argue that tactile perception solely involves information registered via cutaneous receptors. In the context of interfaces Jones et al. (2006) also refer to tactile as information that is picked up by sensors in the skin while the recipient is not moving. Once other sources of information are integrated into the percept, such as kinesthetic information, we might preferably refer to haptic perception.

In the end, haptic perception is almost always multisensory. Humans integrate tactile information from mechanoreceptors in the skin and kinesthetic information (i.e., force and posture) from joints and tendons into a holistic percept. Gibson (1962) gives a similar distinction regarding the involvement of active movement in touch perception. In interaction design, most interactions, such as pressing and swiping, require active exploration and thus almost always implicitly involve kinesthetic information. As all interactions, feedback, and technologies in the context of this thesis are based on active exploration, I will subsequently refer to haptic feedback. For haptic devices, the user is usually not permanently in direct contact with the interface but actively engages with the device. In contrast, tactile interfaces require direct and continuous contact with the user and no active user involvement to convey tactile information. Usually, external sources trigger feedback, making it highly usable for notification, warning, and other externally-triggered use cases. A typical example of tactile devices in automotive are vibration motor-equipped steering wheels. Once the car crosses a white line indicating a traffic lane, vibration alerts the driver of lane departure[3].

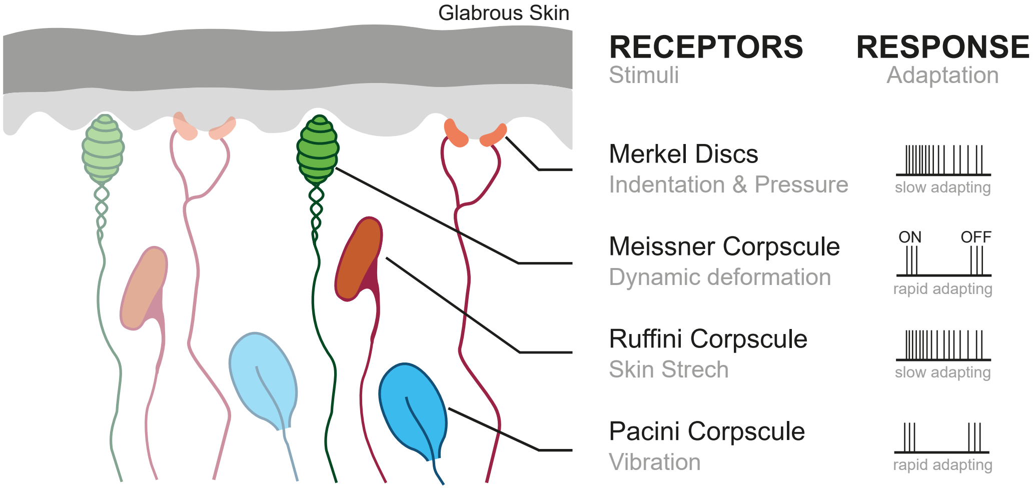


Fig. 4.: Tactile information is sensed by different specialized mechanoreceptors embedded in the skin, which are characterized by their adaptation rate.

1.1.2 Why use (Active) Haptics in Interaction?

> *In stark contrast to the importance of touch in our everyday experience, the use of touch is marginalized in contemporary computer interfaces*
>
> — **Karon MacLean (2008)**

While touch interfaces have played a crucial part in taming the exploding number of functionality in electronic devices, haptic feedback has merely kept up with this development. Reasons for the lack of haptic feedback in this first generation of touchscreen devices potentially lie within the implications active haptic technologies have on electronic and mechanical design. Also, the lack of higher fidelity actuators may have limited the range of appropriate haptic experiences[4]. Additionally, proper

[3] For more examples of tactile devices in automotive interiors, see Gaffary and Lécuyer (2018)
The quote was published in *Do It Yourself Haptics: Part II [Tutorial]* (MacLean & Hayward, 2008).
[4] See Section 1.3.2 on p. 51 for a more detailed discussion on haptic actuators that describes the different levels of haptic fidelity.

implementation of active haptic feedback is often accompanied by high costs considering additional hardware components, such as an actuator, driver ICs, cables, mechanical integration, development costs, etc. Active haptic feedback is often one of the first cost-down measures in cost-driven discussions. In many cases, other means of feedback, such as audio, are considered equal to haptics. "Audio feedback will do the trick as well" is one example of a sentence often used in practice.

As a result of an increasing fidelity of haptic actuators since the late noughties, one can slowly observe the renaissance of haptic feedback, which was lacking in previous generation electronic devices — in plenty of cases, devices with a strong haptic legacy, e.g., mobile phones. Nevertheless, even in safety-relevant contexts, such as automotive, where touch interactions combined with haptic feedback could substantially influence safety, interaction is still increasingly pushed towards flat tactility-lacking surfaces. It seems that haptic is still often seen as "optional" — a nice-to-have but not necessary add-on — even though there is clear interaction-focused reasoning to integrate (active) haptic feedback into products. MacLean (2008) describe two primary functions of haptic feedback in interaction contexts: (1) restore tangibility of interaction elements in virtual environments and (2) provide an additional channel of communication to reinforce task requirements or enable the handling of multiple tasks by using different modalities to convey information. Even though functionality has primarily been the main driver of haptic technologies, there has been a shift towards a more experience-based view in recent years. I found it helpful to develop a "bullet list" — a line of argumentation — how haptic feedback augments user interaction as well as user experience and thus should be an integral part of interaction and product design.

Enhancing user experience: Overall, haptic feedback enhances user experience (see Table 5). In automotive studies, haptic devices have been shown to alleviate the subjective workload and are preferred and more accepted than their non-haptic counterparts. Even though participants are not quicker and more precise during the interaction, they tend to feel safer, more efficient, and more confident by having haptic feedback (Breitschaft et al., 2022b).

Enhancing performance: In unimodal scenarios, additional haptic feedback enhances performance (Hoggan et al., 2008; Tivadar et al., 2022). In multimodal, cognitively complex, and demanding multitask scenarios, such as automotive, the relationship between driving or task performance and haptic feedback is somewhat more diffuse. It seems to depend on the implementation of the interface and feedback design (Breitschaft et al., 2022b).

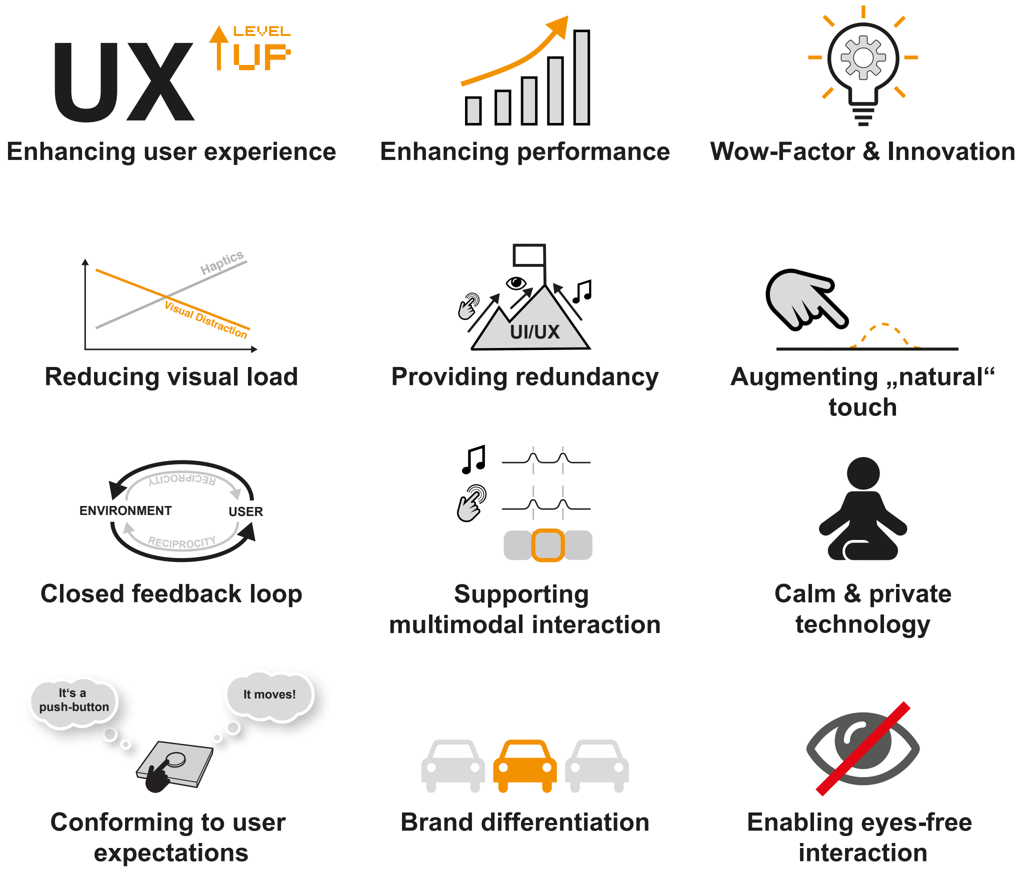


Fig. 5.: Haptic feedback contributes to user interaction in multiple valuable ways.

Wow-Factor & Innovation: Even though novel interaction technologies "break" perceptual habits and might be unfamiliar at first, they bear the potential of triggering a "wow-factor" impression due to their novel experience. Haptic feedback makes uninspiring touchscreen surfaces "come to life again" (Breitschaft et al., 2022b). Active haptics potentially becomes a decisive marketing and discriminating factor for perceived innovativeness and brand image.

Reducing visual load: Haptic devices seem less visually distracting (Beruscha et al., 2017; Mullenbach et al., 2013b; Tunca et al., 2018) in vision-heavy interactive scenarios, such as automotive. Users seem to spend less time looking away from the road and feel less visually distracted (Breitschaft et al., 2022b). This finding supports a widely used claim in automotive: "Eyes on the road, hands on the wheel" (González et al., 2007).

Providing redundancy: Haptics provides an additional and redundant communication channel that the user can never really switch off from picking up information. This significantly impacts cognitively demanding contexts where redundant information poses the potential to increase safety. A crucial role of haptic feedback is to "reinforce the same task or to handle different tasks performed simultaneously" (MacLean & Hayward, 2008).

Augmenting "natural" touch: Featureless and screen-focused devices often lack a deeply rooted tactile experience which is an essential basis of human's sense of touch and how they explore their surroundings. Haptic technologies enable to restore tangibility on seamless tangible user interfaces. Haptic feedback allows augmentation of touch interactions, leading to greater immersion and connection between user and device, thus making interaction more "natural".

Providing an immediate & closed feedback loop: Haptic feedback requires direct contact between users and interfaces. Hence, haptic feedback is directly "at your fingertip" and reinforces interactions due to the feedback's direct and immediate nature. Furthermore, the haptic sense utilizes a closed-feedback loop (Ishii, 2008) — i.e., interaction is based on a continuously monitored, reciprocal relationship between input and output. This makes haptic perception the only truly bidirectional sense. The "touching-and-being-touched" mentality also applies to automotive interaction, where haptic feedback upon button presses has been integral to button interface elements in recent decades.

Supporting multimodal interaction: "Haptic design is nearly always multimodal design" (MacLean & Hayward, 2008). Looking at studies in the context of automotive haptic feedback, modalities including visual, audio, and haptic feedback outperform uni- and bimodal conditions with respect or user experience variables.

Calm & private technology: Norman (2013) describes haptics as a "calm technology". Haptic feedback requires direct body contact, which means it's "always on". Its direct feedback loop requires little attention and is unobtrusive. The private nature of information communication might be valuable in contexts where information is targeted at a specific audience. Instead of using auditory feedback, only the user receives confirmation.

Conforming to user expectations: Haptic feedback is essential to user expectation towards interaction in several specific scenarios. Users often are unaware of the impact that haptics has on interaction and experience. However, it seems that once users are used to the haptic impression (which they don't necessarily need to be explicitly aware of), they will miss haptics if it is not available anymore (Breitschaft et al., 2022b). Especially in automotive, haptic feedback has established itself as one (if not the most) appropriate feedback, as buttons, levers, and dials (mostly with strong mechanical feedback) have been a part of automotive interiors for decades. Interface elements that appear to be buttons but lack the tactility of switches might lead to confusion and frustration. This might not yet (as of 2022) be true for touchscreen interactions. Yet, haptic feedback is increasingly integrated into everyday products, gradually leading to a higher familiarization with haptic interactions. Eventually, this will lead to changes in their perceptual habits and premises towards touchscreen interactions, meaning that touchscreens that do not offer haptics fall short of user expectations in the future.

Brand differentiation: Haptic feedback restores tactility on featureless surfaces. Flat touchscreens merely differ in terms of surface haptic quality. Grunwald even goes as far as to say: "Touchscreens are unmanly" (Stockburger, 2013). Haptics has shown to be a sensory modality with "brand-shaping potential". For example, BMW's iDrive Controller has been one of the most iconic haptic interface elements in the automotive industry since its introduction in 2001. This "haptic legacy" vanishes with the introduction of touchscreens, which lack haptic touch as a differentiating factor. Highly flexible interaction technologies enable a new haptic language that carries the haptic legacy into digital interactions.

Completing "phygital": Haptic technologies are completing the "phygital" modalities — they are bridging the gap between the analog/physical world and digital interaction spaces (Heijboer et al., 2019b). Haptic technologies offer the possibility to transfer the haptic quality known from classic interfaces into the digital interaction space. Haptic also allows for enriching virtual and mostly intangible interaction with a physical layer of experiences.

Enabling eyes-free interaction: Haptic enables eyes-free interaction. Haptic cues provide orientation and detection of interactive elements in flat interfaces without looking. This is especially helpful for interactions with restricted visual input, for example, "blindspot" areas within car interiors (Breitschaft et al., 2019a). Shape and geometry already communicate functionality (Breitschaft & Carbon, 2021).

1.1.3 In Which Areas can Haptics be Applied?

The field of haptics has always been of interest to a wide variety of different professions, from perception science to psychology, design, and robotics. Especially in recent decades, the field of haptics has experienced massive diversification in terms of haptic applications for multiple reasons. The digitalization of information reveals the profound intangibility of virtual experiences. Furthermore, haptic technologies have exceeded the state of immature, lab-grade prototypes and have become much more accessible to non-engineering practitioners. The idea to recreate naturalistic interaction in digital interaction spaces has driven the continuous development of haptic devices in many areas. Haptic applications are manifold and may involve various differently shaped haptic devices. Haptics has become mainstream in human-machine interaction. This also means that haptic feedback is increasingly becoming a denominating factor for user experience and innovation. I believe that looking at how other areas have implemented haptic feedback allows drawing inspiration for applying haptics in the automotive context. The following paragraph describes exemplary applications of haptic feedback:

Transportation: Haptic feedback is an essential component of easy, efficient, and safe-to-use interfaces in various areas of transportation like automotive and aviation (Federal Aviation Administration, 2011; Gaffary & Lécuyer, 2018). The importance of haptic feedback in automotive is discussed in detail on multiple occasions in this thesis. The automotive group from the *Haptics Industry Forum* recently published their "Recommended Practices for Automotive" (Haptics Industry Forum, 2021a).

Consumer electronics, mobile devices & wearables: More consumer-grade products are equipped with haptic feedback every year. Especially in the smartphone and gaming market, higher fidelity actuators and systems are increasingly integrated to provide a high-quality haptic experience (e.g., Apple Taptic Engine) and create a haptic brand experience. The central use case of active haptics is to replace mechanical switches and allow a flush and monolithic appearance — e.g., see the new Dell XPS 13, which integrates the touchpad in a closed-interactive surface (Engadget, 2022). There is an increasingly deeper integration of active haptic feedback into the user interface. Haptic is becoming an integral part of the interaction as primary use cases, such as typing, scrolling lists, setting the timer, etc., are augmented via vibration and haptic clicks. This also dramatically impacts the expectation of haptic interaction in other application areas. Once users are used to having a haptic click during slide-and-tap interactions on their smartphones, this expectation might also transcend to different types of touchscreens, such as the ones in cars.

Entertainment: Haptic feedback is integral to an immersive multisensory experience. Rumble packs in gaming controllers augment different in-game situations, such as shooting a gun or driving off-track. Force-feedback steering wheels aim to simulate forces exerted during a typical driving situation. In recent years, haptic actuators have been increasingly integrated into gaming accessories, such as chairs (Arcadeo Gaming, 2021), headphones (Razer, 2021) and vests (bHaptics, 2021) to expand haptic sensations to the whole body. A heavily debated example of next-gen haptics is the Playstation 5 DualSense controller, which integrates a high fidelity haptic actuator and adaptive triggers to augment in-game events for an immersive experience (Warren, 2020). In virtual reality, haptics is indispensable in creating the perfect virtual illusion of real-life experiences. An extensive description of how haptics can be used to "extend" virtual experiences is described in Vezzoli et al. (2022).

Medical training: Haptic feedback devices are implemented for training in minimally invasive surgical procedures. Devices are used to emulate the feeling of real-world tissue palpation, which is crucial for a surgeon's performance during surgery. Using haptic feedback, particularly force feedback, has increased performance in telesurgery contexts (El Rassi & El Rassi, 2020; Weber & Eichberger, 2015).

Teleoperation: Haptic feedback also plays a crucial role in teleoperated (remotely operated) systems. This means that instead of directly being involved in hazardous situations (e.g., radioactive environments, military situations), the operator controls a robot or another tool at a safe distance. This decouples the operator from the actual situation. Real-world information sensed by the remote devices is "played back" to the operator via haptic impulses to create support task completion.

Affective & social touch: Touching and being touched is an imminent part of social interaction and non-verbal communication. Touch not only communicates emotions but can also elicit behavioral patterns in a social context. The Covid19 pandemic has only intensified the lack of social and intimate interactions. Yet, digital communication tools are mainly vision- and audio-based. Haptic devices have been used to mediate and render social and affective communication stimuli (van Erp & Toet, 2015). For example, haptic vests with embedded haptic actuators have been examined to recreate the feeling of a hug when activated (Tsetserukou, 2010; Tsetserukou et al., 2009). High-fidelity haptic technologies are also increasingly integrated into the context of sexual well-being and adult entertainment devices.

Motor skill training: Sigrist et al. (2013) conclude that augmented haptic feedback might enhance motor learning in multiple contexts, from production to rehabilitation and sports training. Haptic devices such as suits (Teslasuit, 2021, e.g.), wearables (SenseGlove, 2021), and desktop systems are being implemented. Haptic feedback may be used to provide reinforcement or constraints for movement execution of basic and complex motor skills. For example, in professional sports training, a golfer's swing movement can closely be monitored and corrected or reinforced by a haptic impulse of the suit once a deviation from the optimal motor execution is detected.

Education: Haptic is also valuable in various learning environments — primarily by employing a virtual reality paradigm (Barfield, 2009; Minogue & Jones, 2006). The hands-on mentality of haptics in virtual environments might facilitate understanding abstract and hard-to-grasp concepts in STEM and other fields. For example, haptic devices have shown to ease understanding of basic physical principles (Han & Black, 2011) and also biological processes on a cellular level (Tokatli et al., 2018).

This is only a small selection of areas where haptics have proven valuable. More capable devices and technologies will push the boundaries of how haptic interaction even further to yet unforeseen levels.

1.1.4 What Makes Haptic in Everyday Life?

> *And I found that of all the senses the eye was the most superficial, the ear the most haughty, smell the most voluptuous, taste the most superstitious and inconstant, touch the most profound and philosophical.*
>
> **— Diderot (1749)**

Before going on, I would like to encourage to think about the following question: If you can only keep one of your senses, which would be the sense you cannot live without? Why would this be the one to keep? Why could you live without the other senses? I also asked this question in a presentation on haptic aesthetics during my masters' studies. The majority answered that they would not want to trade in their sense of vision as, without vision, they would be disconnected from the outside world. Seeing is vital as it allows one to perceive information quickly from a distance. From an evolutionary point of view, this has been extremely important to spot dangers from afar. To my surprise, only a small number said they never want to be without their sense of touch because, in reality, the lack of touch disconnects one from the environment. In the context of modern society, where media and information are flooded with visual and auditory cues, it is understandable that the importance of the sense of touch often seems to be marginalized.

Haptic perception describes how humans integrate information from internal and external sources to perceive, understand and interact with the outside world. The sense of touch is the most fundamental connection to the environment. We react to

The quote was published in *Lettre sur les aveugles à l'usage de ceux qui voient* (Diderot, 1749).

stimuli in the mother's womb long before we perceive visual information. Haptic information is continuously evaluated to fulfill everyday tasks without us being aware. The automatic monitoring and integration of kinesthetic information on body posture and the position of limbs allow us to sit, walk and do every kind of manual task with a staggering amount of precision. Just by touching a finger, we can perceive minor surface imperfections that would otherwise only be perceived with magnifying glasses or a microscope. I believe that a deeper understanding of the role of haptic perception in everyday life also transfers to the role of haptics in interface design.

Humans are extremely efficient in exploring and interacting with the outside world. That is also because everyday haptic interactions are highly specialized. Lederman and Klatzky (1987) describe six typical exploration procedures that are fundamentally geared towards perceptual requirements. Table 2 describes the exploration procedures alongside the haptic features they are most fit to extract (Klatzky & Reed, 2009). Exploration procedures and movements are chosen and adapted based on the features users require to fulfill the task at hand. For example, if we are looking for a key in our pocket, we might follow the object's contour to judge whether it's the desired key. This also means exploration procedures are limited concerning the haptic information they are most suitable to pick up. For example, if we want to measure the weight of a mango, we pick it up and hold it rather than just grabbing or pinching it. Considering how users employ their sense of touch to explore objects is essential in the context of haptic design. Haptic information needs to be geared towards the mode of interaction and exploration to be perceived most optimally. For example, haptic shape cues of an object may only be perceived properly when the user can actively explore the object. Similarly, surface haptic technologies provide high-quality feedback upon tangential surface interactions. Still, they fall short once the primary mode of interaction is geared towards static or orthogonal surface interactions, such as push and tap.

Even in an oculocentric world, where most information is conveyed via visual and auditory input, we heavily rely on haptic information to perform everyday tasks as there are layers of information in the environments not accessible via vision. While (especially rougher) textures can very well be inferred via visual information, compliance (or hardness), slipperiness (or friction), temperature, and resolution of very fine textures can only be evaluated via touch. Klatzky and Lederman (1993) indicate that visual information modulates haptic exploration. There are visual and cognitive indicators that invite users to touch an object. Klatzky and Peck (2012) call this the *touch-ability* of things.

Tab. 2.: Overview of haptic exploratory procedures, their associated haptic properties and interaction movements based on Lederman and Klatzky (1987).

Procedure	Haptic Property	Movement
Lateral Motion	Texture, Roughness	The finger is sliding across the surface in a tangential movement.
Pressure	Hardness, Compliance	Force is applied in an orthogonal direction onto the object, e.g., by pressing.
Static Contact	Temperature	Properties are extracted by static contact without active movement.
Unsupported Holding	Weight	Properties are extracted by holding the object, e.g., lifting it.
Enclosure	Volume, Global Shape	Enclosing an object with the fingers.
Contour Following	Shape	Following an object's outline through active movement.

Note: This table is based on information from Klatzky and Reed (2009) and Lederman and Klatzky (1987).

If visual information about object surface properties is present, haptic touch is often used to confirm prior visual assessment. For product design, the visual and haptic impressions must be congruent, as users could be confused and disappointed. An incongruency might harm product experience. Haptic exploration is indispensable if required object information cannot be inferred from visual information alone or is insufficient for evaluation. A striking everyday example is when we want to assess the ripeness of fruits or vegetables. By changing their color from green to yellow to brown, there is much visual evidence of the ripeness of bananas. However, for other vegetables, such as avocados, mere visual appearance does not provide enough information to judge whether it's already overripe inside. Pinching it does provide this information, though.

There is an abundance of other occasions we tend to favor haptic over visual information, for example, in dark environments where visual information is scarce, in cases where we want to confirm a visual or auditory impression, or in cases where we do not trust our eyes and ears and need to touch it for ourselves. In general, it's situations where we believe that haptics provides a more reliable source of information. Welch and Warren (1980) describes this as *modality appropriateness*. For example, holding an object provides more trustworthy information on weight than just looking at it. Especially in the context of haptic-enabled touch-sensitive interfaces, there is a special challenge to create a matching haptic and visual experience. As the movement of actuators is within the range of microns, it can only be perceived via the haptic channel — and, to be frank, by the auditory channel due to the actuator's noise. Users are often unaware if and how they integrate haptic information into their evaluation process. But they will notice when haptic feedback is missing, e.g. when they expect it upon interaction. Technology fails to provide haptic feedback when touch is prohibited due to hygiene regulations or in the context of artworks where the aesthetic experience still mostly relies on visual or auditory information.

All of the previous examples put haptic perception in the context of an actively exploring agent. Haptic does not only mean touching but also being touched — on a physical as well as philosophical and emotional level. Haptic perception is the only sense that directly allows for direct manipulation and interaction with the environment. Haptic interaction is an inherent part of emotional and social development. The haptic sense is probably the first to develop in ontogenesis — long before all other senses and even before the development of other important inner organs (Grunwald, 2017, p.22). Grunwald describes that embryos already react to external stimuli from the seventh week of pregnancy. In the 15th week of pregnancy, the entire range of exploration movements is almost fully developed and subsequently exercised to prepare for the challenges of the outside world [5].

Haptic information is not only essential to cope with everyday challenges but also an important factor in social interaction and emotional well-being. Direct skin contact of the newborn child with its mother seems to foster and stimulate vital biological processes within the child. Tactile stimulation is necessary directly after birth and in the first years of life. An abundance of (with today's standards ethically not acceptable) psychological studies depict the influence of intimacy on bonding behavior as well as social and emotional development (Grunwald, 2017, p.59-63). This might even be more graspable when thinking of the comforting impact when touching or being touched (in a physical sense) by people we care about — we feel involved and safe. Haptic perception is the only sense that allows for real, physical intimacy. In this sense, haptics connects us to the outside world as it establishes a reciprocal relationship. It enables us to directly manipulate our environment and simultaneously monitor the impact and consequences of our actions.

In a nutshell, haptics does not mean only touching but also being touched. From an evolutionary standpoint, we are driven to explore the outside world not only at a distance but by engaging and thus also actively changing it. The reciprocal relationship of actively changing and being changed separates the haptic sense from all other senses. It also makes the sense of touch highly interesting for interface design — haptics is a fundamental driver of involvement. This reciprocity of haptic

[5] A much more detailed description of how the tactile senses develop throughout fetal development can be found in Grunwald (2017, p. 21-52).

interactions yield some particular opportunities and challenges in perception science and interface design.

1.1.5 What are the Potentials and Challenges when Implementing Haptics?

Moussette (2012) describes two major mindsets within the haptic community — (1) *human-centric* and (2) *techno-centric*. The human-centric approach focuses on the human haptic perception and its psychological foundations. It is about **WHAT** we feel and perceive and how we integrate haptic stimuli through cognitive processes. The techno-centric approach focuses on haptic technologies to display haptic stimuli to the senses. It incorporates an engineering-driven perspective developing methods of **HOW** to convey perceivable haptic sensations. This involves actuators and devices but also rendering algorithms. Interaction design is happening right at the cross-section of these two haptic perspectives. Designing with and for the haptic sense requires a basic understanding of the human and techno-centric approach. A basic understanding of capabilities and limitations in human haptic perception might guide and drive the development and design of haptic devices. On the other hand, technological advancements benefit haptic research and push the boundaries of haptic interactions. What's important for practitioners is to understand how we perceive using the haptic sense. Also, what sets haptic perception apart from other sensory modalities, and how we can potentially leverage these characteristics for interaction design.

First and foremost, haptic perception is based on serial processing of information (Carbon & Jakesch, 2013). Compared to vision, haptic object information is processed in a serial - one-at-a-time - and hierarchical manner from local to global information (Carbon & Jakesch, 2013). Only haptic object properties that fit into the perceiver's hand can be perceived "at once". Once the object size exceeds the capacity of the human hand, objects need to be explored subsequently, which also requires more time. This is in stark contrast to visual and auditory processing, where more layers of information about an object can be picked up within a short period of time — or at once. This discrepancy might be less for simple stimuli but certainly increases for more complex stimuli, such as multimodal interfaces, displays, or artworks [6]. For example, think about a tactile map of a city. A short visual glance

[6] There is also non-salient visual information which leads to a more serial-type visual search. For a more detailed discussion on visual salience see Itti (2007).

allows us to infer information on the general layout of the town, its size, and maybe already the relative distances and locations of some hotspots. In the context of haptic perception, all this map information requires serial and, thus, more-time consuming exploration when performed haptically. The factor of response time can often be observed in automotive studies investigating the effectiveness of haptic feedback on user interaction. The haptic conditions often yield slower response times, which boils down to the serial-type mode of interaction. That means instead of just tapping the correct item on a list, haptic interaction inherently "requires" more steps during selection.

Haptic research has employed "haptic search" paradigms to explore the tactile saliency of object features, such as roughness, edges, etc. (Kappers & Bergmann Tiest, 2015b). These search paradigms have been adapted from the visual domain. Search tasks usually consist of a haptic display with distractor and target stimuli. The participant's task is to determine whether or not a specific target stimulus is present. The slope of the relationship between response time and the number of times indicates the "*pop-out*"-effect (or tactile saliency) of perceptual features. Shallow slopes indicate parallel search while steep slopes indicate serial search patterns (Kappers & Bergmann Tiest, 2015b). Overall, it seems search slopes are flatter the greater the disparity between the target and distractor stimuli — which sounds somewhat trivial (Kappers & Bergmann Tiest, 2015a; Lederman & Klatzky, 1997). Highly salient features can also be detected and recognized within "haptic glances" — a term which Klatzky and Lederman (1995) used to describe the act of a very brief touch. This seems highly relevant for application contexts, such as automotive, where the manual and cognitive resources for exploration are very limited. Saliency and haptic recognition might not only be modulated by perceptual dissimilarity but also by factors such as familiarity, prior cuing, and exposure (Klatzky & Lederman, 1995). This means that haptic information should be carefully distributed and laid out in interfaces for haptic design. Designers need to avoid "overcrowding" of haptic information and restrict the display of haptic information to some well-selected and designed locations. Visual cues might already modulate haptic search at the most basic level, for example, where users start to explore in the first place. Visual and cognitive cuing might also foster haptic recognition and saliency within temporally restricted exploration procedures.

The haptic channel is limited to the perceptual space of one's personal and direct environment. You can only touch what you can reach out to. This is also in contrast to the visual and auditory modalities, which allow one to pick up information from a distance. Visual observation is a passive, indirect, and disconnected perception of the environment. In contrast, haptic and tactile perception requires direct and close contact with the perceived object and an actively exploring agent. This directness of haptic perception creates a sense of intimacy and trust which is why it can also be called the "social" sense. A lack of touch becomes even more prevalent in times of social distancing.

Haptic perception is the only modality that senses information from the external world and can directly act upon it (Jones, 2018, p.7). Haptic exploration involves a deeply anchored bidirectionality and reciprocity of agent and object, which means haptics does not only involve touching (active) but also being touched — "What you touch, touches you" (Ranaweera et al., 2021). The notion of reciprocity also differentiates haptics from other sensory modalities, as simply observing the environment is already fundamentally changing it. We are aware of our graspable impact on the world and expect a proper reaction to our interactions. Immediate and direct feedback is an essential asset in interaction design as well (Kaaresoja, 2015).

Since haptic perception requires close contact, it can't be "switched off" as opposed to vision and audio, which can be sealed off from external influences by simply looking away, wearing blindfolding goggles, or putting on headphones. The haptic sense is always in a receptive state. This means it also picks up undesired signals, such as surface resonances, due to bad dampening of haptic systems.

Direct contact allows for private and discreet information communication as it is restricted to the interacting user. This private information channel might be highly relevant in certain interaction contexts. For example, in automotive haptic feedback, warning signals can be delivered solely to the driver without disturbing the other passengers. Norman (2007) refers to haptic feedback as a "*calm technology*". The direct contact between body and device allows for continuous yet subtle information communication. It does not require the perceiver's full attention. The direct nature of haptic information makes it especially useful in hazardous settings and environments where visual and auditive info is limited (Jones, 2018, p.101). Haptic perception can play a pivotal role in interaction contexts that are saturated by visual and auditory information. For example, in automotive, which is a visually and mentally demanding task, the haptic channel offers free processing capacities to convey important information to the driver.

Haptic perception allows the exploration of "hidden" information layers in objects. Some material properties are exclusive to touch, i.e., they explicitly require direct contact for perception and cannot be inferred from visual or auditory information (as already described in the previous section). While rougher types of textures and shapes may be inferred from the visual appearance, finer textures and material properties, like hardness, friction, and thermal conductivity, require direct haptic exploration as they hardly have any visual denominators. This is an interesting view on haptics in interaction design as it allows for visually calm but tactually rich interfaces.

The skin, which embeds the mechanosensors, constitutes the largest human organ. In this sense, haptic perception fundamentally differs from audition and vision as haptics involves spatially distributed sensors across the body. In contrast, sensors that receive visual and auditory information are highly localized (in the ears and eyes). Mechano- and other haptic-related receptors are not evenly distributed across the body. Receptor distribution and density vary as a function of usage for exploration procedures. Areas, which play a more significant role in haptic exploration, such as the hand, display a higher density of mechanosensors than areas of the body, such as the back, that are hardly used for haptic exploration. Perceptual sensitivity is often described by physiological parameters, such as perceptual thresholds[7]. The highest density of mechanoreceptors can be found in the regions of the lips, hand, and especially the fingertips. These areas also have a bigger cortical representation than areas like the back (Goldstein & Brockmole, 2017). This means that displaying the same tactile information at different body locations might result in different sensations. It's essential to have the user's touch points with the product in mind. Products might already fail to be appreciated as the haptic impression may not be strong or precise enough.

A higher density of receptors is associated with a higher tactile sensitivity, which is indicated by lower two-point touch and point localization thresholds (Birbaumer & Schmidt, 2018b; Lederman & Klatzky, 2009). Figure 6 depicts tactile sensitivity based on spatial two-point thresholds distributed across the body. Thresholds at the fingertips go down to 10mN (for force impulses) and 10μm for displacement impulses (for comparison, a mere tap impulse on a screen equals roughly 1N). Perception thresholds vary, among others, as a function of exploration force and movement. For an extensive discussion on perception thresholds for different haptic qualities, I would like to refer to Bergmann Tiest (2010), Jones et al. (2006), Klatzky et al. (2013), and Lederman and Klatzky (2009).

Even though haptics is the first to develop, it still seems to be marginalized in research and interaction. Compared to the strong body in visual and aesthetic research, information on how the haptic sense works is developing slowly. Also, active haptic technologies are just starting to be fully integrated into consumer devices. The result of the prevailing *ocularcentrism* is that media and interaction are mainly based on

[7] Goldstein and Brockmole (2017) give an in-depth overview of psychophysical procedures. Perceptual thresholds are reported in Birbaumer and Schmidt (2018a), Lederman and Klatzky (2009), and Weinstein (1968)

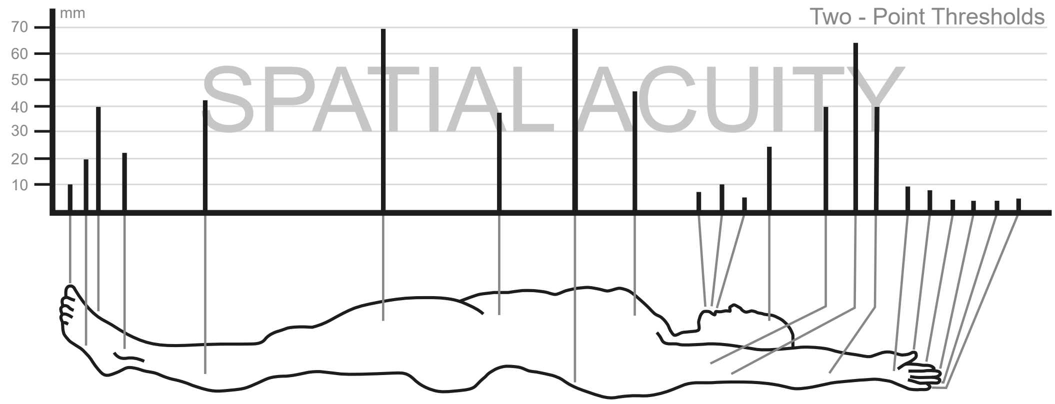


Fig. 6.: Tactile sensitivity varies across the body. This figure depicts two-point thresholds (approximate values) distributed across the body based on information from Birbaumer and Schmidt (2018a), Lederman and Klatzky (2009), and Weinstein (1968).

visual and auditory information (Moussette, 2012; Pallasmaa, 2012). What this means for interaction is that humans seem to be more accustomed to information transmitted via the visual and auditory channels. Due to the recent implementation in consumer products, haptic feedback is often a novel and unfamiliar experience that participants are not yet accustomed to.

Haptic design is inevitably multisensory — simply because haptic actuators almost always generate a certain noise level but also because haptic feedback is mostly implemented in multimodal contexts. Sensitivity towards temporal and spatial information varies across different modalities. This leads to specific modalities being more suitable to convey certain information than others. Jones (2018) suggests that within touch, the "amount of information [that can be] process[ed] is lower than that of the other senses". This also fits the notion of serial processing of haptic perception. Even though we can detect bumps with the size of 0.13nm during active haptic exploration (Skedung et al., 2013), spatial acuity is still higher for the visual sense. Two-point thresholds are lowest for vision, which is why lots of information from the external world, such as distances, movements, and objects' appearance, are mainly encoded using visual information.

Regarding the temporal resolution, haptic, again, is a mediocre sense compared to audio, which is specialized in processing speech. Within the haptic sense, we can discriminate two impulses that are up to 5 ms apart. For audio and vision, the temporal discrimination thresholds are 0.01 ms and 25 ms Kaaresoja (2015). Temporal acuity varies whether both stimuli are applied to the same locus or separate sites. Thresholds are also subject to the availability of additional sources of input. Kaaresoja (2015) extensively explored the role of latency in different modalities in a virtual interaction space. He examined the point of subjective simultaneity (PSS) in rendering virtual buttons and found that the PSS for touch input and tactile feedback was around 5ms (audio 19ms, vision 32ms), which coincides with the tactile temporal acuity described by Jones (2018). Kaaresoja also looked at the latency at which perceived quality starts to deteriorate. In uni- and bimodal conditions, the recommended latency for tactile impulses is much lower than for vision and audio, which pinpoints its importance in interaction. Delayed haptic impulses facilitate the impression of a lagging interface. Jones concludes that while comparisons may vary as a function of stimuli type and tasks, processing capacities of the haptic sense are inferior to those of the other senses. This does not implicate the quality of the impression. It's the practitioner's task to choose the most appropriate form of feedback for the task at hand.

A Psychological Turn 1.2

> *21st century design practice still treats psychology as an interesting add-on but not as the basis of consumers' needs and requirements*
>
> — **Claus-Christian Carbon, (2019)**

"Beauty is in the eye of the beholder". Even though this common saying mainly refers to the visual sense, it perfectly summarizes the essence of human perception — which is highly subjective. Psychophysics — an empirical discipline founded by Fechner in the 19th century — seeks to extract the influence of the perceptual apparatus by describing the relationship between physical stimuli and how they are perceived. In the early days of systematic haptic and psychophysical research, tactile devices have been designed around the need to produce knowledge about the functionality of the tactile senses (Parisi, 2018). Modern haptics originates from the field of robotics, characterized by a background of admiration for technical complexity (Hayward & MacLean, 2007; MacLean, 2008; Moussette, 2012). Despite increasing interest from psychologists and designers since the 1980s, the haptics community still seems to be driven by a techno-centric perspective. Commercial haptic systems are still often designed around technical considerations rather than actual user needs and expectations.

Moussette (2012) is one of many who points out that haptics perception equally entails a technic- and human-centric approach. Human (haptic) perception is not a mere and unfiltered sensation and processing of information. Perception often does not follow a clear relationship between input and effect but is heavily prone to cognitive processes. Goldstein and Brockmole (2017) describe perception as a continuous process of sensing, processing, and integration of information using prior experience (also see Figure 7 on p. 34). Prior experiences and context information decide which information and stimuli are paid attention to and picked up in the first place. How receptors are embedded in the skin also influences how information is coded and transmitted to the brain. So even before specific information "reaches" the cognitive apparatus, it has been altered on multiple occasions along the way.

The quote was published in *Psychology of Design* (Carbon, 2019).

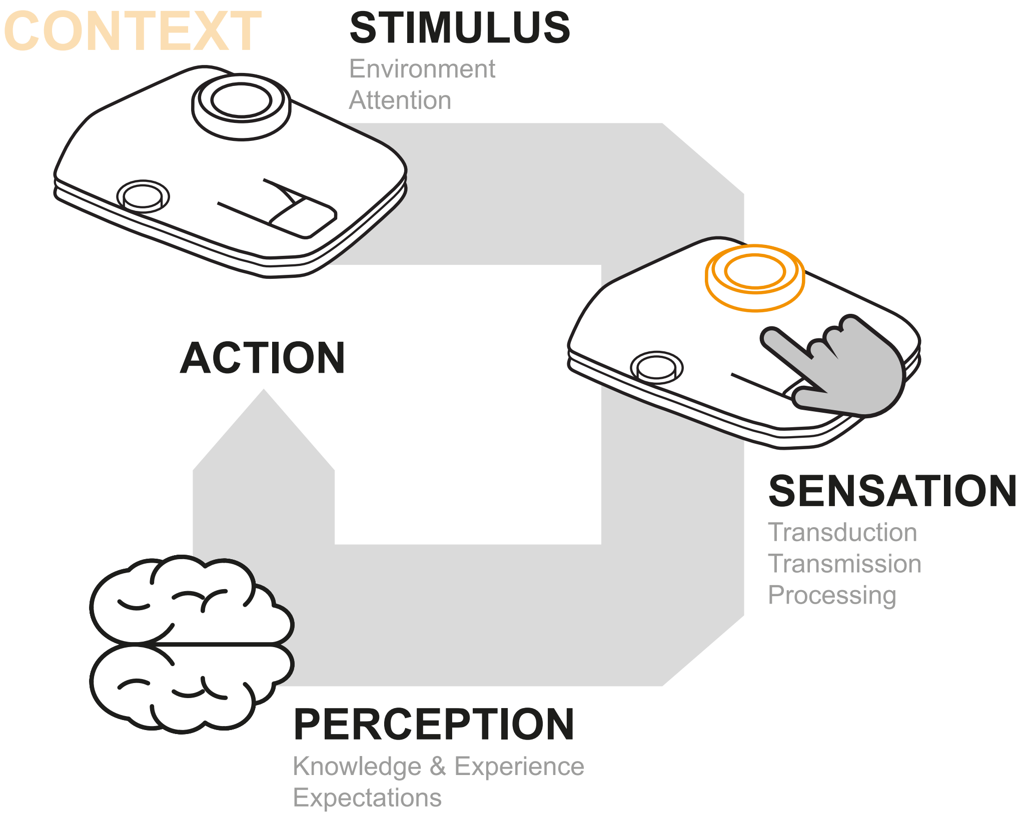


Fig. 7.: Perception is a continuous cycle of stimulus, sensation, perception, and action. Stimuli are modulated through context, environmental factors, signal processing, and cognitive factors (Goldstein & Brockmole, 2017).

Acknowledging and understanding the psychological basis of perception and interaction is critical for successful haptic design. Besides a safe and sound understanding of how technical systems work, stakeholders need to keep in mind who they are designing for — not just consumers, but humans (Carbon, 2019). Phrases like "human-centered design" and "customer-focused" must not be mere catchwords but the foundation of design as human perception, and thus, product experience is fundamentally influenced by cognition, emotions, and evolutionary- and culturally-developed behavioral patterns. Products meant to be used by humans must be designed around this specific set of perceptual requirements and challenges. For example, tactile embossing on public installations and maps enables visually-impaired people to participate. Also, tactile cues (such as seams, edges, etc.) on interactive surfaces alleviate visual and mental demand in highly demanding contexts, such as automotive, as acquiring control buttons does not rely on the visual channel.

Carbon (2019) advocates for a more profound psychological turn in design, which also applies to haptic interface design. This means that the design process needs to include a fundamentally human-centered approach. This requires (1) acknowledging the importance of an empirically-driven design and engineering process instead of focusing on the opinion of higher-level managers and (2) a proper understanding and application of psychological and cognitive processes in standard design practices. The *Psychology of Design*-framework Carbon (2019) specifies several important conceptual moves for the aesthetic appreciation and evaluation of design. Table 3 describes these conceptual moves and explains their implications for design. This thesis builds on these universal design principles and applies them to the context of haptic feedback design.

The following chapter will introduce some of the psychological fundamentals applied throughout the scientific contributions in this thesis to lay the foundation for a deeper understanding of the importance of psychological processes within the multidisciplinary field of haptics.

Tab. 3.: Summary of the conceptual moves from the *Psychology of Design*-Framework by Carbon (2019) and their implications on design.

Conceptual Move	**Summary & Implications on design**
1. *The object is dead, long live the subject.*	Reality is a mental reconstruction of the physical world. People might perceive similar stimuli widely differently.
2. *Perception means prediction, prediction means error.*	Perception is not a continuous bottom-up processing. It can rather be seen as continuous "*hypothesis testing*" (Gregory, 1980) to preserve perceptual and cognitive capacity
3. *Nothing is more constant than change.*	Design is driven by "Zeitgeist". Preferences do change over time.
4. *If you ask people about the future, they will talk about today's world.*	Users will judge and interact with objects by well-known and familiar standards. Innovations require familiarization.
5. *Cognition without the body is like voice without sound.*	Cognition and emotions need to be considered in an embodied framework, i.e., how they influence somatic aspects and vice versa.
6. *Design without context liquidates meaning.*	"Context creates meaning". Context information massively influences the evaluation and perception of aesthetic and utilitarian product properties.
7. *Consumer products are like persons, persons with character and potential for identification.*	Product functionality is no longer a decisive competitive factor in most markets. Design beyond mere product functionality. Designing towards specific personality-related traits creates a product personality that makes products "more predictable" and "more reliable" (Carbon, 2019).
8. *Affordances are task-dependent.*	Signifying design features depend on task requirements, e.g., a sticky surface material may be helpful if applied to the handle of a hammer but irritating on a steering wheel.
9. *There is nothing better than analogies.*	Perception is association-driven. Analogies result from our lifelong learning & perception history, which is driven by associations. They are crucial in how we perceive and interact with environmental factors. Employing deeply rooted analogies helps to guide novel experiences and interactions.
10. *Let the senses play together.*	Design is a fundamentally multisensory experience. Multimodal redundancy reinforces interaction.
11. *Analyzing the parts evidently kills the Gestalt.*	"The whole is something else than the sum of its parts" (Koffka, 1935). Product design creates a holistic experience that is qualitatively different than the addition of single product property. Breaking experience down into its sub-modalities during design and evaluation neglects the impact of "Emergence" and "Gestalt" (Carbon, 2019).

Note: The conceptual moves are derived from Carbon (2019).

1.2.1 Reality is a Construct of Predictions

The cognitive apparatus is geared towards highly efficient information processing to cope with the overwhelming complexity of external influences and everyday challenges. Psychological research preferably refers to perception as a top-down process that is driven by continuous testing of hypotheses[8]. This means that the perceived (and psychological) reality is not constructed piece-by-piece from the bottom up, as this information processing would be highly inefficient. Rather, new information is integrated based on assumptions and predictions. Behavior is adapted based on the continuous testing and evaluation of these predictions (through confirming or falsifying) in real-world experiences. This way, predictions allow us to organize and prioritize relevant information, prepare different action plans and choose the best option for interaction (Carbon, 2019). Especially cases with contradicting expectations and predictions might capture our attention (Carbon & Jakesch, 2013). Ontogenetical learning history, social and cultural influences, and personal experiences modulate predictions on everyday interaction. Ultimately, this means different people will never come to the same conclusion about a specific physical object.

The prediction-based nature of perception is also a fundamental driver of haptic exploration — especially in a functional-driven context like user interaction[9]. For example, Lederman and Klatzky (1987) already stressed the inherently psychological components of exploration procedures. They describe exploration procedures as highly efficient and specialized information collection strategies. The exploration movements that fit best to extract the required information to complete a particular task are performed. So, even before touching an object, perception is already guided by various object properties, such as prior visual information.

Klatzky and Peck (2012) describe visual preview as an essential parameter for predictions in the context of haptic exploration. They also depict a two-stage process of visual preview and haptic confirmation in their *visual preview model* (Klatzky & Peck, 2012). Visual preview is used to infer basic haptic object properties. Once visual information is insufficient for decision-making or task completion, objects are evaluated via haptic exploration on a much more detailed level (Carbon & Jakesch, 2013). For example, a surface with a brushed metallic appearance is often associated with a slightly colder feeling than plastic and wooden surfaces. However,

[8] The idea of "perception as hypothesis-testing" (Carbon, 2019) was initially established by Gregory (1980). Modern psychological research refers to this idea as "prediction coding" (Clark, 2013)

[9] This might be somewhat different for hedonically-driven contexts where people touch objects to experience pleasure (Peck & Childers, 2003)

the thermal impression can only be evaluated through direct finger contact. Users expect it to feel somewhat cold if it looks like a metal surface. A contradicting experience might impede perception, i.e., the touched surface does not adhere to the expected coldness impression. Another example would be using fake versus real material in automotive interiors. For example, suppose an interior surface looks like a real-material wooden panel but lacks the distinct haptic impression of wood grain. In that case, user evaluation of overall quality might be hurt due to the diverging material quality. In interaction contexts, false predictions might harm product experience and usability. For example, suppose symbols that indicate control elements visually. In that case, users might also expect to acquire them haptically. Users might be confused and frustrated if elements are not augmented via search haptic cues[10]. In hedonistic contexts Klatzky and Peck (2012) also refer to the "touch-ability" of objects to express how strongly visual surface properties "invite" haptic exploration.

Carbon (2019) emphasizes that understanding how predictions originate and why they sometimes fail is essential within the design process. The prediction-based nature of perception is also highly relevant in the evaluation of innovative technologies, as predictions are based on experience and context. In novel interaction contexts, users will likely apply familiar perceptual patterns that might not fit novel interaction premises. "Breaking the perceptual habits" (Carbon, 2019) and thus not conforming to previous predictions might negatively impact usability and overall product experience in initial contact scenarios. For example, in the *Where's my Button*-study (see Section 3.2.5), the overall haptic strength was perceived as relatively weak. Among other reasons, a potential issue was that participants were not accustomed to the kind of haptic feedback and expected vibration impulses as they were instructed to participate in a study that evaluates a novel haptic design approach. Designers must factor in a familiarization or elaboration period for innovative products (Carbon & Leder, 2005). Predictions are made upon exploring specific haptic forms and stimuli strongly connected to user associations, which play an essential role in later parts of this thesis (e.g., see Section 2.2.2).

[10] An interesting, positive example is the wooden version of the 2021 BMW iX center console. Even though there are no seams, the symbols itself is slightly elevated so that buttons can be haptically acquired effortlessly.

1.2.2 Experience is Different Than the Sum of Physical Sensations

> *The whole is something else than the sum of its parts.*
>
> **— Kurt Koffka (1935)**

"We do not perceive with the physical eye, but with a mental eye" (Ortlieb et al., 2020). Fechner, the pioneer and founding father of psychophysical research, already emphasized the highly subjective nature of perception in his notion of the "Aesthetic Association Principle" in the 19th century. Following Fechner's argumentation, it's not the physical appearance defining the object but rather the semantic information connected to it. One of the most prominent of Fechner's explanations is the comparison of an orange (the fruit) and an orange wooden ball. Even though the fruit and the ball are perceptually almost identical — they are both round, orange, and have a not perfectly smooth haptic touch — they are not identical from a psychological and cognitive perspective. What separates the wooden ball from the orange is that it lacks the mellow associations of exotic fruit, the association of health-promoting vitamins and nutrients, and so on.

From a purely psychological point of view, it seems secondary whether a person physically feels a specific object property or thinks they feel it. Both events probably trigger similar semantic information — a pivotal factor in understanding how to create immersive virtual experiences. In the context of virtual reality, vibration or force-feedback devices are used to infer real-world interactions and perceptions, such as textures and so on. Users are undoubtedly aware that they wear a VR headset and actuator-equipped garments. Nevertheless, they consider the virtual experience realistic and immersive because it triggers similar associations as the real-world pendant. Instead of meticulously recreating physical experience using the highest-grade technology and complex algorithms, designers and engineers might want to focus on user needs and triggering proper associations first: "Human problems are usually better solved by looking closely at the need, then surveying technologies to find the best match" (MacLean, 2008). On the other hand, further improvement in rendering algorithms might not be necessary as more straightforward approaches might already convey the proper semantic information.

The quote was published in *Principles of Gestalt Psychology* (Koffka, 1935). It also represents one of the basic conceptual principles of Gestalt Psychology

In line with Fechner's presumptions, gestalt psychologists would probably argue: "Experience is more and something else than just the sum of pure physical sensations" (Koffka, 1935). Understanding the association-based nature is also essential in interaction contexts and interface design. For example, interaction-based haptic feedback and the haptic impression of the surface (with all the associations that go with the perception of certain materials) constitute the haptic experience of the device. Furthermore, the haptic sensation of haptic impulses may vary drastically depending on the use case and context. While a specific impulse may be perceived as strong and precise upon a push interaction, it might feel different if the same impulse is used to augment a sliding interaction. The same haptic impulse might also be perceived differently when accompanied by specific sound or visual feedback. For design and evaluation, this means not solely focusing on creating a uni-modal feedback sensation but keeping an eye on the bigger picture of how users experience products overall. Even though uni-modal experiences are carefully designed with respect to their perceptual prerequisites, the overall product might still be perceived as unfitting.

Similar to predictions, associations are driven by context, experiences, and personal learning history. Knowing about associations means knowing about user expectations, which are crucial in making interfaces more efficient and pleasing to use. Conforming to user expectations and triggering familiar associations makes interfaces feel more natural as they integrate into existing perceptual and behavioral patterns effortlessly. Using familiar analogies and metaphors might govern the introduction of novel interface technologies that users might not have yet had the chance to adapt to. Especially in the context of a hapticification of seamless automotive interface surfaces, transferring the high-quality haptic impression from traditional button interfaces into the digital interaction space has been troublesome. This mainly lies in the fact that even though users have become accustomed to touch interactions, they have not yet fully adapted to the different kinds of haptic feels that come with active haptic technologies. While active haptic actuators are geared toward recreating a button click that may conform to prior associations, designing a more complex haptic pattern requires the implementation of a new haptic language tailored to user needs, expectations, and associations.

By applying an association-based perspective on interaction, designers might take advantage of the semantic content that each novel technology offers. Associations are a strong design tool as they implicitly communicate potential courses of action — similar to Norman's notion of affordances and signifying design features — and hence only require little to no specific learning or training (Norman, 2007, 2008, 2013). Instead of mimicking traditional elements, semantic content, such as functionalities or operations states, might be augmented via haptic feedback by triggering associations learned through previous interactions. This includes that designers need to know which kind of associations are triggered when using a specific haptic profile or technology. Kim and Schneider (2020) refers to *timbre* as a technology-specific component of haptic experience. Even though designers vary the pattern duration, strength, or sharpness of the signal, the basic perceptual character of the technology remains similar — analogous to acoustic timbre. For example, in a later described study that implemented electrostatic friction modulation, multiple participants reported genuinely negative associations that might have a substantial negative impact on haptic experience (see Section 3.2.4 and Section 3.2.5). The haptic feeling reminded them of small electric shocks.

Later sections of this thesis describe how an association- and experience-driven design may improve the overall product experience. The first example is the introduction of the *Haptic Fidelity Framework* (Breitschaft et al., 2022a). We argue that instead of focusing on technical parameters to compare and evaluate different haptic technologies for their appropriateness in UI contexts, it's more important for designers to evaluate the semantic content technologies offer for haptic design. In preliminary studies described in Heijboer et al. (2019a), we also stress the notion (even though it sounds trivial) that users do not think and speak in technical terms when experiencing vibration haptic patterns but rather use metaphors and semantics. Especially longer-lasting vibrations can convey plenty of semantic information, such as a "don't touch" and "alarming" association. In Breitschaft et al. (2022b), we employed an association-based paradigm to examine the perceived functionality of haptic forms to derive guidelines for haptic interface design.

Edges and seams have been a driver of search haptic qualities in interfaces for a long time. This thesis's early draft aimed to examine if active haptic technologies, such as linear resonant actuators, piezos, or friction modulation, can be used to "simulate" real, physical edges (inherent in traditional button interfaces). However, I quickly realized that from a perceptual perspective, it might hardly be possible to answer this research question with "Yes". The most important insight was that it doesn't really make sense from a user's point of view. First, the sensory input of active and passive haptics is widely different. Additionally, what is also missing is the visual impression of the deforming finger. From a psychological perspective, it misses another fundamental point: Is the perfect vibration or friction-based recreation of an analog edge sensation the decisive factor for good search haptics on other flat surfaces? To keep it short: not necessarily. Moussette (2012) hits the nail on the head when he says that designers should focus on user experience instead of trying "to recreate naturalistic stimuli using unnatural systems". Even though one might develop an active system that perfectly renders the frequency responses of the edges sensation, the psychological component will still be different. Users don't touch a traditional button-enriched control panel but rather a flat digital touch-sensitive surface. So instead of mimicking real-world experience using artificial systems (Moussette, 2012) we might want to focus our resources on how to provide the same set of associations that evoke a sense of search haptics using different technological approaches.

1.2.3 Scenario is What it's all About

> *Interactions with products do not take place in a vacuum.*
>
> — **Hekkert & van Dijk (2017)**

Amongst others, Hekkert and van Dijk highly emphasize the importance of context for product design as it "creates meaning" (Carbon, 2019). As already depicted in Figure 7 (p. 34), perception does not start at the receptors but with the context in which perception and interaction take place. Experience and contextual information determine which information humans pay attention to and are processed in the first place — it is setting a reference frame for perception and interaction. This is important for safety-relevant and cognitively demanding contexts, such as automotive. For example, haptic exploration cues, which are highly salient in single-task conditions, may be much less salient once they occur in cognitively demanding environments with limited mental resources. This coincides with findings from the *Where's my Button*-study examining electrostatic friction modulation (Breitschaft et al., 2022b).

Carbon and Jakesch (2013) describe a fundamental influence of contextual information on aesthetic and utilization evaluation in haptic processing. They illustrate that the same haptic sensation has a different functional and affective value in different contexts. Context information is highly task-dependent and establishes a cognitive reference frame. For example, a car's price segment defines the user's quality benchmark. In cheaper cars, "fake materials", such as artificial leather or interior trims, using wooden- or metallic-looking foils, may still be considered high-quality. However, they will probably deteriorate appreciation in luxury models where customers expect the application of real materials. Conversely, depending on social peer groups, market position, and personal beliefs, applying artificial leather instead

The quote was published in *Vision In Design* (Hekkert & van Dijk, 2017).

of real leather might be evaluated as a more sustainable and high-quality approach. Especially for haptic material properties, it is almost impossible to establish a context-independent association of aesthetic evaluations, such as pleasantness and specific haptic parameters. For example, while a smooth surface might be pleasant to touch, it might be inappropriate when applied to a hammer's handle requiring a tight grip. The context and task demands govern how people interact with and evaluate specific design features. Considering this context-dependence is also important when testing design iterations. Jakesch et al. (2011) call this *scenario-based* testing. The testing scenario requires an appropriate imitation of the most important features of the original context (Carbon, 2019).

Due to the nature of haptic perception (direct contact, sequential information processing, etc.), "bottom-up" factors, such as the temporal and spatial context that modifies processing on a sensory level, play a role in haptic processing in addition to "top-down" context information. In contrast to visual and audio processing, haptic information is mainly integrated in a serial fashion. Also, the sequence of exploration and how many hands are involved impact how objects are perceived. Using different fingers and hands might lead to masking effects (Vardar et al., 2018). Tactile salience is highly influenced by local context information (MacLean, 2008; MacLean & Hayward, 2008), i.e., a rough button texture is much less salient when the surrounding non-interactive areas have a textured touch, too. Tactile perception is also prone to sensory saturation and tactile aftereffects. For example, when exploring a rough surface for a prolonged time, receptors become oversaturated with the perceptual input. This means the sensory system adapts to the perceptual input and perceived roughness decreases over time. Kahrimanovic et al. (2009) depicts that for roughness, this also happens the other way around, meaning that the perceived roughness of surfaces increases if the previously explored surface is smooth. These aftereffects seem to persist for different haptic parameters, such as size, shape, and curvature (Kappers & Bergmann Tiest, 2015a).

Studies suggest that tactile aftereffects underlie a crossmodal influence for specific perceptual parameters. Visual perception of surfaces might lead to sensory adaptation of subsequently haptically explored surfaces (Kappers & Bergmann Tiest, 2015a). This shows that haptic feedback is inherently embedded in a multisensory experience. Multisensory information provides essential context information that influences haptic perception and vice versa. Tikka and Laitinen (2006) describe a biasing effect of audio on piezo-actuated haptic impulses. In automotive, the "Audi-Click" is a well-known example. In addition to a button click feeling, Audi has incorporated a strictly defined high-frequent click sound upon pushing buttons and turning dials. This fuses the haptic and audio impression into a highly precise experience. It may also allow the haptic impression to appear more robust than in unimodal conditions. This we also observed when comparing the effectiveness of the different feedback modality conditions in the *Where's My Button*-study (Breitschaft et al., 2022b). Overall it is essential to understand how uni-modal impulses are perceived "on their own", but designers need to be aware of the impact that different sensory inputs have on each other when employed in joint feedback events. Multimodality is a crucial part of the scenario.

In a nutshell, context, which refers not only to the situation and task in which interaction takes place but also to the "perceptual" scenario, is a crucial parameter that practitioners need to consider. This also refers to how different design iterations are evaluated. Testing design without proper context is meaningless (Carbon, 2019).

1.3 Haptic Technology

Haptics takes place at the intersection of psychology, design, and engineering — good haptic design results from a symbiosis of perception and technology. Hence, designing compelling experiences requires understanding the psychological reality of users and how to translate this reality into hardware and vice versa. From my studies, I found that — for psychologists and user-focused practitioners — a firm understanding of how different haptic technologies work and what differentiates them from one another facilitates the design process by giving a better overall knowledge of the product and eases communication with process partners. It allows for a better evaluation of technologies for specific use cases. Especially in search haptics, the different technological prerequisites significantly impact the overall effectiveness of interfaces.

The field of haptics has attracted a lot of attention in recent years, which also means that plenty of practitioners from different academic backgrounds and levels of expertise have been — and are still — entering the haptics community. While it may already be difficult for proficient practitioners to keep up with the current status quo of haptic technologies and follow ongoing trends, it might even be more difficult for novice practitioners. In an enterprise context, it's crucial to know how different technologies work and which technologies are currently available on the market. This section covers the efforts to provide a snapshot of commercially available haptic technologies and clear the fog on a somewhat intransparent marketing-driven business by introducing a novel experience-driven approach to evaluate and categorize haptic technologies based on their fidelity.

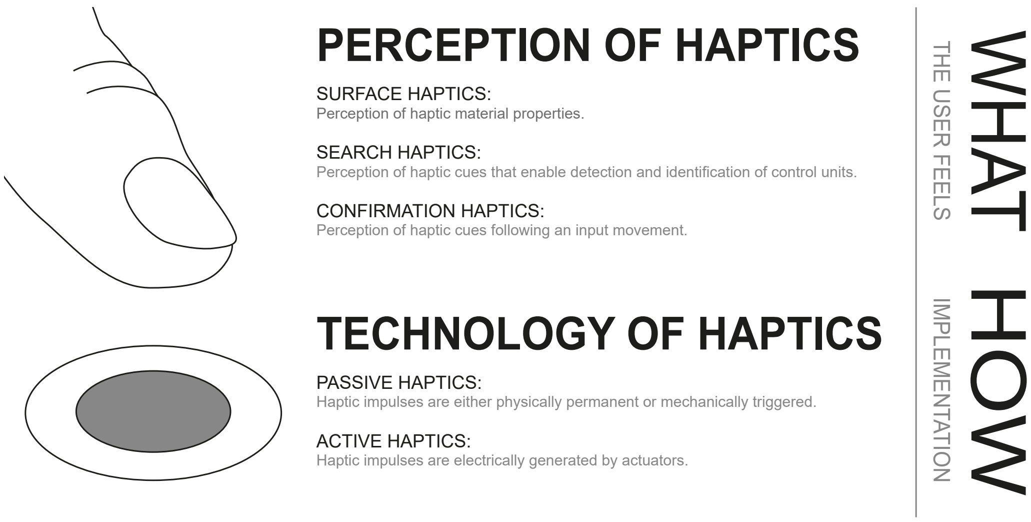


Fig. 8.: Interaction-based automotive haptic feedback consists of a perception- and technology-focused perspective, each with a specific set of terminology: active & passive, surface, search & confirmation haptics (Breitschaft et al., 2019a).

Active and Passive Haptics

When designing haptic interaction, practitioners can use various technological approaches to make virtual content "more graspable". In the context of interaction and specifically automotive, haptic technologies can basically be categorized into two major groups regarding their technical implementation: active and passive haptics (see Figure 8)[11].

Passive Haptics refers to cues that are either created by mechanical, non-electrical elements or manifested in the physical environment through material or surface properties. Passive feedback is produced by mechanical parts and does not require an electrical current to give haptic feedback. As passive systems rely on purely mechanical components, they are usually cheaper than their active haptic counterparts. In the context of buttons, feedback is mainly created by a silicon mat or metal dome (or a combination), which collapses due to pressure. Displacement ranges from 0.2 to multiple millimeters, meaning button surfaces require circumferential joints that allow this movement. Passive haptic elements are usually described by force-displacement or torque-angle curves — depending on the type of control element[12]. Specific combinations of force and displacement parameters correspond (actuation force, stroke, etc.) to how users perceive the elements (Reisinger, 2009). This means buttons can be designed to convey a specific impression. For example,

[11]The haptics terminology will be described in more detail in Breitschaft et al. (2019a), as well as Figure 8 (p. 46) and Figure 14 (p. 83); Figure 8 ©2019 Breitschaft, Clarke & Carbon, CC-BY
[12]Exemplary haptic curves are described in Figure 14 (p. 83)

a stiffer feeling button press (a higher actuation force) was reported to have a sportier feeling (Rösler et al., 2009). Surface cues conveyed via physically anchored and permanent material properties, such as seams, bumps, textures, etc., are also described as passive haptics — even though haptic surface properties are often not directly characterized as technologies. As tactile cues, such as shapes and textures, are physically permanent, they do not allow completely flat surfaces (Continental, 2018). Passive haptic technologies are highly adaptable (also through technological advancements in material sciences). They can thus be applied in many contexts, i.e. supporting eyes-free haptic exploration and confirming user input. However, this flexibility can only be facilitated during the research and design process as the feedback is physically permanent and cannot be altered after production or adapted through software. As passive haptics depends on different types of perceptual qualities, search- and press-related use cases require the application of other haptic technologies (even though seams and joints are often a by-product of mechanical switches). Mechanical switches, levers, or rotary encoders, which have been integrated into in-vehicle control panels for decades, can be classified as passive haptics. This also means that users are familiar with passive technologies' haptic impression.

Active Haptics refers to tactile stimuli generated by devices that require electrical current and voltage to operate. Operating voltage can vary from some to multiple hundreds of volts. Active haptic systems are mainly described by acceleration curves (sometimes also by displacement-over-time curves). Active systems consist of numerous interconnected elements, such as an enclosure, spring-damper-system, actuators, sensors, etc., which often makes them reasonably complex. This complexity is further increased by the influence of different driver systems and control algorithms on the haptic experience (for a more detailed description, see Figure 10). The bill of materials is mostly much higher than for passive systems. Hence, passive systems are often preferred if only a simple button click is required. Active systems do not necessarily need active user input to convey haptic stimuli. They can also act as purely tactile interfaces, for example, vibrate in certain situations like lane deviation. From an interaction design point of view, active haptic systems are much more flexible as they are mostly fully programmable and theoretically only limited by the actuator's (and the system's) capabilities. Due to the programmability of active haptics, a single actuator can cover a gamut of different haptic use cases. Haptic stimuli can be fully adapted to different scenarios and contexts on the fly. For example, it can be used to recreate a mechanical button click while pressing but also to simulate a haptic texture pattern during exploration. Active haptic systems can provide highly customizable and personalized experiences. From an aesthetical point of view, active haptic systems allow for a cleaner-looking and monolithic appearance (as opposed to passive haptics) as they usually actuate the entire interaction surface and movements are within microns. Active haptic feedback is often based on novel interface technologies that users are not yet familiar with (see Chapter 1.2). On the one hand, experiences often still need habituation. On the other hand, novel active haptic technologies can potentially create a "wow"-factor and brand-shaping experiences.

Even though passive haptics is a valuable resource in interaction design, the following section will only cover active haptic technologies. Part 2 describes how to leverage passive haptics forms and material properties in the context of automotive surface haptics.

1.3.1 Conference Poster: Physical Fights Back

This section, including all figures, is based on:

Breitschaft, S. J., Heijboer, S., Shor, D., Carbon, C.-C., & Tempelman, E. (2020a). Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.32973.26086

Abstract - Haptic feedback is an inherent part of future, seamless user interfaces. From the ever-growing list of companies and startups to the thriving and diverse community of engineers, psychologists, and designers, the moment for haptics and touch-based feedback has arrived. Yet, the abundance of review papers on haptic feedback fails to give an application-based overview of haptic technologies for practitioners. They mainly offer a psychological perspective, focus on pure technical details, or lack contextual, emotional, and application-focused details. Finally, the current literature focuses on research-based outcomes and refrains from directly connecting with current commercially available solutions. To create a practical review of current commercially available technologies, we seek to provide a perception-based technology selection method for practitioners that considers engineering, psychophysical, and design perspectives. This method will enable practitioners to label their interaction requirements to a haptic perception – improving the selection of appropriate haptic technology. A preliminary setup for a decision tree will give ground for further discussion on how to incorporate a product's emotional, engineering, and interaction requirements into a common set of selection criteria. The goal is to create a practical haptic design guide that links product emotions and psychophysical effects to technologies and their hardware integration and settings.

The conference poster can be found in Appendix A.1 (p. 192).

Physical Fights Back is a striking description of a theme that reverberates throughout the interaction community in recent years: bridging the gap from tactually-rich analog interfaces to digital and tactually-poor interaction spaces that became a ubiquitous part of interaction since the introduction of the first iPhone in 2007. Ever since, efforts have been made to examine how an additional physical layer can enrich virtual interaction and bring back tactility to previously hands-on interactions.

As haptic technologies have been around for quite some time (also in the context of consumer interfaces), one might expect that the integration of haptics into everyday products should be far more advanced. However, it feels that technologies are applied somewhat inefficiently. This means actuators are primarily chosen based on costs and marketing reasons instead of which technology fits best to user and task requirements. Additionally, technologies are mainly evaluated and compared on a purely technical basis instead of the range of experience, they can deliver. Also, an up-to-date overview of which technologies are available to practitioners is missing.

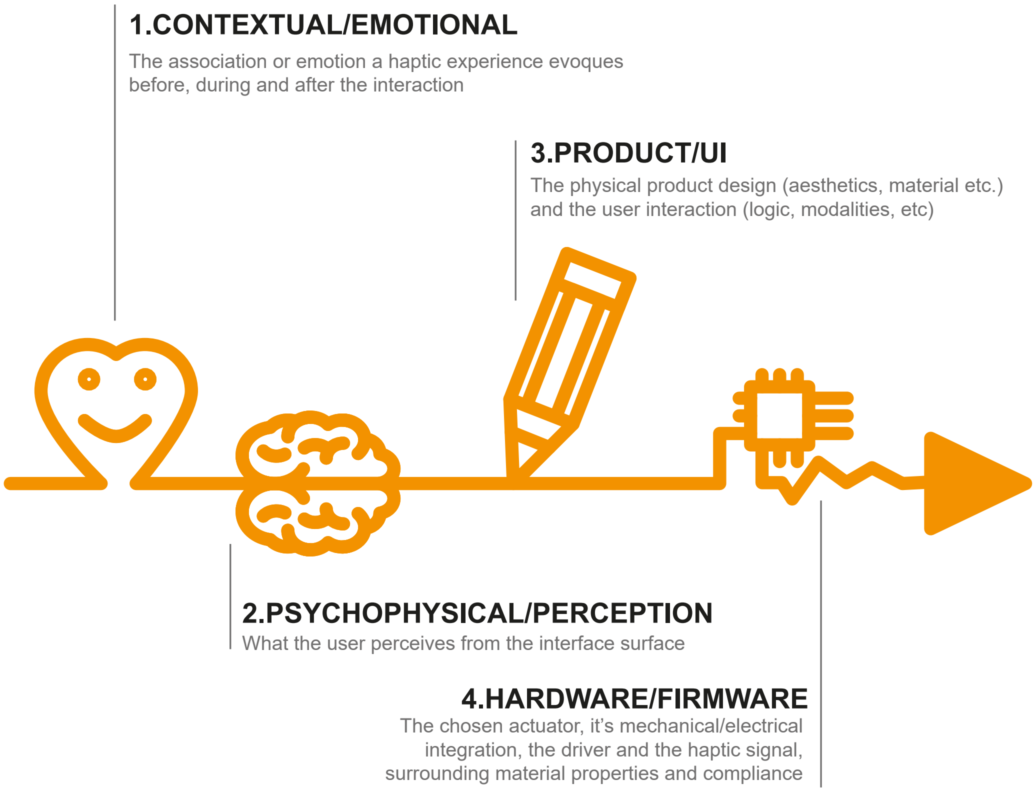


Fig. 9.: Starting the haptic design process by defining contextual, perceptual and interaction-related prerequisites helps practitioners choose and implement the most appropriate technology.

We aimed to introduce the *Haptic Fidelity Framework* as a novel way of categorizing and comparing haptic technologies, which is based on fidelity and appropriateness for interactions rather than technical descriptors. The framework idea was presented as a work-in-progress contribution at EuroHaptics 2020 conference. We sought to iterate the framework based on feedback from academic and industrial practitioners from multidisciplinary backgrounds. Initially, we intended to follow up this work-in-progress contribution as a two-part paper: Part One, which covers the idea of the fidelity framework as an experience-based categorization methodology and Part Two, which provides a technology selection guideline that also takes contextual, emotional, psychophysical, perceptual, user interaction as well as hardware aspects into account (Figure 9). The basic idea of the technology selection guideline revolves around implementing a Why-What-How approach to choose more appropriate technologies for haptic products (for a brief description, see Section 1.4.2 and Chapter 4.2). As including both parts may have resulted in an overly complex academic article, we focused on adequately introducing the *Haptic Fidelity Framework*, its premises, and its application of categorizing currently available technology first.

1.3.2 Journal Article: Haptic Fidelity Framework

This section, including all figures, is based on:

Breitschaft, S. J., Heijboer, S., Shor, D., Tempelman, E., Vink, P., & Carbon, C.-C. (2022a). The Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-Based Haptic Technologies Through Fidelity [Journal Article]. *IEEE Transactions on Haptics*, *15*(2), 232–245. https://doi.org/10.1109/TOH.2022.3152378 ©2022 IEEE

Abstract - After decades of research and development, haptic feedback is increasingly appearing in consumer products. While the prevalence of haptic feedback is increasing, the integration rarely offers increased fidelity to previous generations. We argue this is because of the tremendous complexity of successful haptic design engineering and because of information saturation. With novel cutaneous feedback technologies and companies emerging almost daily, the multi-disciplinary nature of haptics and the marketing-driven terminology used to stand out in a crowded market makes it challenging to select and integrate actuators correctly. To manage this complexity and facilitate the interdisciplinary exchange of user requirements and material affordances, we introduce a novel classification criterion for haptic actuators focused on the bandwidth and fidelity of potential effects. We introduce vocabulary for describing the precise experience the actuators and corresponding systems should deliver. Lastly, we summarize currently commercially available cutaneous-based haptic technologies. In the near future, the same criterion and language can also prove valuable for steering technology development of new and improved actuators and enabling novice and experienced practitioners to understand and integrate cutaneous feedback in their products.

The journal article can be found in Appendix A.2 (p. 193).

Motivation

Following David Parisi's notion on the *Archeologies of Touch*, we currently face the fifth phase of interfacing (Parisi, 2018). Marketers are promoting the necessity to include haptic feedback in interactions to make them more human-centered. Increasing safety concerns in automotive due to tactually poor and visually demanding control interfaces and the request for higher fidelity virtual experiences (Stein, 2021) are only two discussions that push towards a stronger implementation of haptics into everyday products. Haptic start-ups increasingly gain recognition at trade shows for introducing prize-winning haptic-enabled products (Consumer Electronics Show, 2020, 2022; Hap2U, 2020).

This "rediscovery" of the haptic sense and its growing implementation into everyday products partly originates from technical advancements in actuator technologies.

Haptics is crucial in enhancing user experience in otherwise mainly rigid and featureless haptic interfaces. For a fact, the recent haptic trend led — and still leads — to a new wave of practitioners with different academic backgrounds and varying levels of expertise entering the domain of haptics. They are confronted with an overwhelming amount of different technological solutions which can hardly be separated and compared due to different and often proprietary working mechanisms, the marketing-driven terminology of haptic capability, and the focus on technical specifications. Essentially, what is missing is (1) a current overview of haptic technologies that are accessible for novice hapticians but also veterans and (2) a pragmatic approach to analyzing, comparing, and evaluating haptic technologies for their purposes. Schneider et al. (2017) already pinpointed the necessity for a common language to communicate haptic experiences.

Currently available overview papers are often impractical as they (1) only focus on the broader perspective of haptic feedback often without going into much detail on specific use cases (Sreelakshmi & Subash, 2017), (2) summarize haptic technologies in a narrow field of application, e.g., telesurgery, virtual reality (VR), automotive, etc. (Gaffary & Lécuyer, 2018), (3) review particular kinds of haptic actuators, e.g., dielectric elastomers (O'Halloran et al., 2008), (4) recreate particular phenomena using active haptic technologies (Culbertson et al., 2018) or (5) entail non-peer-reviewed white papers published by haptic companies (e.g., Boreas Technologies, 2020b; Rao, 2012). Due to the research-focused nature of most scientific journals, peer-reviewed contributions mostly rely on proof-of-concept research devices with a low technological readiness level. Thus, practitioners hardly have access to them. Those contributions are undoubtedly valuable in pushing the field forwards. However, they often yield only limited practical values for practitioners.

Haptic actuator technologies are mainly described and reported using different technical parameters like frequency, amplitude, and power consumption. This indeed allows for a technical evaluation concerning mechanical integration and the calculation of business cases. However, a purely technical description does not allow for a direct conclusion on the range of haptic experiences a specific technology can convey — or, more precisely, what it should best be used for. The focus on technical descriptors also does not reflect how practitioners work and design haptic feedback. Schneider and colleagues describe that haptic experience constitutes multiple technology-specific design parameters, such as timeliness, density, intensity, and timbre (Kim & Schneider, 2020; Schneider et al., 2017). They propose that even though technologies may provide a broad range of haptic qualities (e.g., very low, diffuse to high intensity, and sharp vibrations), these qualities usually stay within a certain range of experience. This limited range of haptic experiences is based on

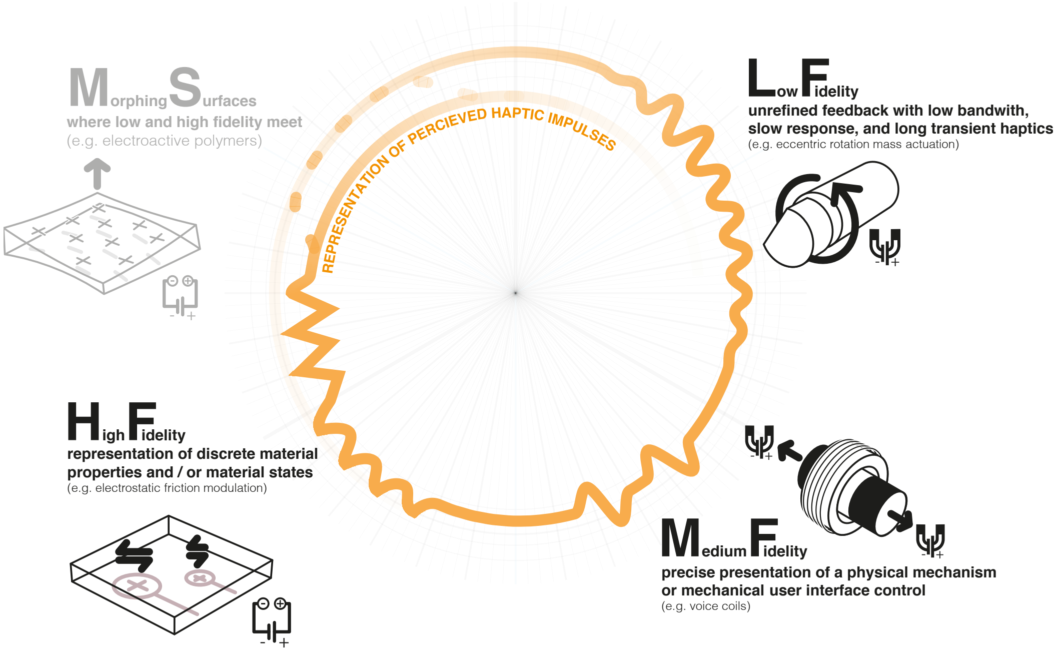


Fig. 10.: The *Haptic Fidelity Framework* is characterized by three levels of fidelity: low, medium, and high. The orange lines characterize the haptic experience at each stage of haptic fidelity (Breitschaft et al., 2022a). ©2022 IEEE

technical prerequisites, which also impact an actuator's appropriateness for specific use cases.

To reflect practitioners' reality, we propose the *Haptic Fidelity Framework* as a perceptual and experience-driven approach to communicate, compare, evaluate, and categorize haptic technologies. This systematization is based on fidelity rather than actuator bandwidth to emphasize the relevance of the haptic experience for haptic design. The *Haptic Fidelity Framework* strongly promotes the idea that practitioners should choose haptic technologies based on how well they fit the use cases and interaction they want to create instead of merely looking at the quality and "realism" of the experiences.

Conceptualization

The goal of the paper itself was twofold: (1) proposing an experience-driven way of organizing haptic technologies and (2) at the same time applying this framework to provide an up-to-date overview of currently available haptic technologies. While haptics covers a vast range of information channels (also see Figure 3, p. 15), we decided to tailor this overview to technologies that rely on cutaneous and predominantly vibrotactile information, i.e., technologies that require direct skin contact. We applied this limitation to minimize complexity and provide a focused overview of the type of actuators that are highly relevant in current-gen display-based user interfaces.

As the haptics market is evolving rapidly, this overview only provides a snapshot of the haptics market status quo (end of 2021). The summary of technologies is based on an extensive review of available haptic technologies carried out between March 2020 and January 2021. Minor updates were performed throughout the review process. The author's professional experience and expertise in designing for and working with some of the reported haptic technologies influenced the review. We did not restrict our research to scientific and peer-reviewed papers, as plenty of information on products and technologies is only available through the manufacturers' websites or third-party articles. Technologies were categorized using available data from spec sheets, information found in prototypes/demos, and personal experience with each technology. Only technologies that met the inclusion criteria mentioned above were included.

The *Haptic Fidelity Framework* is organized into three distinct and progressively increasing levels of haptic fidelity that actuators can deliver (Figure 10): low, medium, and high fidelity. Based on their *timbre*, haptic technologies can generally be assigned to one of these levels.

> **Low-Fidelity:** Haptic events resemble mere vibrations (varying in frequency and amplitude), but mostly with no clear start and end stop. Demarcated haptic events can hardly be achieved.
>
> **Medium-Fidelity:** Actuators allow demarcated haptic events and thus the recreation of physical mechanisms, such as mechanical button clicks, within a narrow or broad frequency and amplitude bandwidth (depending on the actuator).
>
> **High-Fidelity:** Technologies can convey complex and highly precise haptic patterns either by tangential or orthogonal interactions on a surface.

There is another subcategory, *Morphing Surfaces*, which bridges the gap between smart materials and haptic technologies and sits at the intersection between high and low fidelity. This type of technology is not described in detail in the published article, basically due to the haptic impression's complexity, which makes it hard to categorize it into discrete levels. The material impression is often high-fidelity as it involves material changes, e.g., from soft to hard or flat to rigid. In contrast, the generated vibrations resemble those of low-fidelity type technologies.

The term *fidelity* is used in an interaction-driven manner. Fidelity neither indicates an actuator's accuracy in recreating physical information in digital interactions nor is it synonymous with the perceived quality of haptic impulses. It refers to a "technology's capabilities to convey a broad range of perceivable haptic effects" (Breitschaft et al., 2022a). The framework does not imply that low-fidelity experiences are inherently low quality. Instead, it emphasizes the appropriateness of each technology for specific haptic interactions and use cases. As such, the framework proposes that the perceived quality of haptic experiences depends on the appropriateness of haptic stimuli and technologies rather than technical supremacy. For example, eccentric rotating mass actuators (ERMs) — the early ancestor of modern-type screen-type haptic actuators — are usually deemed to have a low-quality rumbling haptic quality. One of the main applications of ERMs has been notifications in mobile phones, which ERMs are highly suitable for due to their high strength. If implemented in use cases requiring relatively short and precise haptic impulses, ERMs can feel somewhat unfitting and cheap. On the other hand, higher-fidelity actuators, such as piezo, are also capable of producing lower-fidelity experiences, such as simple vibration. However, they would be highly overpriced if the vibration is the primary use case.

The fidelity levels and technologies are not further specified in this thesis. For a more specific description of the fidelity levels and an overview of the haptic technologies, I would like to refer to the published article: Breitschaft et al. (2022a)

Discussion

Apart from providing an up-to-date technology overview, a major goal was to propose a **practitioner-focused approach** to working with haptic technologies for novice and proficient practitioners. Evaluating haptic technologies purely based on technical parameters lacks the honesty of the actual haptic impression (Kim & Schneider, 2020). Actuators only make a small (but crucial) part in complete haptic systems that consist of an enclosure, mechanics, electronics, firmware, software algorithms, etc. There are a lot of building blocks that effectively influence the haptic experience. Only looking at actuator spec sheets neglects the embedded nature of haptic interfaces and experience.

The *Haptic Fidelity Framework* does not advocate abandoning the consideration of technical values for the product design process but rather complements it. Following technical instructions is crucial as technical information, such as operating voltage or power consumption, fundamentally impacts mechanical and electric design. Instead, the framework advocates that spec sheets should not be the sole basis for assessing haptic experience. Different technologies have different working principles and technical prerequisites. Hence, technical specifications and their impact on haptic stimuli can hardly be compared — in most cases, it is like comparing apples with pears. Users do not have a fixed reference frame for which type of haptic feedback they deem high definition. It's not graspable for users what certain frequencies, amplitudes, or voltages mean and how these specs relate to what they feel (also see Heijboer et al. (2019a) and Section 3.1.1). It depends on factors such as integration into the UI, experience, context, overall product impression, etc. It basically depends on the appropriate haptic experience within the given interaction.

From a technical perspective, there is hardly any standard as to which specifications qualify technologies as *high-definition*. The recently formed *Haptics Industry Forum* leads efforts to introduce a parameter-based industry standard for *HD-Haptics* (Haptics Industry Forum, 2020). Similar to video and audio resolution, this might ensure a certain level of capability and complexity from a technical perspective. However, it will not ensure a high-quality experience as there is still the risk of technologies being applied in a manner they are not designed for. Instead, the *Haptic Fidelity Framework* proposes to implement technologies based on their **suitability** for specific interactions to create a high-quality experience.

As already described earlier, this overview only provides a **snapshot of the current industry** as the haptics market is almost evolving at an almost exponential level. The initial research was done from April 2020 to January 2021 (initial submission date). Some information was already outdated upon publication as technologies and companies were either discontinued, just entered the market, rebranded their products, or enlarged their portfolio. Even though the overview will probably soon be outdated and requires constant updates, we believe it provides a solid basis for the upcoming years. This revision of the *Haptic Fidelity Framework* only includes an overview of active haptic technologies within the field of direct touch display interactions. This article was explicitly tailored to this type of interaction for reasons of complexity and comprehensibility. However, a similar approach might be valuable for other technologies and applications, such as kinesthetic and force-feedback devices or VR/AR[13] applications.

During the review process, there was an intense discussion about whether this kind of article might be fitting and relevant for publication in an academic peer-review journal. The arguments included: the proposed categorization method is based on experience rather than hard facts, the overview lacks technical specifications to be called a tech review, and the style of describing technologies is too colloquial. The

[13]VR/AR: virtual reality, augmented reality

Haptic Fidelity Framework may only provide a coarse and — for engineering-focused practitioners – somewhat fuzzy and "soft" perspective on haptic technologies. The framework should help practitioners by following their workflow and provide a **pragmatic** and easy-accessible approach to assess and evaluate haptic technologies. A lot of practitioners entering the field of haptics have a non-technical background. Using a more colloquial language reflects the user's and practitioners' reality. Especially in design contexts, haptics is mostly communicated via descriptions, analogies, semantics, and metaphors – e.g., "The feedback should feel like the clicking of a massive vault lock". Describing haptic experience via metaphors also reflects how we (my co-authors and I, all of which actively work in the field of haptics) communicated our ideas throughout this manuscript's ideation and writing phase. We believe that especially practitioners with a non-engineering background will profit from a more pragmatic way of speaking about haptic technologies.

1.3.3 Implications of Haptic Fidelity on Haptic Design

By taking a more experience-focused perspective on haptic technologies, we want to encourage designers to think from experience to technology instead of the other way around. Instead of designing experiences around technologies, practitioners should start by defining the experiences they want to create. I already described in Chapter 1.2 that contextual, emotional, and perceptual factors greatly influence the overall product experience and should be considered when designing haptic experiences. Figure 9 (p. 50) describes initial considerations for an experience-focused haptic design workflow based on insights from the *Haptic Fidelity Framework* in an idealized process.

First, practitioners must define the overall context in which the interaction occurs: Which environmental factors will be prevalent during the interaction? What's the general mode of interaction? Which kind of interaction will entail haptic feedback at all? Will there be any multimodal influences? After defining the general context, designers should start detailing perceptual experience and interaction as well as general product requirements, eventually leading to the selection of hardware. In reality, other non-technical factors, such as costs, are often far more detrimental and further confine the space of solutions that come into question. Nevertheless, starting with the user instead of the actuator allows for generating a set of requirements that facilitates choosing the most appropriate technology that fits the budget.

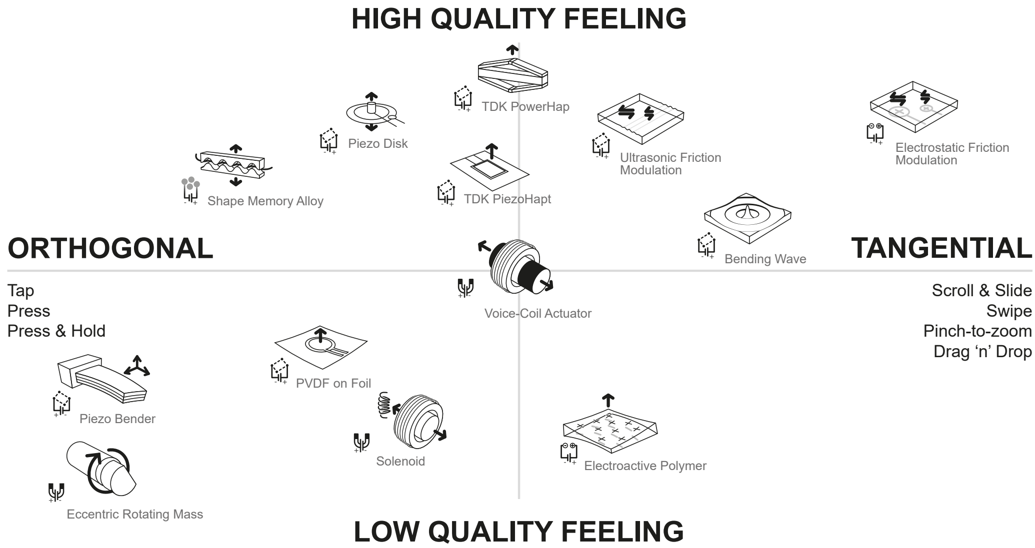


Fig. 11.: Haptic technologies differ in terms of their haptic quality and appropriateness for automotive haptic use cases. This figure shows a subjective classification of potentially automotive-ready haptic technologies regarding perceived haptic quality and suitability for interaction use cases (orthogonal/tangential finger movement).

While the suitability of technologies should ideally be evaluated for each product, technology-specific technical prerequisites make some technologies inherently more suitable for specific types of screen interactions than others. Based on the kind of finger movement, interactions can be boiled down to tangential or orthogonal interactions relative to the surface (see Figure 11). Orthogonal movements mainly involve exploration movements like tapping, pressing (i.e., exerting orthogonal force), or press & hold. Tangential movements are characterized by spatially expanding exploration movements like scrolling, swiping, sliding, drag & drop, and pinching. All interactions rely on active exploration movements. Press & Hold (i.e., a time-sensitive interaction based on prolonged static surface contact) is somewhat special as the finger usually rests on the surface when the impulse is fed back to the user. These types of interaction require actuators that do not rely on active user input like, for example, friction modulation devices do.

Figure 11 describes a coarse classification of different haptic actuation technologies based on the press-/search-continuum. Technologies suitable to recreate mechanical button presses may not be the proper choice for search haptic impulses. For example, solenoid actuators, a common type of actuator in automotive haptic-enabled touch displays, provide strong feedback and are thus very suitable to simulate a mechanical button click. Despite a high intensity, they are generally not very suitable for simulating button edges as start-up time is low.

Automotive information and control systems include a plethora of different interactions and types of feedback. Therefore it is even more critical to define the overall type of context and relevant kinds of interactions[14]. With the move towards touch-sensitive surfaces and the growing implementation of active haptic technologies into in-car interaction surfaces, the touch-and-feel qualities of analog interfaces are deserted. Implementing active haptic actuators allows for restoring the haptic qualities upon user confirmation by simulating button presses. However, the feel-and-explore parts of the interaction, i.e., searching for the desired controls while driving and how active (and passive) haptic cues can facilitate these "haptic search tasks", has so far been neglected in interface design. Proper implementation of technology — following the notions from the *Haptic Fidelity Framework* — requires an understanding of the building blocks of automotive interaction. The following section will detail automotive context requirements, the different stages in in-vehicle haptic interactions, and how haptic cues need to be designed to support (eyes-free) interaction optimally.

[14]In this case, interactions do not necessarily mean specific use cases, such as turning the volume up or down or scrolling through a list, but rather the underlying modes of interaction, such as pressing, tapping or sliding, etc.

Automotive Haptics

1.4

> *Design without context liquidates meaning*
>
> **— Claus-Christian Carbon (2019)**

1.4.1 Driving Cars - a Complex Multimodal Scenario

In-vehicle interactions are unlike interactions on mobile phones or other consumer electronic devices due to the multitask and multimodal nature of the driving task. Context, scenario, perceptual prerequisites, and user needs are vital factors when designing and evaluating interfaces for specific purposes (for a more detailed discussion, see Chapter 1.2). Practitioners need to keep in mind that conclusions from CE-focused studies may be a good starting point but have limited validity for automotive design due to differing context requirements. The following section will focus on the automotive context and explore its cognitive and perception-related prerequisites for haptic design.

Information Processing While Driving

Driving a car is a complex interplay of multisensory information. It requires the evaluation and integration of a multitude of information from various channels, making it a cognitive extremely demanding task. Thus, it requires the driver's undivided cognitive and visual attention. Driving can be divided into multiple sub-tasks: primary, secondary, and tertiary driving tasks (Bubb, 2015; Vollrath & Krems, 2011)[15]. These sub-tasks are usually described by the following three sub-categories that involve driving-relevant tasks in descending order. Figure 12 provides a paradigmatic depiction of how driving-relevant information and interaction spots can be laid out in vehicles.

The quote was published in *Psychology of Design* (Carbon, 2019).

[15] A more extensive description driving-relevant factor can be found in Vollrath and Krems (2011) and Bubb (2015)

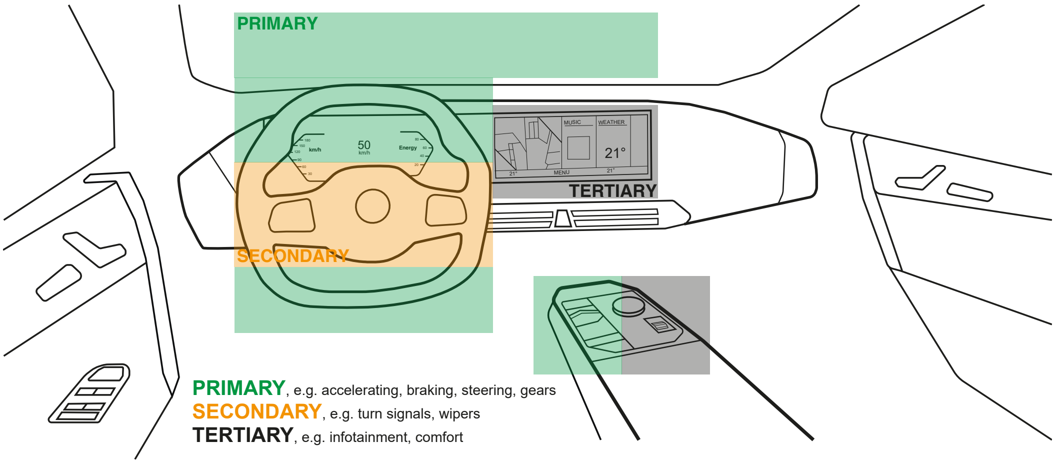


Fig. 12.: Driving is a complex multisensory interaction of various sub-tasks which can be categorized based on their relevance for successfully maneuvering a car: primary, secondary, and tertiary driving tasks.

Primary driving tasks are directly related to driving, such as longitudinal and lateral control, velocity, and navigation. In a nutshell, it's all tasks that are directly relevant to get from point A to point B.

Secondary driving tasks are usually relevant for driving on public roads but often not specifically necessary for keeping the car on track, such as following traffic signs, actuating wipers and turn signals, etc. They ensure traffic rule-related behavior and support navigating to the goal without provoking an accident.

Tertiary driving tasks are not necessarily relevant for driving, such as comfort and infotainment functions like adjusting music or temperature. However, they potentially make the journey more pleasurable.

Despite, but also mainly because, driving is a highly visual task[16] also other sources of information like auditory, tactile and kinesthetic information are essential. Sounds inform the user about environmental information (e.g., strong wind), vehicle status (e.g., squeaking tires or brakes), or other road users (e.g., a horn). Users also assimilate other types of haptic feedback — mostly proprioceptive and kinesthetic stimuli from joints, tendons, and muscles— due to exerted forces on the body while accelerating, braking, and steering into their driving. For example, posture and forces while sitting or driving give implicit information on conditions of the environment or the car (e.g., the tires start slipping). "Popometer" (German, in Engl.

[16] Even though there is debate on the exact number of information allocation — researchers claim visual information driving make up to 90% — it's safe to say driving without any severe restriction is not possible without the use of visual information (Vollrath & Krems, 2011).

"seat-of-the-pants feel") is a humorous but fitting depiction that race-car drivers often use to describe the use of subjective proprioceptive information to assess driving and car performance. However, this proprioceptive information is primarily relevant for primary driving tasks and will not be discussed further. This thesis mainly refers to carefully crafted haptic feedback in the context of *controlling a car's functions* (Gaffary & Lécuyer, 2018).

Use Cases for Automotive Haptic Applications

Most of the above-mentioned proprioceptive cues are inherently connected to environmental conditions and driving. Deliberately designed haptic cues (often in from vibrotactile patterns) at different locations in the interior (e.g., screen, dashboard, steering wheel, seat, etc.) can be used to convey a wide range of driving-relevant information. van Erp and van Veen (2001) provided an initial classification of vibrotactile stimuli in automotive: spatial, warning, communication, coded, and general. Gaffary and Lécuyer (2018) used a more condensed classification of how haptic information is used in automotive. They only describe two categories with respective sub-categories: *assistance* and *warning*. Assistance systems support the user in fulfilling voluntarily initiated tasks (e.g., parking or controlling a car's function). Warning systems are engaged to inform users about the deviation from a specific nominal value. Petermeijer et al. (2015) describe haptic systems as having a warning or guiding character.

All these classifications focus on functional aspects of haptic feedback. Haptic information can also be carefully crafted for purely aesthetical purposes, e.g., to convey a certain interior experience using soft, cozy, or sustainable materials. Carbon and Jakesch (2013) describe that haptic information contains a high-level layer of aesthetical information. Table 4 describes the experience-enriched classification of haptic information in automotive based on the classification proposed in Breitschaft et al. (2019a).

Haptic Feedback Supports Driving Performance - but not Inevitably

The basic nature of primary and secondary driving tasks, which refers to keeping the car on the road and arriving safely at the desired destination, has mostly stayed the same over decades. Still, technological innovations and the introduction of

Tab. 4.: Classification of various haptic information in the automotive context adapted from Breitschaft et al. (2019a)

Haptic Information	Description
Spatial	Using haptic information to indicate the car's location and relevant surrounding objects.
Warning	Using haptic information to warn the driver.
Communication	Using haptic information as a subtle communication channel.
Information	Using haptic information to display current status information concerning the car status.
Interaction	Using haptic information during interaction with control units.
Aesthetic	Using haptic information to convey non-utilitarian information and evoke aesthetical appreciation and brand image.

screen-based infotainment systems led to a dramatic increase in in-vehicle infotainment, entertainment, and comfort functions. Driving-relevant environmental stimuli already saturate visual and auditory information channels. Additional, not necessarily driving-relevant, tertiary driving tasks — which many of the newly added functions, such as entertainment, represent — pose a risk of further distraction.

Employing haptic feedback to convey vehicle state and environmental information can alleviate some visual distraction and cognitive load, for example, by vibrating the steering wheel to avoid lane deviation or vibrating the gas pedal to indicate following up too close to the car in front. It can also support minimizing visual distraction introduced by tertiary driving tasks[17].

The impact of haptic feedback on driving performance, visual distraction, safety, and user experience has been well documented for different kinds of applications, technologies, and in-car device locations[18]. Petermeijer et al. (2015) provide a literature survey on the impact of haptic support systems on driving performance. Gaffary and Lécuyer (2018) review the current state (as of March 2018) of in-vehicle haptic technologies regarding their applications, locations in the car, and impact on driving safety and performance. They describe that haptic feedback has been supportive in a gamut of use cases, such as turn-taking, navigation, eco-friendly driving, speed control, and collision warning.

[17] Haptic feedback can certainly never really eliminate distraction as any additional task, especially if it involves a manual interaction, is distracting. For example, Maciej and Vollrath (2009) found that in a dual-task setting, participants were not looking at the road for 30-40% of the time during the completion of the secondary task. There was also visual distraction even when speech was the primary mode of interaction.

[18] For more detailed information, see (Breitschaft et al., 2019a, 2022b; Gaffary & Lécuyer, 2018; Petermeijer et al., 2015)

Tab. 5.: Overview of literature on haptic feedback in automotive user interfaces in the context of controlling a car's function

Authors	Task	Conditions	Device	Main Outcome
Pitts et al. (2009)	1) LCT, 2) Touchscreen use cases	V, VH, VA, VHA	8.4-inch Haptic Touchscreen with TouchSense	No difference in driving and task performance; Acceptance higher for H than for V
Pitts et al. (2012b)	1) LCT, 2) Touchscreen use cases	V, VH, VA, VHA	8.4-inch Haptic Touchscreen with TouchSense	No difference driving and task performance; preference for multimodal feedback
Pitts et al. (2010), Pitts et al. (2012a)	1) Vehicle Following in Driving Simulation, 2) 2D-Target-Selection (Feedback at push)	3 x 2 design, Visual: immediate, delayed, none; V only + VH	8.4-inch Haptic Touchscreen with TouchSense	No difference in driving performance; Confidence and hedonic Rating higher for H, perceived difficulty and driving interference lower for H; H reduced total glance time by 19% when V delayed or absent
Rydström et al. (2009)	1) LCT, 2) Target-Selection	V, VH_{ridges}, $VH_{ridges+textures}$, $H_{ridges+textures}$	Rotary encoder	Driving performance and mental load did not differ across conditions
Grane and Bengtsson (2012)	1) LCT, 2) Target-Selection	V only, partly corresponding VH, fully corresponding VH, H only	Rotary encoder	"some" haptics enhanced driving performance, H increased RT; No differences in mental workload
Grane and Bengtsson (2013)	1) LCT, 2) Target-Selection	V only, partly corresponding VH, fully corresponding VH, H only	Rotary encoder	effectiveness depended on implementation of H; H reduces visual load
Tunca et al. (2016)	1) Driving Simulation, 2) Target-Selection (search)	Active + Passive Haptic, Blindfolded	Featureless Active + Passive Haptic control panel	No difference for RT, error, and lane deviation higher for active haptics, aesthetical appreciation higher for featureless panel
Tunca et al. (2018)	1) Driving Simulation 2) Target-Selection (search + push)	Haptic, Non-Haptic, Blindfolded	8-inch haptic touchscreen with four-button layout	Lower error rates and response times and subjective operational stress for haptic vs non-haptic
Beruscha et al. (2017)	1) LCT, 2) Target-Selection (search + push)	V, VH, H	7-inch touchscreen with electrodynamic actuator	H reduced eye-off-road time and subjective mental workload
Mullenbach et al. (2013a)	1) Driving Simulation 2) 1D-Target-Acquisition	Visual, Haptic, Visual/Haptic	Ultrasonic Friction TPad	Negligible differences for task performance, H reduced the eyes-off-road time by 19% and 39%, Participants preferred combined V and H
Weddle and Yu (2013)	Use-cases in parked car	Cadillac Cue Haptic UI vs. non-haptic iPad UI		H perceived easier to use, more pleasant, more confident, more responsive, and more direct
Richter et al. (2010)	1) LCT, 2) Input phone number	V, H	8.4-inch screen with linear actuator	H reduced errors and response time; H was more preferred, but very small sample size (n=5)

Note: V = visual feedback, H = haptic feedback, A = visual-audio, M = Multimodal, LCT = Lane-Change-Task, RT = Response Time. This table was published in Breitschaft et al. (2022b). ©2021 IEEE.

While these resources provide excellent insights into the effectiveness and implications for future haptic design of haptic warning and guiding systems, they predominantly focus on supporting the primary or secondary driving task. Reported systems are triggered mainly by external cues which do not require active and deliberate user interaction. Information ranges from kinesthetic to vibrotactile signals. In most cases, stimuli from vibrotactile systems are "only picked up" by the user, which preferably classifies them as tactile interfaces. Hence, conclusions are somewhat limited for feedback in the context of controlling a car's functions. This is due to the type of interactions as well as applied technologies. In Breitschaft et al. (2019a) and Breitschaft et al. (2022b) we extended Gaffary and Lecuyer's chapter on "Controlling the Car's Functions" and provided a succinct overview of research examining the use of different haptic technologies during in-car interactions (see Table 5).

Studies examining the effectiveness of in-vehicle haptic devices in the context of controlling tertiary functions usually consist of a dual-task setting, including a primary driving-related task and a secondary interaction task. In general, the effectiveness of haptic systems is described by various objective or subjective measures. Objective measures include primary or secondary task performance measures, e.g., lane deviation, response times, and error rates. Subjective measures usually cover UX variables, such as acceptance, pleasantness, and aesthetical appreciation, but also cognitive measures, such as subjective workload. More advanced and complicated measures include eye-tracking data, such as eyes-off-road time or the number and duration of glances on- and off-road.

When looking at the literature summarized in Table 5, multiple conclusions can be drawn regarding haptically enriched tertiary driving tasks. As opposed to the overall results reported in Petermeijer et al. (2015) there does not seem to be a general effect of haptic, audio, or multimodal feedback on objective primary and secondary performance measures. Findings are mixed for objective measures. Some studies, such as Tunca et al. (2018), report a positive impact on response time and error rates. However, we already argued in an earlier publication (Breitschaft et al., 2022b) that the findings might vary as a function of the experimental methodology, technology, and haptic interface design. Studies employing eye-tracking and visual data measures seem to indicate that haptic feedback alleviates visual distraction.

Even though studies do not report consistent differences with regard to objective variables, they do show a somewhat consistent impact on subjective variables. For example, interfaces including haptic feedback scored higher acceptance and appreciation ratings, were perceived to be more pleasant, and were mentally less demanding. Studies including multimodal feedback conditions mostly showed a preference for the multimodal scenario (visual-audio-haptic feedback) in contrast to visual-only, visual-audio, or visual-haptic conditions. Despite haptic feedback having a detrimental impact on user experience, subjective measures are often only measured in a rudimentary fashion in the form of a few questionnaire items. So, even though haptics often does not increase performance, haptic feedback still seems to positively influence user experience and, thus, long-term user appreciation.

Future studies might examine the influence of haptic feedback on controlling a car's function more systematically. A meta-analysis might be carried out to infer the influence of haptic feedback in haptic display interactions.

Automotive - A Special Case for Haptic Interactions

The automotive context is unlike mobile or consumer electronics, as vehicles, experiences, and interactions need to fulfill a plethora of technical, consumer-related, safety, and regulatory requirements.

Specific User Requirements and Task Demands

Driving is a cognitive and manually complex and highly demanding process. As opposed to consumer devices that are maximized towards experience, automotive is an immensely safety-relevant context. An accident following distraction or misunderstood interactions puts peoples' lives at risk. Consequently, interactions must be safe, efficient, easy to understand, not distracting, and unequivocal for proficient and inexperienced drivers. Automakers must design and evaluate their systems based on regulatory standards (National Highway Traffic Safety Administration, 2016). The automotive sector exerts a massive multiplying impact. That means already minor errors, e.g., looking too long away from the road, may have fatal consequences. On the other hand, already minor interface-level improvements (i.e., bigger symbols that allow for easier detection) may save lives.

Literature and current haptic prototypes have mainly focused on a functional application of haptic feedback due to the safety-relevant context. However, in automotive, the semantics of haptics goes far beyond a purely functional or utilitarian background. The functional-driven view of automotive haptics in interaction may have been partly true for the last century of self-driving. Still, with the introduction of higher levels of automation, there are dramatic changes to driving behavior, which gives users more freedom while driving. Haptic feedback is no longer a mere by-product of functional considerations that "just needs to work", but becomes an inherent part of the interior and brand experience.

Haptics is already heavily used to convey aesthetical impressions that exploit deeply rooted associations. For example, natural materials like wood, glass, and metal convey a high-quality impression. The use of soft and textile materials perfectly fits the cozy lounge character of nowadays interiors. Multiple studies examined the connections of physically-based force-displacement parameters and their psychophysical counterparts in translational and rotational passive haptic controls (Kühner, 2014; Reisinger, 2009; Rösler et al., 2009; Wellings et al., 2008, 2010). Car makers use these insights to tailor their haptic feedback of control panels to promote a specific brand-related experience. Active haptic impulses offer even more significant potential for effective communication due to higher flexibility in how haptic impulses are created, e.g., by changing duration, waveforms, frequency, amplitude, etc. of the haptic driving signal (Heijboer et al., 2019a). Making flat touch-sensitive surfaces react to user input creates a sense of innovation (a "wow"-effect) and follows user expectations towards interaction known from mobile and consumer electronic devices.

Even though cars progressively assimilate consumer electronics and become "smartphones on wheels", they come with very specific user expectations. Lead times in automotive (update cycles, hardware development, etc.) are much longer than in the consumer market, which means that future explorations need to go beyond best practices to keep up with the fast-paced update cycles of consumer electronics. Furthermore, cars are highly priced items and a big investment for most people. In addition, cars are considered status symbols and luxury goods to show off, which requires them to comply with a high-level standard of quality and exclusivity. This has implications for implemented materials. Imitations of "high-quality" materials, such as wood, glass, and leather, are often used for economic reasons. These imitations mostly lack specific material properties exclusive to touch, which can negatively impact the overall experience. For example, plastics may look like real metal but miss the "cold touch feeling" usually associated with a heavy and high-quality material impression. Haptic has the power to damage carefully crafted experiences.

Specific Technical Requirements

Besides driving- and safety-relevant aspects, cars are a special case for UX design as they are technically much more complex than consumer electronic devices. Interactions and experiences need to be geared towards the driver and the passengers (who, for example, might be annoyed by continuous audio feedback). The spectrum of encapsulated interactions must be composed to form a compelling and orchestrated holistic experience. It’s important to not only polish simple interaction use cases but rather their integration into the bigger picture. This requires insights into how haptic stimuli are perceived and what they are associated with.

The automotive context poses not only special requirements for perception but also the technical integration of haptic technologies. Haptic actuators require a high level of integration within interior components, often at the expense of complexity and costs. For example, vibration-based technologies, especially powerful solenoid, and voice-coil actuators like the ones currently used in haptic in-vehicle touchscreens of the 2018 Audi A8 or 2020 Mercedes S-Class, need to be mechanically decoupled from other interior components to avoid wave propagation into the dashboard or center console. Additional kinematics and dampening mechanisms add an extra layer of mechanical complexity. Applying haptic feedback often interferes with other technical requirements, which hurt haptic performance. I will give two examples of possibly conflicting requirements for automotive haptic systems: Generally, haptic systems should be designed as stiff as possible to achieve crisp effects. However, components in specific crash-relevant areas require some compliance and flexibility to soften the head impact. Also, with increasing display sizes, haptic actuators are approaching their limit in providing a compelling haptic experience. Haptic systems should be designed as light as possible to maximize the conciseness of haptic effects — low mass requires less energy and smaller actuators, smaller actuators require smaller package sizes and are cheaper, etc. Yet, bigger screens (which often also include the backlight) have a higher mass. Thus, they require more energy and powerful actuators, which in turn require more powerful actuators, more package size, a more profound mass-damper system, etc. Even if the actuator is powerful enough, the system is constrained with respect to haptic fidelity due to the system's overall moving mass. Potentially conflicting requirements need to be discussed in the early phases of the research and development process.

Another important factor to consider is that, as opposed to consumer electronic devices, vehicles are designed for much longer life and update cycles (usually 7-10 years). This means there are profoundly different performance, robustness, and longevity requirements. For example, cars need to operate reliably in an extensive range of temperatures from well below -20° to well above +50° Celsius. Active haptic technologies must comply with certain EMC (electromagnetic compatibility) standards so that they do not interfere with driving relevant functions. Especially in the case of haptic devices using ultrasonic vibration (mid-air haptics) or sound, manufacturers need to ensure that systems do not exceed harmful emission levels.

In a nutshell, automotive haptic interfaces are influenced by various stakeholders, which means that systems are often compromise-ridden. It's important for design to define critical features relevant to haptic performance early on. While this section mainly covered what makes automotive unique as a design context, the following section will go into more detail about how haptic feedback can be designed to support in-vehicle interaction and alleviate visual distraction in the context of controlling a car's functions.

1.4.2 Journal Article: Theoretical Framework of Haptic Processing Framework in Automotive User Interfaces

This section, including all figures, is based on:

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019a). A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. *Frontiers in psychology*, *10*(1470). https://doi.org/10.3389/fpsyg.2019.01470

Abstract - Driving a car is a highly visual task. Despite the trend towards increased driver assistance and autonomous vehicles, drivers still need to interact with the car for both driving and non-driving relevant tasks, at times simultaneously. The often-resulting high cognitive load is a safety issue, which can be addressed by providing the driver with alternative feedback modalities, such as haptics. Recent trends in the automotive industry are moving towards the seamless integration of control elements through touch-sensitive surfaces. Psychological knowledge on optimally utilizing haptic technologies remains limited. The literature on automotive haptic feedback consists mainly of singular findings without putting them into a broader user context with respect to haptic design of interfaces. Moreover, haptic feedback has primarily been limited to the confirmation of control actions rather than the searching or finding of control elements, the latter of which becomes particularly important considering the current trends. This paper presents an integrated framework for haptic processing in automotive user interfaces and provides guidelines for haptic design of user interfaces in car interiors.

The journal article can be found in Appendix A.3 (p. 207).

Motivation & Rationale

Haptic feedback has ever since played a crucial role in reducing driver distraction, which is well documented for many automotive use cases (for a detailed discussion, see previous sections). Recent design trends, such as the surface integration of functions, the reduction of buttons, the fusion of design and interaction surfaces, and the widespread adoption of touchscreen devices, led to a "*flatification*" in automotive user interfaces that took away the subtle but helpful haptic cues that created a safe and high-quality tactile impression in previous vehicle generations (see Figure 1, p. 3). Despite major advancements in the area of haptic technologies and the knowledge of the importance of haptics in automotive, UI manufacturers are only just starting to "reintegrate" the sense of touch in nowadays vehicle generations. Active haptic technologies allow retrieving at least some of these tactile qualities while retaining clean-looking interior surfaces. Given the potential of electronically driven haptic actuators, one might wonder about the sluggish transition from passive elements to flat, but haptic-enabled surfaces. There seems to be a missing link between engineering, design, and user interaction.

The abundance of user-driven research fails to provide a clear understanding of why certain haptic interfaces work while others don't. User research in the field of automotive haptic feedback often resembles mere feasibility and proof-of-concept studies. While most authors report how their study relates to previous literature, their findings are often hardly put into a broader user interaction context. A majority of studies report the effectiveness of haptic feedback on driving and task performance but seem to neglect the subjective nature of haptic perception, even though most automotive haptic studies suggest that haptic feedback significantly impacts UX. Evaluating how haptic feedback has been implemented in studies to support user interaction is often difficult. Part of this lies in the indiscriminate use of the term haptic feedback. Even though active haptic actuators allow for a broad range of haptic effects — from detents while scrolling a list to clicks upon pressing — and are thus very well suited to augment different parts of the interaction, it's often merely referred to as "haptic feedback". The incoherent landscape of studies and inconsistent use of haptic terminology makes it hard to paint a clear picture of best practices in active haptic design.

In the recent decade, suppliers and carmakers presented plenty of applications that brought back tactility to touch-sensitive surfaces. However, these "innovations" tend to be tech-centric, focusing more on marketing than a truly user-centric application. Tech demos often lack compelling real-world use cases as they mostly try to "rebuild" familiar passive haptic interactions in a digital space, e.g., by augmenting virtual edges via haptic clicks. Focusing on these "traditional" modes of interaction does not automatically make interfaces safer or less distracting. Rebuilding impressions from passive haptics using active haptic technologies must not be an issue. However, it hinders examining the true potential of active haptics in the context of automotive user interfaces.

Most tech demos, real-world in-car applications, and studies so far (as of the beginning of 2018) have mainly focused on confirmation haptics, i.e., the haptic augmentation of press events in the form of button clicks as this has been the dominating mode of interaction for decades. Only a few studies actively examined the "search" part of the interaction. This hasn't been a major issue in passive haptic interfaces. Tactile cues that allow effortless detection and recognition of control elements (buttons and dials) have often been a by-product of the technical integration of passive haptic components into interior structures. However, since the lack of a tactile reference creates a great source of distraction for drivers, considerations on effectively supporting haptic exploration (e.g., with the help of active haptics) are crucial in designing flat interfaces.

In a nutshell, the surface integration of control elements somewhat created a problem that didn't exist with previous traditional interfaces. Current active haptic technologies still fail to provide convincing real-world applications due to the uncertain and partly unknown user requirements with respect to haptic design. What's missing is a common and interdisciplinary understanding of how to effectively design and optimally exploit haptics in the context of flat automotive user interfaces during the "search" and "confirmation" part of the interaction. Creating a common communication platform requires an explicit in-depth description of all the different steps of interaction, how haptic information is perceived along the way, and how haptic information should be designed to support interaction optimally. Consequently, the *Theoretical Framework of Haptic Processing in Automotive User Interfaces* proposes a systematical and step-wise description of haptic processing in automotive user interaction, which integrates findings from haptic, psychological, perception, and usability studies. The main goal of this framework is (1) to establish a common haptic terminology for automotive haptic feedback, (2) to summarize and streamline current findings in the field of automotive haptics, (3) to foster communication and collaboration between different professions within automotive research and design, (4) to promote an understanding for the perceptual, as well as psychologically and context-driven user requirements towards haptic feedback during different steps of interaction, (5) to ease the derivation of best practices and design guidelines and (6) identify blind spots in research (Breitschaft et al., 2019a).

Towards a Common Automotive Haptic Terminology

Collaboration and communication require a clear and understandable vocabulary — something I found was often missing in research, various development projects, and tech demonstrations. This paper aims to establish a clear terminology when talking about the *how* and *what*, i.e., the technology- and semantics-side of haptics in automotive user interfaces (Figure 8, p. 46). The technology part of haptics terminology has already been covered in Chapter 1.3. Concerning technologies, there is a distinction between *active* and *passive* haptics. Describing what kind of information haptic feedback displays, i.e., the semantics, requires a clear definition of the context in which interaction occurs. With respect to an automotive application of haptics, more precisely in the context of controlling a car's function, haptic feedback can generally be referred to as *search haptics* and *confirmation haptics* (see Figure 8, p. 46).

> **Search Haptics** refers to all tactile cues that support eyes-free and "tactile-only" exploration, detection, and identification of functions within control panels. Search cues are usually picked up via tangential exploration movements.
>
> **Confirmation Haptics** refers to all tactile cues that indicate a system's reaction to user input, for example, upon pressing. It's essentially a tactile approval for a system's or function's status change. Confirmation cues may also account for haptic system information conveyed through turning a dial or adjusting a slider.

Especially in active haptics, studies also often refer to another kind of haptics: **surface haptics**. While search and confirmation haptics only account for the utilitarian aspect of haptic feedback in automotive interfaces, surface haptics is a more generic term for tactile surface and material qualities in the context of passive and active haptics (Bubb, 2015, p.285). Surface haptics is also a common term for technologies that allow to "simulate" real-world material attributes, such as texture, through friction modulation (Basdogan et al., 2020). Surface haptics encompasses aesthetic and utilitarian aspects (Carbon & Jakesch, 2013).

Haptic Interaction is Sequential Information Processing

Beyond establishing a common vocabulary and providing an overview of current automotive haptic literature, the core of the publication lies within the *Framework of Haptic Processing in Automotive User Interfaces*. Dissecting the process of "controlling a car's function" into its separate micro-interactions allows for a clearer and more comprehensible description of user requirements and the types of haptic information relevant throughout the various stages of interaction. It also reveals that to create safe and joyful experiences, designers must not only apply haptics when confirming user input but already support the acquisition of different functions (which is even more important in flat interfaces). Subsequently, the framework explicitly focuses on the "search"-part of the interaction.

Conceptualization of the framework was heavily influenced by earlier theoretical considerations within the field of haptics, such as the *Model for Haptic Aesthetic Processing* (Carbon & Jakesch, 2013). The stage-wise setup originates from the fundamental principle of haptic perception — sequentiality. As opposed to vision, haptic perception is an inherently sequential process, as only a single finger or hand is used for exploration. This is even more true for automotive, as visual attention lies on the road and environment instead of controls on the dashboard. Furthermore, information bandwidth is limited, so automotive user interface design needs to account for the sequential nature of haptic processing. The backbone of the proposed haptic framework is the systematic, sequential, step-by-step approach to analyzing all touch-points during the interaction of controlling a car's function — *Exploration, Detection, Identification* and *Usage*. Every stage of the framework describes how information processing takes place, how external top-down feedback loops influence it, and which type of haptic cues are relevant for haptic design. The sequential process is visualized in Figure 13. Earlier sections (e.g., Chapter 1.2) described that context information is highly relevant for the aesthetic and utilitarian evaluation of haptic information. This framework focuses on automotive interaction, which inherently defines the context requirements. The premises of the automotive context are described in this section.

The framework is based on a closed-loop principle, which means that processing only proceeds to the next stage once information acquisition is sufficient from a user perspective. This means that users focus on haptic cues that fit the current task at hand. For designers, this means that only task-relevant information should be displayed. The framework outlines phase-specific top-down loops that constantly modulate the haptic stimuli interpretation throughout interaction to account for the subjective, constructive, prediction-based, associative, dynamic, multisensory, and scenario-based nature of perception. The premises are described in Chapter 1.2. In the context of this thesis, the stages of the framework will briefly be described. For an in-depth description of the framework, I would like to refer to the complete publication (Breitschaft et al., 2019a).

The interaction starts with the vehicle's interior, which poses a certain context with a specific set of tasks. In the context of controlling a car's function, haptics is primarily used to reduce visual distraction and ease interaction with in-vehicle function while driving.

Exploration: The *Exploration*-Stage describes the initial haptic contact with the interface. Visual preview (Klatzky & Peck, 2012) and previous experience guide haptic exploration, i.e., where to touch first and how to proceed with exploration (see Chapter 1.2). Visual surface and shape features already communicate different modes of functionality and interaction (Götz, 2007). *Predicted cues* provide an initial orientation and reference frame. At this early stage, the interface layout immensely influences haptic exploration. Moving interactive elements to the borders

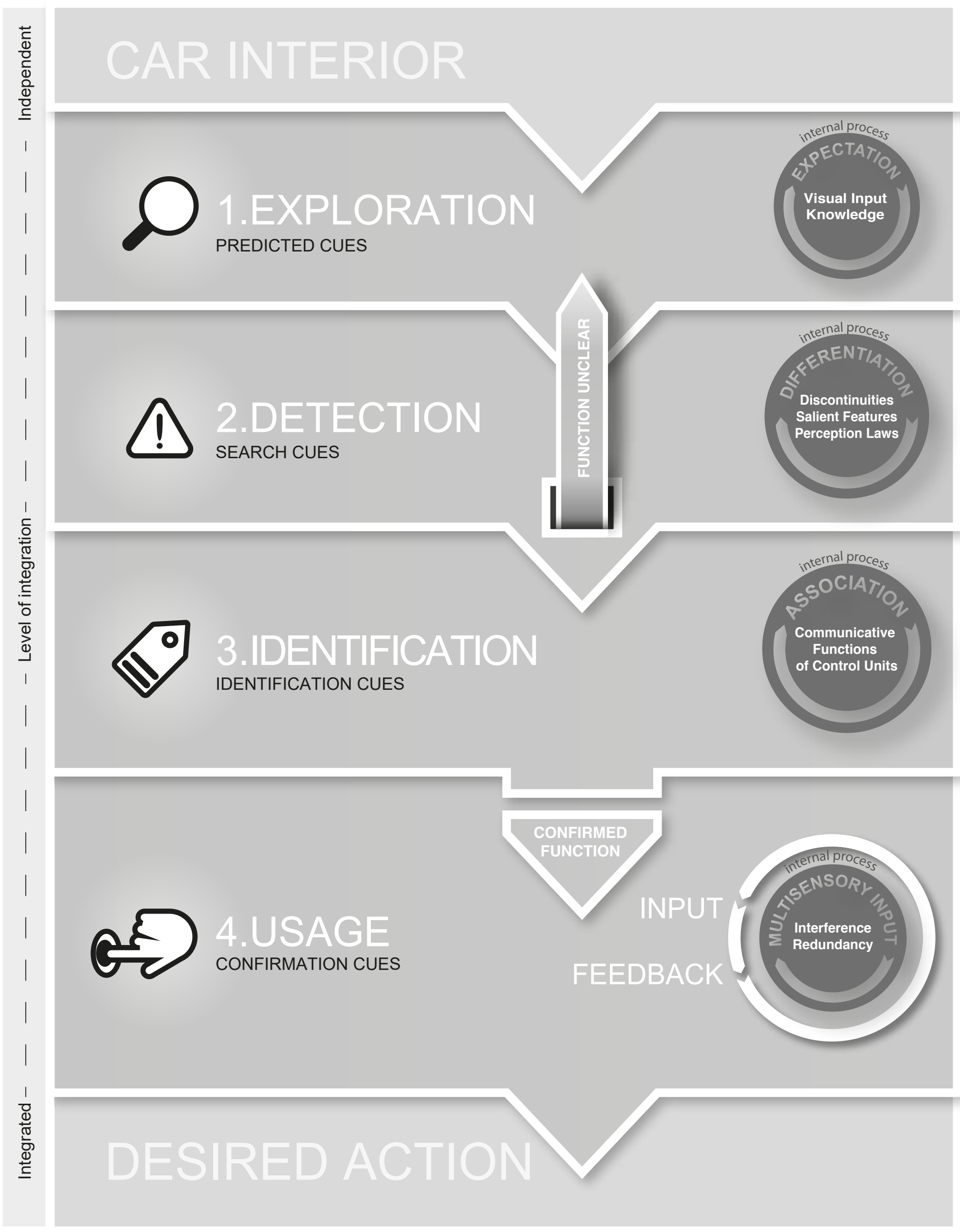


Fig. 13.: The *Theoretical Framework of Haptic Processing in Automotive User Interfaces* describes four different stages of interaction in automotive interfaces: Exploration, Detection, Identification, and Usage. Each stage poses a specific set of haptic requirements (Breitschaft et al., 2022a)

of the interface facilitates vision-free interaction as bezels, which are inherent design features, serve as a tactile reference frame and starting point for haptic exploration (Pielot et al., 2012).

Detection: The *Detection*-Stage describes how users subsequently scan the interface for information that helps them to locate interactive areas. This stage aims to discriminate between interactive and non-interactive surfaces as well as to detect and acquire the desired functionality (hence the wording "search haptics"). Haptic information that "pops out" has an inherently salient character and is thus a highly relevant indicator during the detection process. These *search cues* range from textures to clicks, edges, shapes, and other uneven surface features. Haptic search is governed by tactile salience, i.e., maximizing the haptic figure-ground contrast to enhance detection, discrimination, and differentiation. Haptic information at this level allows for detection and differentiation but not identification.

Identification: The user's next step is *Identification* of the desired functionality — i.e., a precise evaluation of which kind of function the user is currently exploring. In reality, identification might not always be governed by haptic information alone. Rümelin (2014) proposes that visual attention is required in the *search*- as well as *selection*-phase of interaction. During *localization* of interaction elements *search glances* deliver visual information on positions while *confirmation glances* are used for *positioning*, i.e., a final confirmation before the actual input (Harrison & Hudson, 2009). However, haptic information potentially entails underlying semantics that might facilitate identification. Similarly to Götz (2007), who described the communicative strength of visual shapes for interaction, also haptically explored forms trigger discriminative functional associations (Breitschaft & Carbon, 2021). Identification is governed by associative strength of element shape and kinesthetic information (posture, hand position, etc.) that enable spatial orientation within interfaces (Rümelin, 2014). For example, specific elements are identified by their position in the interior. The exploration, detection, and identification process repeat until users "find" the right interactive element.

Usage: The *Usage*-Stage concludes the interaction process. The user is performing the input of the correct functionality to reach the desired action, for example, changing the radio station. The type of input movement depends on the control element, i.e., translational, rotational, touch input, slide gestures, etc. The mode of interaction is also already "prepared" based on information from previous stages. Visual and haptic information "guide" the general mode of interaction, i.e., if an element can be pressed or rotated (Breitschaft & Carbon, 2021; Götz, 2007) and to precisely adjust grasping mechanics (Cuijpers et al., 2004). Haptic feedback upon input confirms that the system status has successfully been changed. Confirmation cues can be manifold. For passive systems, it's mostly a button click sensation that confirms switching between different system states. In active systems, confirmation cues range from simple button click impulses to more complex click patterns. Functions based on an incremental adjustment of values on a continuum (e.g., temperature, volume, etc.) include an additional feedback loop that monitors whether the desired value has been activated. Haptic feedback upon the change of increments, such as detents or items in a list, supports choosing the desired value. This kind of haptic feedback has previously also been referred to as *information haptics* (Haptics Industry Forum, 2021b). Multisensory information heavily influences haptic processing throughout the complete interaction process (Breitschaft et al., 2019a; MacLean & Hayward, 2008). Multisensory feedback is implemented to reinforce interaction by providing redundant information (Pitts et al., 2009, 2012b). Multisensory cues need to be designed so that the perceptual channels do not interfere, as this might lead to performance loss otherwise. Multisensory information is often explicitly exploited to alter the haptic impression (Tikka & Laitinen, 2006).

Affective Evaluation: This framework focuses on the functional application of haptic feedback for search- and confirmation haptic use cases. While haptic cues should be easy-to-understand at first contact, the level of integration of haptic cues into experience and expectations is becoming a crucial part of the interaction. Haptic cues are an essential part of user experience, making them subject to utilitarian and aesthetical considerations (Carbon & Jakesch, 2013).

Discussion

The major goal of this publication was to bridge the gap between the different professions within the automotive design process by providing **common terminology** and proposing a systematic framework that integrates findings from different professions. While the underlying semantics of haptic feedback varies greatly, the terms haptic feedback or haptics are often used indistinctively. The idea was to consolidate the communication on automotive haptic use cases by introducing a simple terminology for the two basic modes of in-vehicle haptic interactions, "exploring" and "activating" functions: *search* and *confirmation* haptics. However, after participating in multiple projects and prototyping haptic interfaces, only using search and confirmation as the basic terms to cover the full gamut of haptic use cases might not be sufficient. For use cases that allow for a continuous adjustment of values (e.g., volume, temperature), the dichotomy of searching and confirming is minimalistic and often a bit confusing. For example, the detents felt while scrolling can be described as search cues (finding the proper volume stage) and confirmation (they give feedback on a system status change) simultaneously. Referring to these kinds of cues as *control haptics* might resolve the confusion. Active haptic devices allow to convey more semantic information to users than mere search and confirmation cues, e.g., vibration impulses indicate that certain information cannot be displayed while driving. In their "Recommended Practices for Automotive Haptics", the *Haptics Industry Forum* introduced the term *information haptics* to cover these type of haptic information (Haptics Industry Forum, 2021a). Even though clear descriptions foster communication, stakeholders must avoid micromanagement of haptic terminology as this might be a source of confusion. Instead, practitioners should establish a common terminology during project kick-offs. Haptic might potentially be described based on the mode of interaction, e.g., push/turn haptics, or use case, e.g., list haptics, toggle haptics, etc.

The explicit segmentation of the haptic perception process into **sequential steps** may seem over-engineered and artificial. However, with the increasing implementation of haptic feedback in interfaces, practitioners with different levels of expertise and professional backgrounds are entering the field. The step-wise segmentation allows for describing all relevant touch-points where practitioners can influence haptic design. This provides a common basis for communication and collaboration during the design process. It also facilitates the definition of haptic use cases, technical requirements, and haptic design as information can be tailored specifically to support interaction at specific stages. The systematic description of haptic processing and integration of different study backgrounds structures the fragmented view of haptic studies, establishes a multidisciplinary status quo of current research, and eases the integration and evaluation of novel study findings. One of the greatest strengths of the framework is that its systematic nature allows to describe and explain compelling features of already existing haptic interfaces and to derive a set of guidelines for the haptic design of future interfaces. A basic set of guidelines that are directly implied by the stage-wise approach of the model itself are: (1) Keep in mind a holistic user experience, (2) clarity of haptic cues, (3) intuitiveness of haptic feedback, (4) discriminability of haptic information. A deeper discussion on haptic design guidelines will be carried out in Chapter 4.2.

This paper was never intended to answer all questions regarding automotive haptic design. Despite an application-driven background of the framework, it describes a rather **generic**, theoretical approach to haptic processing. This rather tech-excluded perspective allows having a closer look at user requirements, i.e., how we need to design haptics to support user interaction optimally. The framework only describes guidelines related to the search-and-selection phases of controlling a car's functions. More "basic" perceptual requirements, such as latency, are not explicitly discussed in detail. It's important to note that the broad nature of the provided guidelines shall be viewed as a **starting point** in the design process and require the application of specific technological approaches. For example, the framework describes the importance of search haptic cues for effective eyes-free interaction. How these search haptic impulses are characterized depends on multiple factors, such as the applied technologies. The same goes for the design of highly salient surface features. What high tactile saliency means depends on technology. Nevertheless, the step-wise approach allows the framework to be used as a "red thread" and a simplified "checklist" during development projects. I believe it is highly adaptable to most technological approaches and helps identify potential technology-specific haptic design requirements.

The framework emphasizes the importance of a **holistic** approach to haptic processing in automotive user interfaces. Haptic cues within automotive interfaces range from search to confirmation cues. Also Rümelin (2014) describes a search- and selection-phase during interaction. In the context of haptic-enabled automotive interfaces, research and tech demos have primarily focused on the confirmation part of the interaction. The "flatification" of in-vehicle interface surfaces has led to the elimination of the subtle haptic cues, which have been one of the main drivers for vision-free interaction in previous vehicle generations. While plenty of studies, suppliers, OEMs, and experts acknowledge this problem, research has hardly approached this topic from a systematic psychologically-driven perspective. This framework focuses on how haptic feedback can optimally support haptic exploration to alleviate visual load as acquiring a desired functionality on flat interfaces significantly impacts visual distraction.

Another major point during the review process of this publication was that this framework poses a **theoretically-grounded systematization** of findings but has not yet been validated in user studies. This framework resulted from the first extensive literature research in the context of this PhD project. It was not supposed to present a perfectly validated perception model. Its goal was to structure and harmonize the findings from the various haptic studies, identify gaps in the existing literature, evaluate current findings from haptic studies based on their contribution to vision-free interaction, and set out an action plan on how to make interfaces more safe and accessible through haptic feedback.

Ultimately, it follows a practitioner-focused approach instead of a purely theoretical one, which also lies in the highly complex nature of haptic interfaces. This framework also became an underlying "red thread" to streamline research activities within this dissertation project. For example, Section 2.2.2 shares insights into the form-functionality association of passive haptics forms to be used in the *Identification*-stage. Section 3.2.5 aimed to contribute insights to the *Detection*-stage by exploring the effectiveness of electrostatic friction stimuli.

From Basics to Application

> *The [button] is dead, long live the [button].*
>
> — **Phrasal template (adapted)**

In recent years, haptic feedback has gone mainstream in consumer electronics, with consumer electronics manufacturers increasingly integrating haptics into their ecosystems (e.g., the introduction of the haptic keyboard in Apple's iOS 16). This also leads to car-makers reintroducing haptics to interaction surfaces that have undergone *flatification*.

Furthermore, a colorful mix of stakeholders and professionals (design, engineering, psychology, marketing, etc.) with various backgrounds are involved in haptic projects. What I believe is crucial for the success of these projects is that haptic feedback is not only employed for the sake of novelty and marketing but is designed with the users' haptic and cognitive capabilities in mind. It's crucial to understand the basics of haptic perception and to establish a common vocabulary to communicate and exchange ideas easily — which is the primary purpose of **Part 1 THE BASICS**:

Chapter 1.1 A Tangible Turn covers the perceptual and interactive fundamentals and premises of haptic perception. **Chapter 1.2 A Psychological Turn** underscores the importance of a psychological reality on perception. **Chapter 1.3 Haptic Technology** introduces the technological basics of haptic feedback by proposing the *Haptic Fidelity Framework* as an experience-based technology overview and evaluation methodology. **Chapter 1.4 Automotive Haptics** describes the context-specific requirements and challenges for haptic interaction in automotive. The *Framework of Haptic Processing in Automotive User Interfaces* summarizes the perceptual processing of haptic information in in-vehicle interaction and how haptic stimuli can be specifically crafted towards an effective and potentially vision-free interaction.

Matching Haptic Interaction to Haptic Technology

Both frameworks provide a starting point for everyday haptic design practices. They lay the theoretical foundation for novice and expert practitioners as they cover the technical and perceptual foundation of haptic design. The *Haptic Fidelity Framework* focuses on organizing haptic technologies based on the fidelity of haptic experience. It also summarizes current technologies, actuation principles, and technical characteristics. In contrast, the *Framework of Haptic Processing in Automotive Interfaces* focuses on the functional and interactive aspects of haptic feedback during automotive interaction. It helps designers to precisely sketch automotive interactions and how haptic feedback can be integrated seamlessly. Hapticians might apply both frameworks to find the "best match" between haptic requirements and interactions described within the *Framework of Haptic Processing in Automotive User Interfaces* and the most suitable technology described within the *Haptic Fidelity Framework*. This perspective is also supported in Figure 9 (p. 50), which proposes a WHY-WHAT-HOW-design approach. Starting the development process by defining the desired experiences and interactions (and thus user and interaction requirements) makes designers less prone to focus on technology. It fosters the selection of appropriate haptic technology. From a user perspective, choosing fitting over fidelity concerning haptic technologies seems crucial.

The question of how to exploit different haptic technologies for search haptics design is still not fully answered. Based on the *Theoretical Framework of Haptic Processing in Automotive User Interfaces* I identified two stages that seemed interesting to explore in more detail: (1) the use of **passive haptic** forms to communicate functionality during haptic exploration and (2) the use and effectiveness of **active haptic** electrostatic friction modulation in search haptic interactions.

The following parts will go into more detail on search haptic design in the context of passive and active haptic interfaces.

Part 2

PASSIVE HAPTICS

2.1 Passive Haptic Interfaces

Passive haptic elements — from levers via turn dials to push buttons of different sizes and form factors — have been the main driver of haptic feedback in in-vehicle interaction in the last centuries. Many extensive research programs have examined the parameters that allow creating a tailor-made haptic experience in rotational and translational control elements (Anguelov, 2009; Bubb, 2015; Kühner, 2014; Reisinger, 2009). Translational control elements are usually described via force-displacement curves, and rotational control elements via torque-angle curves (see Figure 14[19]).

The desired haptic experience is created by adjusting the stroke, operating force, and haptic click ratio, often called "snap"[20]. Rotational control elements are usually described via torque-angle diagrams. The desired haptic experience of rotational controls is determined by the diameter of the knob, actuation torque, the number of detents, the slopes from the resting position to the torque maximum, and the slope from torque maximum to torque minimum (Anguelov, 2009). Both Kühner (2014) and Reisinger (2009) indicate that haptic experience is consistent across various application areas within the car, i.e., buttons in the center console are perceived similar to controls in the roof modules. Reisinger (2009) examined which haptic parameters of mechanical switches are the main drivers of rudimentary perceptual sensations, such as preciseness and ease of operation. Rösler et al. (2009) describe how operation force and stroke influence affective evaluation, such as originality and reliability. For example, buttons with a longer stroke are perceived as heavier and slower. In contrast, controls with a short stroke are perceived as sharper, harder, and more precise. Overall, there is a pretty clear picture of how to tailor-make desirable confirmation haptics in the context of buttons and rotatory dials. This not necessarily applies to passive search haptics.

Traditional button interfaces that have been dominating automotive interior surfaces for decades can mostly be characterized by an accumulation of single button control elements. Each button is mainly restricted to a single functionality and equipped

[19] ©2019 Breitschaft & Carbon, CC-BY.

[20] The snap describes the "feelable amount" of haptic feedback. It is characterized by the ratio of the initial force maximum and force minimum of the subsequent drop in actuation force due to the collapsing metal or rubber dome.

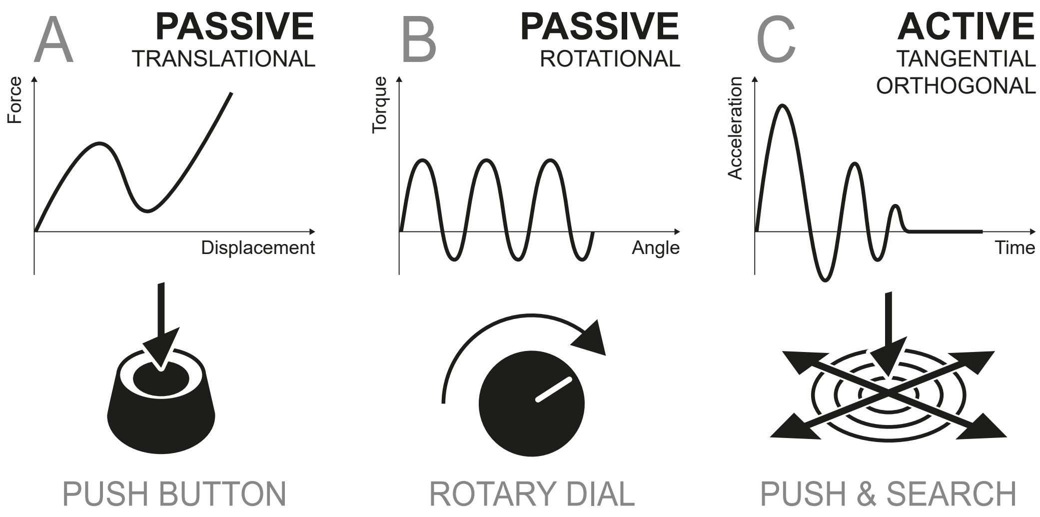


Fig. 14.: Haptic feedback is usually described via (A) force-displacement curves, (B) torque-angle curves, or (C) acceleration curves, depending on the type of haptics (Breitschaft et al., 2019a).

with a mechanical switch which requires circumferential gaps to move. Hence, passive search haptic cues, such as edges and gaps, have mainly been a by-product of the technical implementation of mechanical switches. With capacitive touch buttons, control elements were increasingly consolidated into larger interface areas. While there still is a circumferential gap for the complete button area, singular functionalities are separated by seamless surface features, e.g., alternating bumps and recesses or ridges. Advancements in interface technologies, such as in-mold electronics, novel sensing technologies, and active haptic technologies, allow for even higher degrees of freedom in surface design. They now enable a seamless fusion of interactive and decorative areas, thus making seams and gaps within interfaces completely redundant. A recent example is BMW's iX iDrive controller, which integrates all functions under a single seamless real wooden surface (see Figure 1, p. 3). Earlier sections already discussed that vision-free interaction becomes a real issue with featureless surfaces. Especially in seamless interfaces, automakers implement tactile reference points to alleviate the visual load. For example, in the case of the iX's wooden panel, the symbols of the button functionalities are slightly elevated.

However, in automotive interfaces, passive haptic cues are primarily designed for their visual and aesthetical appearance (and how they fit into the visual design) rather than haptic qualities. For example, tactile saliency is essential for detectability or usability, thus successfully "finding" a button (Kappers & Bergmann Tiest, 2015a; MacLean, 2008; MacLean & Hayward, 2008). Research in the context of "haptic search" also pinpoints perceptual qualities relevant to make buttons "pop out". Despite a high-quality impression, buttons are sometimes hard to separate from each other as haptic features used for detection and orientation are mostly arbitrary and merely exceed ridges, seams, or tactile bumps. Amidst technological advancements in interfacing and manufacturing processes incorporating mere bumps and seams falls short of the technological potential.

Applying novel production technologies enables a new haptic language to communicate interface functionalities and guide interaction without having the user to look. Furthermore, the general reduction of button elements requires the remaining elements to have an even more iconic impression. Similarly to the tailor-made design of force-displacement curves, surface features, such as forms, materials, and textures, inhabit a communicative character that exceeds a mere detection and orientation purpose (also see Figure 13, p. 74). In the context of interaction, haptic cues are embedded into an interactive mindset. By employing deeply rooted functional associations, interfaces may not only feel more pleasant and exciting to use but also more familiar, easier to use, and less distracting. The following chapter describes how an association-based approach to haptic interface design may help to create this new haptic language. I will specifically describe how haptic forms communicate functionality via haptic exploration.

Function Follows Form 2.2

> *When affordances are taken advantage of, the user knows what to do just by [feeling]: no picture, label, or instruction needed.*
>
> — **Don Norman (adapted)**

2.2.1 Conference Poster: Using Haptic Shapes for Orientation and Identification in Automotive User Interfaces

This section is based on:

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019b). Using haptic shapes for orientation and identification in automotive user interfaces [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE

Abstract - Haptic feedback is a crucial part of secure and easy-to-operate automotive user interfaces. These interfaces change through surface-integrated buttons and switches, allowing higher degrees of freedom in haptic design. Passive haptic shapes not only enable the ease of finding control elements without looking but also aid in identifying functionality. This paper presents the preliminary findings of a series of studies examining the perceived functionalities of surface-integrated haptic shapes. Via multidimensional scaling, we showed that there is a variability of associated functionality within a set of pre-selected shapes, depicting mainly three clusters of functionality: on/off, more-or-less, and selection. This knowledge can be used to optimize the haptic design systematically and, thus, the fast and secure operation of automotive interfaces.

The work-in-progress paper and conference poster can be found in Appendix A.4 (p. 225).

This research was published as a work-in-progress conference contribution at World Haptics 2019. The goal was to explore form-functionality associations to facilitate haptic design in the community and discuss it with various experts from the field at

The exact year of publication is unclear. A more elaborated reference to affordances and the quote mentioned above can be found in Interaction Design Foundation (2022).

the conference. The two-page summary and the poster can be found in Appendix A.4. This poster presentation described and discussed the reasoning, method, and results of Pre-Study 2 *Similarity* of the tripartite *Function Follows Form* study series, which is described in Breitschaft and Carbon (2021). The motivation, method, and results of this contribution will be discussed in the context of the journal contribution (Section 2.2.2. Here it is reported to describe the complete list of research activities during the Ph.D. process.

For the sake of transparency, I want to point out that while the data were the same for the work-in-progress and journal publication, the results concerning the multidimensional scaling procedure differed. This was due to a computational error in the data analysis for the work-in-progress publication. The analysis process was completely redone for the journal publication.

2.2.2 Journal Article: Function Follows Form

This section, including all figures, is based on:

Breitschaft, S. J., & Carbon, C.-C. (2021). Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design. *Frontiers in psychology*, *12*, 2619. https://doi.org/10.3389/fpsyg.2021.646986

Abstract - Novel tangible user interface technologies facilitate current trends toward seamless user interfaces. They enable the design of yet unseen interfaces and, thus, the creation of a new kind of haptic language. To use the benefits of a touch-and-feel design for a positive user experience, carefully designed haptic feedback plays an important role in providing aesthetically pleasing product features. Haptic feedback may exceed the mere acquiring of buttons and input confirmation but enable orientation and even identification of functionality governed by the haptic impression. We employed the aesthetic association principle as a deeply grounded psychological mechanism that assists in the effective linkage between haptic form factors and associated functional attributes. To illustrate this powerful principle, we analyzed the specific associations between certain main haptic surface qualities and associated functional aspects. In a series of three subsequent studies (Pre-Study 1: *Perception*, Pre-Study 2: *Similarity*, and main study: *Association*), we explored paradigmatic associations of that kind to develop guidelines that forms are distinct to be used in interfaces. We show how forms are implicitly categorized into functional qualities (on/off, more-less, selection) using a multidimensional scaling procedure and explore explicit form-functionality associations using a think-aloud method in the context of an automotive interface. We revealed clear associative relations to specific functions for a series of forms. We will discuss the general value and opportunities of an association-based approach to user experience to create intuitive user interfaces. We will also develop ideas for specific areas of applications.

The journal article can be found in Appendix A.5 (p. 228).

Motivation

In previous decades haptic feedback has primarily been geared towards a highly functional purpose, for example confirming action upon button presses. Ridges, seams, and joints have provided tactile cues that allow effortless eyes-free haptic exploration, detection, and discrimination of interactive elements and orientation within interfaces. However, they have mainly been a by-product of the implementation of mechanical switches. Innovations within interface and manufacturing technologies — *smart surfaces*[21] — offer new possibilities in designing user interface surfaces in automotive interiors. There is an increasing digitalization within user

[21] Smart surfaces is a term which is used to describe the breadth of surface technologies that implement multiple interactive functionalities, such as lighting, sensing, haptic feedback, heating or shape-changing in a highly integrated hardware stack

interaction which disrupts previously high-class analog experiences. Even with the implementation of active haptics, haptic metaphors from the analog world seem to be the benchmark in a digital interaction space as they are geared towards the recreation of mechanical clicks while pressing or an edge-like sensation while sliding. Integrating novel interface technologies requires a new haptic language to guide this transition from a tactually rich analog to a more "digital" type of interaction. A proper understanding of dealing with the newly available surface features to design compelling, easy-to-use interfaces still seems to be missing. Instead of requiring the user to learn how to use a product, interfaces should be designed to employ deeply rooted mechanical routines that facilitate understanding and product appreciation.

Carbon (2019) highlights the importance of analogies for human perception and learning. The foundation of understanding perception as an association-driven process was laid in the late 19th century by the pioneer of psychophysics Gustav Theodor Fechner. In his early work "The Aesthetic Association Principle" (AAP), he emphasizes that a percept is not solely based on the sensory experience but modulated by experience, context, and expectations — basically, everything that is cognitively connected to the sensory input. The AAP goes beyond the mere psychophysical mapping of physical parameters to subjective perception. Integrating an association-driven approach to haptic design might foster the transition from analog to digital haptic experience and bridge the gap for novel interfaces. Employing common and deeply rooted analogies, associations, and behavioral patterns complies with user expectations and facilitates familiarity, learning, and aesthetic appreciation.

As a consequence, haptic cues might not only be used to enable *Detection* and provide *Orientation* within automotive user interfaces (as discussed within the *Framework of Haptic Aesthetic Processing*), but enable *Identification* of functionality. Beyond a mere augmentation of "there is something you can interact with", cues might already communicate "what and how to interact". The fundamental rationale is that using haptic cues that conform to user expectations by activating familiar functional associations and control elements is visually less distracting. Götz (2007) and Mueller (2016) have already depicted how the visual appearance of traditional button interfaces influences perceived functionality. They found clear relationships between certain surface features and perceived functionality (on/off, more/less, selection/scrolling). There are multiple applications in a car with restricted visual information, such as the middle console or controls located at the side of the seats. Current design practices recommend using signifying design features, i.e., haptic cues that invite a certain interaction. However, the relationship between haptic form features and functionality, which has a tremendous impact on usability, is still somewhat unclear.

The main goal of this research contribution was to explore the functional associations of haptic forms in the context of a highly systematic tripartite study setup (Study 1: *Perception*, Study 2: *Similarity* and Study 3: *Association*), which applies the *Aesthetic Association Principle* as the fundamental methodological approach to create a haptic vocabulary for novel tangible user interfaces. Furthermore, this contribution aimed to depict how a psychologically-driven research approach enriches haptic interface design and bridges the gap between the previous generation's analog experience and the next generation's digital haptic experience.

Method

This research consisted of a highly systematic tripartite study setup consisting of Pre-Study 1, Pre-Study 2, and Main Study. The general approach concerning the goals of each of the individual studies is described in Figure 15. The basic idea of this systematic tripartite study setup was to (1) determine accessible and recognizable forms, (2) examine whether forms do dissociate at all based on their perceived functionality, and use a refined set of stimuli to (3) explore specific form-functionality associations. Even though Pre-Study 1 and 2 give insights into haptic perception that might also facilitate haptic design guidelines, their main goal within this research approach was to serve as a means of stimulus selection. Discriminability and recognizability are essential factors in eliciting associations, so we aimed to have a set of systematically chosen, highly unique, and recognizable forms for the Main Study. This "stimulus reduction paradigm" was implemented to ensure a manageable and adequate number of stimuli at every stage of the process. It also allows retaining a systematic approach to selecting highly distinguishable forms.

Participants & Apparatus: The data for the study series was based on 56 participants. We did not exclude participants already participating in earlier studies for later-stage studies. All participants worked in the automotive sector but were naïve to the background of the studies. Ten people participated in Pre-Study 1, Fourteen in Pre-Study 2, and 32 in the Main Study. Participants were told to participate in a tripartite study series that explores a new haptic language for future tangible user interfaces. Haptic stimuli were placed inside a touchbox modified for each of the sub-studies. The forms were only explored haptically. A curtain prevented participants from seeing the forms. The study setup is described in Breitschaft and Carbon (2021). The touch-box was always placed similarly to the position of the center

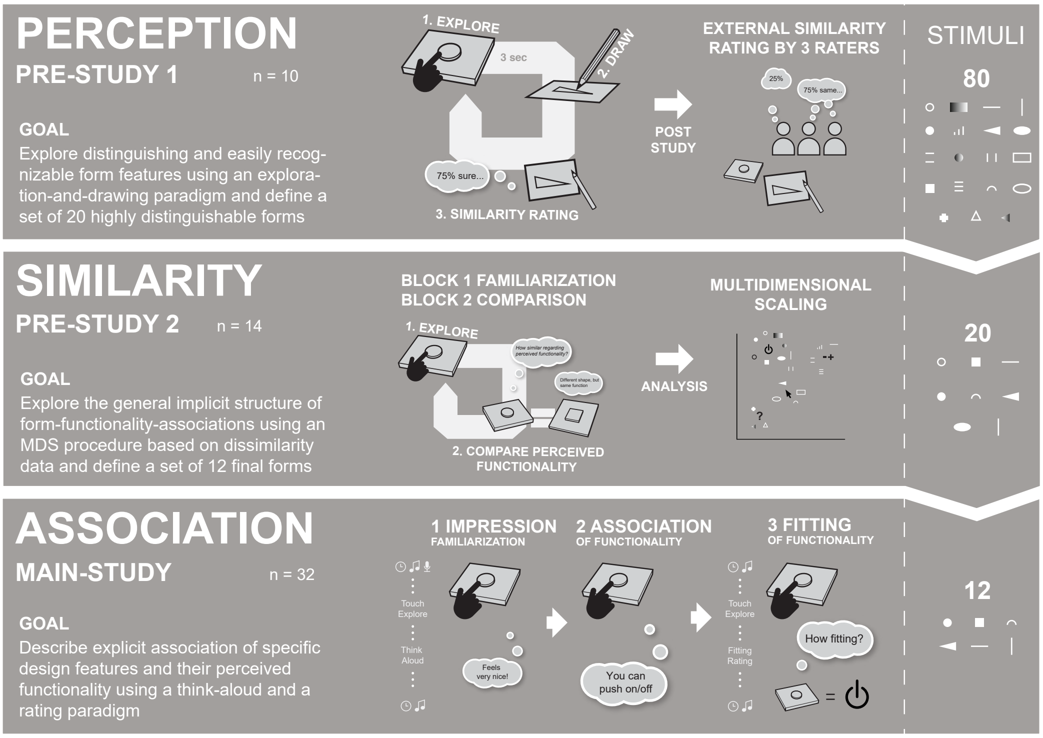


Fig. 15.: The experimental approach in *Function Follows Form* entails a highly systematic tripartite study setup: (1) Perception, (2) Similarity, (3) Association.

console in a car. We did not use an actual automotive interior or seating bucket. Still, participants were instructed to imagine that they were currently sitting in a car with a novel interface. They are required to explore the middle console to find a specific control element. We also instructed participants that we are not interested in specific functions like audio or climate but rather the underlying functional construct, such as more/less.

Stimuli: The same stimuli were used for all studies. The haptic forms were laser-engraved and consisted of polycarbonate material. The dimensions of the engraved forms were 15x15mm (e.g., circles) or 15x30mm (e.g., rectangular forms). All forms had the same height, defined by the engraving process. Physical forms can be described concerning various physical parameters, such as size, protrusion height, surface materials, shape geometry, etc. This makes it almost impossible to systematically examine the influence of every possible form parameter. Hence, we applied a more pragmatic approach in designing and choosing the initial set of 80 stimuli in Pre-Study 1. It was created during a workshop with three experts from the haptics and psychology community. The initial 80 stimuli were designed based on variations of basic geometrical shapes and forms that might be interesting in user interaction contexts. Pre-Study 2 used a set of 20 stimuli, and the Main Study twelve forms. The sets of stimuli are described in (Breitschaft & Carbon, 2021)

Pre-Study 1 — *Perception*-Study — used an exploration-and-drawing task. After a brief exploration period, participants were asked to draw the form they believed they explored. This study focused on discovering forms that can easily be recognized and discriminated. This way, hardly distinguishable forms were eliminated. Participants explored 80 forms in a randomized order. Participants were also asked to rate the similarity of the form they had drawn compared to the form they explored. In a post-study rating, three external raters compared the participants' drawings of the shapes and the actual shapes based on their perceived similarity. The participants' and the external raters' similarity ratings were used to select forms for Pre-Study 2 and examine their potential suitability and application in future tangible user interfaces.

Pre-Study 2 — *Similarity*-Study — employed a shape-comparison paradigm following a multidimensional scaling procedure to examine the dissociation of haptic forms based on their perceived functionality. Before precisely describing form-functionality, we aimed to explore whether various forms differ based on their perceived functionality in the first place. Pre-Study 2 used a set of 20 stimuli. Pre-Study 2 consisted of two blocks: *Familiarization* (Block 1) and *Comparison* (Block 2). During the *Familiarization*-Block, participants explored each of the 20 forms. They were asked to think of the functionality they were reminded of. At this point, they weren't required to express the associated functionality. In the *Comparison*-Block, participants were subsequently shown each possible form pair combination (190 in total) in a randomized order. They were asked to explore both forms and rate their similarity based on their perceived functionality. They were explicitly instructed not to evaluate similarities concerning geometry and form. The resulting similarity data were analyzed using a multidimensional scaling procedure (MDS). The MDS allows to explore and examine implicit similarity structures of a given dataset by describing empirical similarity data in a visual space. We selected twelve forms to be examined in the Main Study.

The **Main Study** — *Association*-Study — used twelve forms to explore specific form-functionality associations. The Main Study included three different blocks: *Impression*, *Association*, and *Fitting*. In every block, participants explored all twelve forms in a randomized order. Participants familiarized themselves with the forms during the *Impression*-block. The *Association*-block employed a think-aloud methodology to collect qualitative verbal data. Participants explored each form but were instructed to describe their associations concerning perceived functionality and how they would manipulate the form. In the *Fitting*-block, participants again explored each of the forms but were instructed to rate each of the explored forms based on their fitting to be used as a (1) on/off, (2) more/less, or (3) selection functionality. The qualitatively and explicitly reported associations and the quantitative fitting rating allowed to infer form-functionality associations. Even though we did not include a video recording of the exploration phases, the verbal data gave insights into exploration patterns, i.e., how participants potentially interact with specific forms.

Results & Stimulus Selection

This section briefly describes the results of Pre-Study 1, Pre-Study 2, and the Main Study. For an in-depth description of the results and which forms were selected at each stage, I would like to refer to Breitschaft and Carbon (2021)

Pre-Study 1: The subjective and objective similarity ratings were averaged for every form. Also, participants drawing were reviewed to derive any qualitative patterns. In general, participants performed surprisingly well in the drawing-and-exploration task. However, the recognition rate seemed to deteriorate with more complex forms. Potentially easy shapes like a raised-line horizontal and vertical line yielded high subjective and objective similarity ratings. Protruded forms seemed to be easier to recognize than recessed forms. Observing the participants' drawings indicate that haptic shape perception (like other senses) is heavily prone to perceptual distortions. Orientation and aspect ratios of forms were neglected or reproduced improperly, e.g., participants hardly differentiated squared- and rectangular-shaped forms. Wider angles were rounded off. For example, trapezoid-shaped forms were repeatedly drawn as semicircles, which made them inseparable from actual semicircles. The 20 forms to be used in Pre-Study 2 were based on the similarity ratings (which indicated forms that were easy to recognize) and pragmatic considerations concerning their application in future interfaces. The 20 forms selected for Pre-Study 2 are depicted in Figure 6 in the original publication (Breitschaft & Carbon, 2021).

Pre-Study 2: The similarity data generated by the shape comparison were analyzed using a multidimensional scaling procedure (MDS). The MDS plot (see Figure 16) shows that the 20 haptic forms differ based on their perceived functionality and can be categorized into multiple functionality clusters. An a-priori stress test revealed four distinct clusters to represent the similarity data sufficiently. Based on previous literature about communicative functions of tangible user interfaces (Götz, 2007; Mlakar & Haller, 2020) and insights from the post-study questionnaire, which

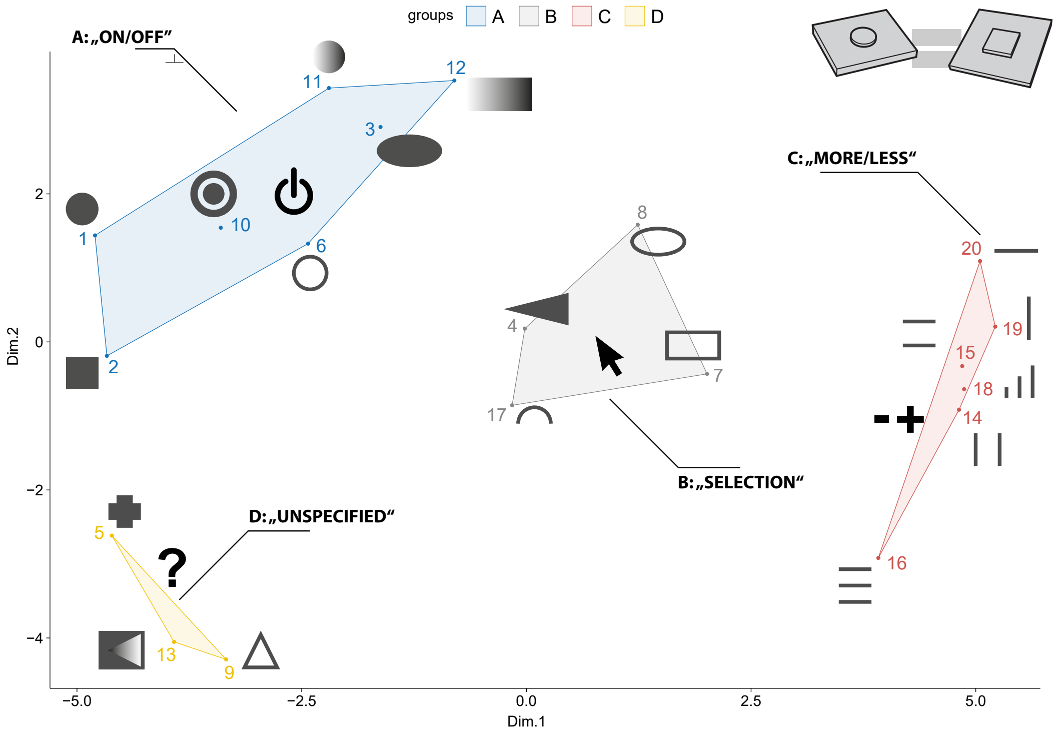
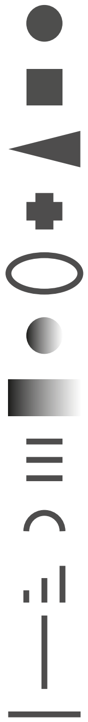


Fig. 16.: The multidimensional scaling procedure performed in Pre-Study 2 *Similarity* of the *Function Follows Form*-study describes four clusters: A) "on/off", B) "selection", C) "more/less" and D) "unspecified".

described participants' initial functional impression, the four distinct qualities, were interpreted using the following functional descriptions: A) "on/off", B) "selection", C) "more/less" and D) "unspecified". Twelve forms were selected to represent the final set of haptic forms in the Main Study.

Main Study: The Main Study implemented a two-fold data analysis strategy to examine form-functionality associations - qualitative (verbal descriptions) and quantitative (rating) data. The verbal associations from the *Association*-Block were categorized into different functional categories and analyzed with regard to how often each form has been described concerning a particular functional category. The analysis strategy also involved looking at how participants described they would interact with each form. The rating data from the *Fitting*-Block was analyzed descriptively. A Uniqueness Fitting Score (UFS) was calculated for each form. The UFS describes the effect sizes between the best and second-best fitting categories. It indicates the ambiguity of a form with respect to perceived functionality. Overall, results indicate that some forms and surface features are associated with functional categories and how participants tend to manipulate and interact. For example, the protruded circular form (Form 1) mostly reminded participants of an on/off functionality that must be pressed. In contrast, vertically or horizontally oriented raised-line forms were associated with more/less and selection functionalities. Some forms are clearer regarding perceived functionality, while others are more ambiguous. Figure 17 (p. 94) depicts exemplified associations described by participants. Figure 18 (p. 96) summarizes form-functionalities based on the results from the main study. This gives an interesting insight into how users perceived and interpreted the forms. An in-depth description and discussion of form-functionality-associations derived from the *Function Follows Form*-study series can be found in Breitschaft and Carbon (2021).



FORM	EXEMPLARY DESCRIPTIONS
1	"A protruded area. Just a simple button", "A circle. I would just like to press it"
2	"You'll get stuck on the protruded surface", "I just want to press it, because it's protruded."
3	"The triangle is a complicated shape", "It reminds me of increasing/decreasing as the shape converge to a point", "could be used for climate control or volume."
4	"it's complicated", "reminds me of a joystick and directional pad", "could be an iDrive replacement"
5	"it's exactly like the click-wheel of the first iPods", "could be used for navigating in a center display", "multifun-ctional", "contours invite sliding", "pressing in-between contours"
6	"slide from left to right", "I would like to slide along the rising area", "The edge invites pressing", "it's like sliding and then pressing at the end"
7	"intensity adjustment", "reminds me of a rocker key", "sliding towards rising area", "I am tempted pressing the protruded edge"
8	"slide control to open the sun-roof", "menu-button", "reminds me of a knurl", "3-staged element", "haptic separation between buttons"
9	"like a dead end for the finger", "finger guidance", "slide on half-moon", "natural contour for button area", "the arc feels like search cue"
10	"3 stages", "more/less", "WiFi-Button", "Volume- control", "three increasing buttons", "three different intensities"
11	"guidance", "increase/decrease", "slider", "separation between buttons"
12	"temperature", "volume", "climate control", "slider", "guidance and orientation for the finger", "more/less", "zoom in/out on a map"

Fig. 17.: Exemplary form-functionality associations from participants in the *Function Follows Form* Main Study: *Association*. This figure was published in (Breitschaft et al., 2019a)

Discussion

The fundamental idea of an association-based approach to interaction design is that haptic forms potentially reduce visual and mental load as they conform to user expectations and employ deeply rooted functional associations. This study aimed to examine the functional character of forms in a tangible user interface context and explore specific form-functionality associations. Overall, it can be concluded that forms seem to convey specific functional associations. In a user interaction context, this means that forms may potentially very well be employed to identify functionalities in user interfaces.

The idea of employing the association-based nature in interaction contexts is not entirely new. It may remind of the concept of affordance-based design introduced to the interaction community by Don Norman (Norman, 2013). The idea of affordances traces back to theoretical considerations by perception psychologist J.J. Gibson (Gibson, 1966, 1979). In Norman's context, affordances refer to object properties that ease interaction as said properties "tell" the user how the object should be used. Norman's idea of affordance implicitly picks up the general idea of the "Aesthetic Association Principle", which Fechner postulated roughly 100 years before Norman. While Gibsons' original concept of affordance is solely environmental-focused and neglects cognitive processes, Norman's idea of affordances — or rather "perceived affordances" and "signifying design feature", which Norman clarified later on (Norman, 2008) — takes user associations, expectations, and experiences into consideration. As advised by many UX experts, using affordances or signifying design features is a mere generic design guideline. Which factor describes signifying for users hugely depends on the mode of interaction and context. For example, Götz (2007) examined the visually communicated functional character of in-vehicle control elements. Similarly, this study series provides insights into how haptic form cues are associated with perceived functionality.

Form-Functionality Associations

The question remains, which forms are associated most with which kind of functionalities? Some forms depicted a clear association with respect to perceived functionality and interaction, while for others, the pattern of perceived functionality and interaction was a bit more ambiguous. Hence, the perceived functionality of a haptic form may depend on the general appearance and singular geometrical features and its implementation into a user interface surface. Figure 18 sums up how forms and features are potentially related to perceived functionality and type of interaction based on the results from the *Function Follows Form* study series. Subsequently reported form number corresponds to the numbers in this figure.

Associative strength seemed to be high for the fully protruded circular and squared shape (Form 1 & and Form 2 in the Main Study) as they were almost exclusively associated with classic on/off button functionality (mainly triggered by pushing). The verbal descriptions from the *Association*-Block of the Main Study make this even

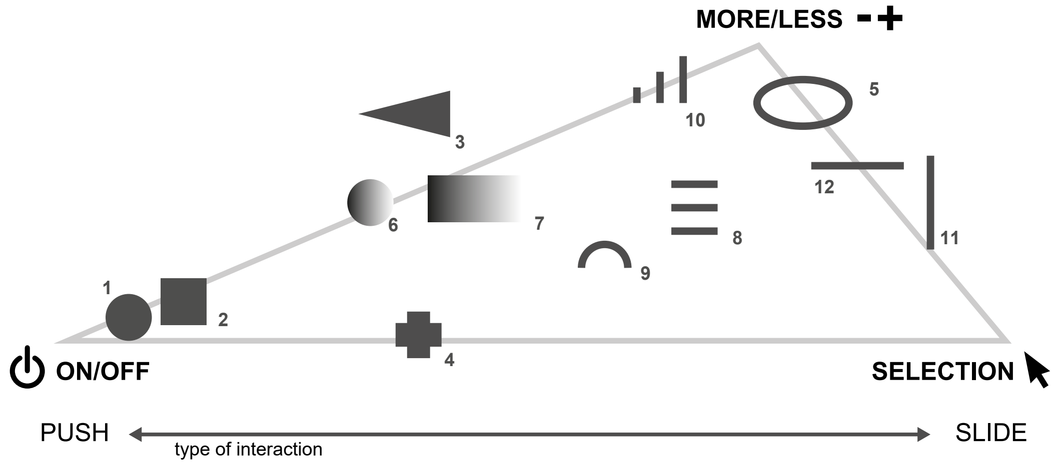


Fig. 18.: Some of the tested shapes seem to have clear form-functionality associations. This figure depicts an overview of form-functionality associations derived from the *Function Follows Form* study.

more apparent. Some participants described Form 1 & Form 2 to be simple buttons. The protrusion invited a push interaction.

The triangular-shaped forms (Form 3 & Form 10) indicated a more/less functionality. The triangular seemed to have reminded participants of the "volume"-symbols often found on audio interfaces. Potential interactivity is a bit more ambiguous. Form 3 (fully protruded triangle shape) tended to invite pressing, while Form 10 was more referred to as a sliding interaction. Form 5 (raised-line elliptical shape) was perceived as a more/less-functionality operated via sliding. Interestingly, this function has often been compared with the first generation iPod's Click-Wheel, which had a similar interface to control volume (Apple, 2020b).

The horizontally and vertically oriented straight raised lines (Form 11 & Form 12) were almost exclusively interpreted as sliding controls. The horizontal raised-lines tended to be perceived as a more/less control (due to the familiar implementation of volume sliders). In contrast, the vertical raised-line tended to be perceived as a selection element, corresponding to the typical vertical orientation of scroll bars.

The "ramp-like" forms (Form 6 & Form 7) were ambiguous regarding their functional and interactive characters as they seemed to combine different signifying design features. Participants described that the protruded edge (even though they could not describe the shape) popped out and invited them to press; some wanted to make the excessive edge flush with the surrounding surface. On the other hand, the gradient-like three-dimensional slope invited participants to swipe along the surface's elevation to the ramp's edge.

Forms 4, 8, and 9 were the most ambiguous forms as they seemed to have incorporated multiple different design features. Participants were not able to derive clear functional-based associations. The protruded cross-like shape reminded participants of a Gameboy's control pad, which is why they described it as a selection-based push button. However, plenty of people also didn't have any functional association — potentially because the form was too complex. Similarly to other forms, the protrusion seems to invite pressing. Form 8 (raised-line "burger menu" symbol) was mainly interpreted as a more/less or selection functionality manipulated by sliding. Many participants compared this form to a modern interpretation of a classical knurl often used to control volume or list entries. Yet, the similarity to a menu symbol made some participants interpret this form as a haptic manifestation of a menu button that should be pressed. Also, Form 9 elicited ambiguous associations. The half-moon shape was often not connected to a function but rather a comfortable feeling aid. One participant described it as a safe boundary for the finger. In multiple cases, the area surrounded by the raised lines invited participants to press. The two-sided semicircle shape also led people to use it as a sliding control to toggle between different states.

Limitations

There are some limitations of the study approach which require a deeper discussion.

This study only examined the general appearance of haptic forms based on a limited set of generic forms in a generic interaction context. Forms were mainly chosen following a pragmatic and application-driven rather than a fully systematic approach. The forms were deliberately restricted concerning materiality, size, height, etc., to ensure a manageable set of forms at every stage of the study series. As the forms are rather generic, they require a more design-driven application in actual interfaces. Associations and associative strength depend on context, experience, and implementation into the interface. Context means that form perception and saliency are influenced by general context requirements (e.g., where a control element is placed) and also local haptic material properties (Kahrimanovic et al., 2009). This means a protruded edge, as in Forms 6 and 7, might be less salient and inviting to press if the interaction surface is not flat but inhabits bumps and recesses. The functional association may also depend on the integration of the element into the tangible user interface, which inhabits more than a single function. This study only focuses on examining one form at a time. Putting different forms in a common panel might impact the perception and evaluation of each individual form.

The communicative function also depends on the integration of the form in the UI system and whether it's used as a direct or remote interaction element. For example, Form 5 (elliptical shape) may function as a volume knob if used in direct interaction use cases. However, suppose a secondary screen is involved. In that case, a raised-line circular shape may also be interpreted as a remote control element to manipulate the information on-screen (similar to the iDrive). As this study was conducted in a lab-type context and focused on exploring basic form-functionality association, we could not fully capture the influence of context. Even though participants were instructed to imagine themselves sitting in a car with a novel-type interface, presenting the forms in an actual car interior (or a more realistic mock-up) might have provided a much more immersive context. Even though the idea of using identifying form features is discussed in an automotive context, the effect on visual and mental load has not yet been examined in automotive user studies.

This study only focused on different shape geometries using the same polycarbonate material. Haptic materials are prone to affective evaluations. Haptic surface properties that are not susceptible to visual preview (Klatzky & Peck, 2012), such as compliance, hardness, slipperiness, and temperature, might be intriguing to examine with regard to their associative strength. I can imagine that using soft materials in interactive areas fosters the association of a push-functionality due to the finger "falling into" an interactive area based on the compliant character of surface material under pressure. "Rough" or "sticky" surface patches on otherwise smooth surfaces are highly salient and underscore the implicit impression of "sticking to a button". The idea of "stickiness" also becomes relevant in the context of active surface haptics technologies, such as electrostatic friction modulation (see Chapter 3.2).

Conclusion

Besides exploring form-functionality associations, the study series allow drawing plenty of conclusions about the use of haptic forms in interface contexts. In the following section, some of these other takeaways are discussed briefly:

Not all forms have an inherent usage-based functional association: For some of the forms in the Main Study participants did not report a clear functionality. Plenty of participants described the arc-like shape of Form 9 as a natural-feeling button boundary. Especially the raised-line forms (Form 5, 8, 9, 11, and 12) were also referred to as mere search and orientation cues.

Some forms may have a very specific functional association: This study did not focus on specific functions, such as volume, but rather on the underlying functional concept. However, some forms were interpreted as haptic symbols for specific UI functions. For example, Form 8 was often associated with a haptic menu button. Also, Form 10 was referred to as a Wi-Fi or connectivity button by some participants.

Define the context of interaction and validate shapes accordingly: We employed a rather generic context. Even though there might be forms that withstand contextual influences, the functional- and manipulation-based interpretation of ambiguous forms may vary depending on the type of context. This study only provides rough guidelines for form-functionality associations. Once the context is defined and forms are applied, practitioners may want to validate if the forms elicit the desired functional associations.

Use simple shapes for identification: Designers should avoid using complex surface geometries and forms to convey a specific type of functionality. Pre-Study 1 indicates that complex shapes are hardly recognized in haptic exploration tasks. So while these salient cues may be helpful for mere detection, they can hardly be used to elicit a proper functional association as users may not recognize them.

Make sure to emphasize the desired association: Ambiguous forms like Form 8 and 9 (see Figure 18, p. 96) indicate that association may not solely be based on the general appearance — the "Gestalt" — of form but rather its particular design features that drive a certain interaction. For example, prolonging the arc shape of Form 9 and adding "end-stop"-like cues might facilitate the "toggle"-impression. Also, prolonging the slope-like gradient of Form 7 might facilitate a sliding impression compared to the push impression from Form 6.

Consider the relationship of functionality and manipulation: The qualitative and quantitative data from the Main Study indicates a strong connection between the type of functionality and how people believe it should be manipulated. Figure 18 (p. 96) shows that most forms that were associated with an on/off-functionality are manipulated by pressing. On the other hand, most forms that were associated with a more/less or selection functionality are manipulated by sliding. In a sense, it seems that the type of interaction already mediates the type of expected functionality.

Implementation of a Psychological Turn in Haptic Design

Another primary goal of this publication — aside from examining form-functionality associations — was to establish and advocate a psychologically-driven perspective in haptic design as I believe it can genuinely benefit user and product experience. For a deeper discussion, also see Chapter 1.2. The association-based design aligns product properties and interactions with actual user needs. Designers and engineers can adapt the step-wise approach to evaluate their current design or explore future design ideas. Implementing an association-driven design approach might also mediate the contact with novel interface technologies that users are unfamiliar with. For example, employing haptic metaphors of real-world experiences might foster the adoption of new technologies by "activating" familiar cognitive patterns. Taking a closer look at metaphor and analogies as a fundamental part of experience also allows designers to reflect on their designs.

This association- and context-aware approach will also be applied in the following chapter to explore the effectiveness of active haptic technologies — and more precisely, electrostatic friction modulation — for search haptic purposes.

Part 3

ACTIVE HAPTICS

3.1 Active Haptic Feedback in Automotive

> *In stark contrast to the importance of touch in our everyday experience, the use of touch is marginalized in contemporary computer interfaces*
>
> — **Karon MacLean (2008)**

The ongoing trend towards the seamless integration of in-vehicle tangible user interfaces is a clear conflict between interaction and aesthetics (see Figure 2, p. 4). While flat surfaces create harmonious-looking and aesthetically pleasing interior surfaces, this tactile featurelessness deteriorates usability and eyes-free interaction by lacking tactile cues that are valuable for detection, orientation, and identification of control functions. The previous section characterized how passive haptic surface features can be utilized to create easier to use interface. However, in many cases, it is not desired to add additional passive haptic cues, for example, when implementing a dynamically changing interface like a touchscreen or in highly design-driven contexts that want to avoid seams and bumps. Implementing active haptics into control panels and touch surfaces mainly follows the goals of decluttering interfaces by replacing multi-button controls with a joint interface surface which is actuated by a single (or multiple coordinated) actuator(s) to retain some sense of tangibility and ergonomics. In this case, active haptic technologies are an essential enabler of a tangible turn as they facilitate the restoration of haptic sensations on an otherwise flat surface.

The *Haptic Fidelity Framework* in Chapter 1.3 pinpoints the breadth of currently available active haptic technologies, their actuation principles, and the range of experiences different actuators offer for haptic design. Automotive OEMs and suppliers have adopted the term *smart surfaces* to account for the multi-functional nature of interior surfaces, i.e., integrating multiple different interface functionalities, such as sensing, lighting, haptics, heating, etc., in a common tech stack. Haptic feedback in interface surfaces is no niche anymore but has gone mainstream in

The quote was published in *Do It Yourself Haptics: Part II [Tutorial]* (MacLean & Hayward, 2008).

automotive and consumer devices. As of 2022, plenty of examples in the automotive industry have already implemented active haptic technologies in series production. Figure 19 gives an overview of the introduction of haptic feedback-enabled interfaces in automotive and consumer electronics since the early 2010s. This overview is far from complete as new haptic products are introduced to the market on an almost daily basis. It depicts that since the mid-2010, there has been increasing implementation of active haptic technologies.

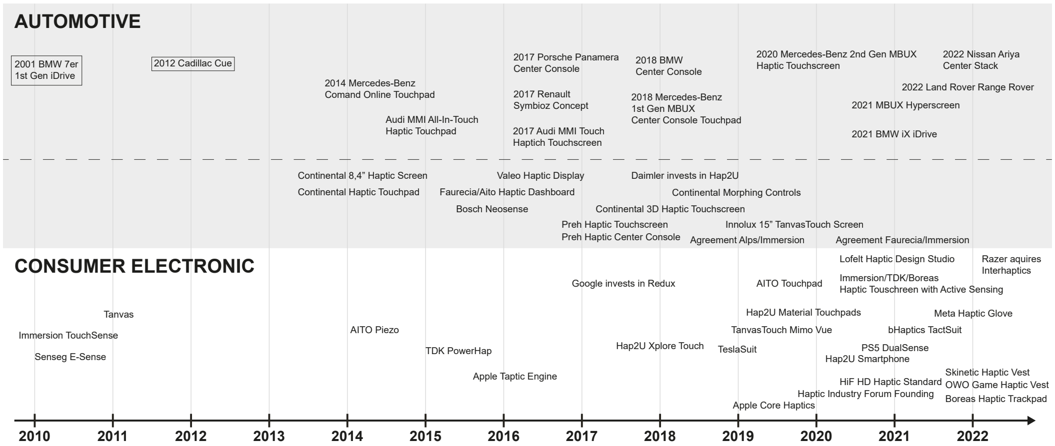


Fig. 19.: In recent years, an increasing amount of haptic products have been launched in the automotive and consumer electronic markets.

Cadillac was one of the first automotive manufacturers to implement active haptic feedback in their in-vehicle infotainment system, Cadillac Cue, in 2013 (Motor1, 2011). It is the same haptic device also used in Moreno and Weddle (2013), Weddle and Yu (2013), and Weddle et al. (2013). It utilized a center screen and center stack control panel with a vibrating confirmation input. While the vibration feedback generally seemed to be appreciated, user experience was deteriorated by the general slow system latency (Gruener, 2013).

In 2017, Audi introduced their new generation of in-vehicle HMI systems called the "MMI Touch" (Audi AG, 2020), which includes a dual touchscreen setup. The 2017 Porsche Panamera features a flat, closed-surface center console control panel (Porsche AG, 2017). Both interfaces use a solenoid-type actuator to simulate a mechanical button click feedback. The first generation BMW iDrive already incorporated interaction-sensitive haptic feedback (Alps Alpine, 2021), such as displaying end-stops while turning the dial. However, these features were discarded in the next generations (Bernstein et al., 2008). BMW introduced active haptic feedback in the center console control panel in their 2018 product range of cars — mainly to recreate a mechanical button sensation using an electromagnetic-type actuator. In the 2021 BMW iX, even some functionalities of the iDrive Controller, such as the tilting of the rotary knob, are designed as active haptic sensations (BMW Group, 2021). The 2022 Nissan Ariya includes vibrotactile actuators in their flat wooden center stack panel (Nissan Motor Co., 2021). Active haptic feedback — mainly using voice-coil and solenoid-type actuators — upon button press and slide gestures (e.g., a click while selecting items on a central information display) have also been integrated into remote center console control elements and touchpads like the MMI Touch Response in the 2016 Audi Q7 (Lust & Schaare, 2016), the Mercedes Command in the 2014 Mercedes C-Class (Continental, 2014) and the Mercedes MBUX Touchpads in all Mercedes vehicles utilizing the first generation of MBUX (Daimler AG, 2018).

Most of these examples only provide haptic feedback geared towards a single mode of interaction, i.e., either a confirmatory button press feedback or a feel-focused search haptic feedback. The 2020 Porsche Taycan, 2020 Mercedes S-Class, and 2021 Mercedes EQS were the first production cars that integrated a haptic touchscreen that combines search and confirmation cues (Daimler AG, 2021b, 2021c; Kessels, 2019). In the Porsche Taycan, the haptic screen is separated into two interaction areas. The upper direct interaction part allows controlling climate functions by pressing. The lower remote control part incorporates a touchpad surface controlling the central information display above the actual haptic screen via swipe gestures. Button presses in the upper part and swipe gestures (search haptics) in the lower part are augmented via haptic feedback. The haptic screens from the second generation Mercedes MBUX systems fully integrate haptic feedback as proposed by the *Framework of Haptic Processing in Automotive User Interfaces* (see Section 1.4.2). Button presses, as well as virtual edges, are augmented via haptic feedback. Interestingly, different haptic profiles are applied to different sliding interactions. For example, setting the color for the ambient light seems to employ higher frequent impulses than scrolling lists or adjusting the seats.

Restoring the tangibility in flat tangible user interfaces is on the technological roadmap of almost all automotive suppliers. Continental showed multiple haptic-touchscreen devices and center console concepts, mostly employing solenoid and voice-coils actuators (Continental, 2015, 2018). Other suppliers, such as Bosch (Neosense), Kyocera (Haptivity), Tanvas, and Immersion, have presented haptic-enabled touchscreens (Bosch, 2015; Immersion Corporation, 2020, 2021; Kyocera Corporation, 2018; Tanvas, 2020a). Faurecia implemented AITO's software-enhanced piezo technology to create a high-quality center stack concept with haptic buttons seamlessly integrated into different materials, such as wood, plastic, and metal (Aito, 2016).

Generally speaking, there is a strong focus on vibration-based technologies to recreate a button-like feeling in automotive. Despite haptics' impact during detection, only a few examples actually implement search haptic cues. Many examples that incorporate search haptic feedback via active haptic technologies, including prototypes from internal haptic projects and current production vehicles, have not been convincing from an interaction and quality perspective for multiple reasons. The haptic impulses do not match the actual button edge due to poor haptic design or system latency. Also, the haptic impression while sliding was often very weak — even when not driving. Most of these examples have in common that they integrated solenoids or voice-coils. This differs from button clicks requiring the user to press the surface. When it comes to **active search haptics**, there are still plenty of open questions to explore. Some of them include the following:

- Which are crucial (perceptual) requirements for active search haptic feedback?
- How should active search haptics feel like? How can this be translated into guidelines?
- Which technologies are suitable to augment search haptic cues? Is there a single best technology?
- Which impact do the different types of technologies have on user experience and usability?
- How can we reliably evaluate novel interface technologies?

The following chapter describes the efforts to explore the abovementioned questions using different types of active haptic technologies. Section 3.1.1 focuses on how participants characterize different piezo-actuated impulses based on the idea of an association-based human haptic perception (also see Chapter 1.2). The remainder of this section focuses on how electrostatic friction modulation can be implemented as a novel search haptics approach in an automotive context.

3.1.1 Conference Poster: Characterization of Active Haptic Feedback for User Interface Design and Development

This section, including all figures, is based on:

Heijboer, S., Breitschaft, S. J., & Carbon, C.-C. (2019a). Characterization of Active Haptic Feedback for User Interface Design and Development [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE

Abstract - Active haptic feedback technologies are increasingly used in user interfaces. However, the relation between technical haptic parameters and the corresponding haptic experience is unclear. This initial study attempts to better understand how active haptic feedback is characterized to aid in user interface development. 26 Participants have each described 30 piezo-actuated haptic patterns, which were arranged into a classification system afterwards. Preliminary results show that participants describe haptics more with evocative descriptions than with using factual descriptions.

The conference poster can be found in Appendix A.6 (p. 251).

Motivation & Rationale

Active haptic technologies are increasingly becoming an inherent part of tangible user interfaces. There is an abundance of different actuator technologies designers and engineers can choose to enrich interaction (see Section 1.3.2). Apart from technical requirements, it is essential to understand the repercussions of active haptic feedback sensations on user experience. The increasing complexity of novel type actuators, which are often advertised using incomprehensible brand-specific and market-driven terms, and the focus on a technology-driven comparison, description, and evaluation of haptic technologies hinder a proper understanding of how active haptic sensations are described and perceived: Which sensations are pleasing? Which sensations are to avoid?

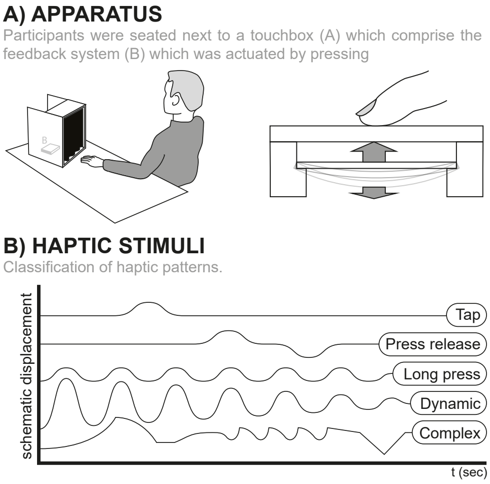
Psychophysical assessments examine the connection of technological parameters and how they are perceived but are often restricted to a single perceptual quality (for example, haptic strength or sharpness). Results can hardly be transferred to other technologies due to technology-specific characteristics — Kim and Schneider (2020) refer to this as *timbre*. Thus, a purely-technical description neglects the true nature of haptic experience (Kim & Schneider, 2020; Schneider et al., 2017).

Understanding how different technologies and impulses are experienced is crucial for haptic designers to convey the appropriate type of experience (Breitschaft et al., 2022a). Previous sections (Section 2.2.2) have provided examples of how an association-driven approach may foster haptic design. Instead of a parameter-driven description of haptic impulses, an experience-focused vocabulary might facilitate communication between researchers, product designers, and engineers. This study explored how users experience and characterize various piezo-induced active haptic patterns. Furthermore, this study sought to depict that in the context of user experience design, communicating haptic experiences via user-gathered associations may provide an alternative, more user-focused even though also a bit softer) basis for collaboration than pure code and technical parameters.

Method & Results

26 Participants took part in the study. All participants were neither aware of the study's background nor had any specific haptic training. They wore noise-canceling headphones during the study. The study employed a think-aloud methodology — similar to the *Function Follows Form* studies in Breitschaft and Carbon (2021). This means that participants were asked to explore the stimuli and describe their haptic experience during exploration. Verbal descriptions were recorded and transcribed after data acquisition. The study implemented 30 haptic patterns that were subsumed into five categories to generate a broad range of possible effects: (1) tap: haptic feedback only at push event, (2) push/release: haptic feedback at push and release event, (3) long press: static haptic feedback during more extended push interaction, (4) dynamic: same as long press with dynamically changing parameters during prolonged touch and (5) weird: complex combinations of haptic impulses. The haptic patterns resulted from an application-driven workshop that focused on defining potentially suitable haptic patterns for UI design. Haptic stimuli did not vary systematically based on parameters such as frequency, duration, etc. Participants were instructed they could interact with the device in multiple different ways. They subsequently explored all 30 different haptic patterns without any time restriction.

The study implemented a similar approach to analyzing the qualitative data as Breitschaft and Carbon (2021) (see Section 2.2.2). We established an initial categorization scheme based on all verbal descriptions, which was refined in subsequent discussions. Based on the discussion, a final categorization scheme was established. Three independent raters categorized verbal descriptions based on the established coding scheme. The categorization system used two main categories: (1) *Factual*



C) CATEGORIES OF HAPTIC DESCRIPTIONS

	Category	Description	Examples
1		**Factual**	
1.1	Technical	use of jargon or specific technical parameters	frequency, sinus amplitude
1.2	Timing	descriptions involing temporal aspects	long, 2 seconds
1.3	Factual Adjective	adjective that seek to precisely describe the sensory experience in a factual way	subtle, too hard, deep, intensive, light, increasing
1.4	Rational	Rationally describing a haptic event without using any of the previous named categories	I feel many vibrations, it gives feedback
2		**Evocative**	
2.1	Action	perceived physical movement	it feels like knocking
2.2	Evocative Adjective	adjectives that seek to figuratively describe the sensory experience in an indirect way	preachy, funny, dangerous, exciting
2.3	Function	assumed or imagined function	it feels like a warning
2.4	Object	object or application related	like a printer, an electroshock
2.5	Sound	sound description or imitation	zoomin, „bzzz“

Fig. 20.: Summary of the methodology, stimuli, and results of the *Active Haptic Characterization* study.

and (2) *Evocative* descriptions. The factual main category incorporated four subcategories: (1) Technical, (2) Timing, (3) Factual Adjective, and (4) Rational. The evocative category included the following subcategories: (1) Action, (2) Evocative Adjective, (3) Function, (4) Object, and (5) Sound. Figure 20 describes the categories and examples of how participants described their feeling. In total, there were 1513 category assignments. Of all assignments, 1048 included evocative descriptions, while 523 were assigned to the factual main category. In cases where all raters fully overlapped, 85% of the haptic descriptions belonged to the evocative category.

Discussion

With the increasing complexity and defragmentation of the haptics market, there is a gap between designers envisioning a certain type of experience and engineers trying to translate this vision into technical concepts. This study was meant to explore how participants describe the haptic sensation based on different piezo-actuated vibration impulses to aid the implementation of haptic feedback.

Participants seem to employ a strongly metaphor-driven interpretation of unfamiliar haptic sensation (Carbon, 2019). Users used more evocative than factual descriptions to describe their haptic impression. Only some participants described their haptic impression mainly using factual reports, such as "it vibrates", "it gives feedback", "strong", or "changing". Surprisingly, even for longer-lasting sequences of vibrations, participants hardly used descriptions, including timing. It seems a relatively trivial finding that untrained users do not seem to use technical terms to describe their haptic impression but rather perceptual associations. Nevertheless, it gives a clearer understanding of how users interpret haptic sensations, which might provide a more efficient way to communicate haptic between different stakeholders. It might also point to the fact that it's far more important to get the overall experience right instead of focusing on sheer strength or precision of the haptic signal.

Interestingly, some patterns can be assigned to specific associations. Haptic impulses were often described to resemble the behavior of certain objects, like an "alarm clock", "drill", or "printing something". One of the impulses was often described as "shots being fired from a machine gun". Longer-lasting vibrations seem to be associated with more negative descriptions, such as "irritating", "unpleasant", "alarming", "warning", and "mistake". A similar conclusion can also be observed in different studies using high-frequency electrostatic friction textures (see Section 3.2.4). While eliciting a warning impression might be helpful in specific interaction contexts, such as indicating a button that is not accessible while driving, long vibrations might harm the user experience due to their annoying character. This is also frequently stated in different haptic design guidelines (Apple, 2020a; Google Inc., 2020). Even though temporal characteristics are important parameters for haptic design, participants have hardly used timing-related descriptions to describe their feelings.

Participants often employed sound references to explain their haptic impression, such as a ringtone melody or "it sounds like printing something". As some of the impulses did produce excessive noise upon actuation, participants wore noise-canceling headphones. However, some noise was still perceivable. Participants might have described not only their tactile experience but also what they heard during exploration. On the other hand, describing sound is a straightforward approach to communicating haptics, as the haptic and audio impressions are inherently tied together. This tight connection between sound curves and haptic is already leveraged in haptic design workflows. For example, the haptic start-up LoFelt offered a haptic design studio whose design workflow is based on using an audio file to create the haptic effect (Lofelt, 2020)[22].

There are also some limitations to the study that are worth discussing. Associative descriptions are heavily based on context, i.e., the same click effect may be interpreted differently based on the haptic context. This study employed a generic interaction context ("Imagine feeling this effect in a future tangible user interface"). Yet, some impulses already yielded quite accurate descriptions, highlighting their

[22] Lofelt has been acquired by Meta in September 2022 and ceased operation of their product line-up (Hayden, 2022).

importance in augmenting user interaction. Furthermore, we did not systematically vary technical parameters, such as duration, actuation force, amplitude, frequency, number of peak amplitudes, and so on but used impulses that were created during an expert workshop. We used a wide array of impulses to explore the design space of piezo-actuated haptic impulses. The goal was to explore how participants interpret their haptic impression in general instead of focusing on the psychophysical relationship of singular perceptual dimensions. We argue that interaction research still lacks a proper experience-focused examination of active haptic sensations (Breitschaft & Carbon, 2021; Breitschaft et al., 2022a). While there is plenty of research on the psychophysical relationship between technology and perceived strength (or comfort and annoyance, etc.), these bilateral descriptors neglect a more holistic approach to haptic experience as proposed by Schneider et al. (2017) and Kim and Schneider (2020).

Ultimately, the customer is not interested in the technical implementation but cares about the experience. Currently, this experience-based view of haptic technology is still missing. While the haptic industry tries to come together to establish a common haptic technology standard, it is still uncertain whether it will be able to capture all different haptic experiences, from vibration- to friction-based experience (Haptics Industry Forum, 2020). In addition to a parameter-driven comparison of performance across different haptic technologies, stakeholders might also communicate via experiences that technologies can convey (see Figure 10). This might help to declutter the haptics market and make it more accessible to designers that are not fully engaged with technological terms.

Friction Haptics 3.2

In recent years haptic companies, start-ups, and suppliers have shown plenty of different technological approaches to restore haptics on featureless automotive interior surfaces — ranging from solenoids and voice-coils to piezo-based concepts and even morphing surfaces. Especially since the late 2010s, the approach of surface haptics has caught the attention of a broad range of practitioners and stakeholders. As opposed to primarily low- to medium-fidelity vibration-based approaches, surface haptics offers a higher-fidelity and mostly friction-based approach. Friction modulation is mainly geared towards an explore-and-feel-focused interaction, making it an interesting approach for a high-quality active search haptic impression. Friction modulation contains two basic approaches: (1) **increasing friction via electrostatic actuation** or (2) **decreasing friction via ultrasonic actuation** (Basdogan et al., 2020; Breitschaft et al., 2022a).

Compared to any other vibration-based technology that creates haptic feedback by moving a certain amount of mass, surface haptic technologies like electrostatic and ultrasonic friction modulation use different haptic paradigms. In a nutshell: Electrostatic friction displays vary the friction force between the bare finger and the surface during the exploration of a surface with the bare finger through an electrode layer embedded in the technical stack of the touch surface. In return, this highly localized change in perceived friction is felt by the users and can be used to generate various sensations, ranging from single clicks to complex textures. Ultrasonic friction modulation technologies actuate piezo-electrics at an ultrasonic level to create an air-cushion that locally reduces friction while the finger is moving across a surface[23].

Even though both friction modulation approaches seem very promising for automotive interfaces, this chapter will only examine electrostatic friction modulation for several reasons. The following advantages of friction-based haptic technologies make them highly intriguing for application in automotive and other CE products (Klein, 2022; Shultz, 2020):

[23] For a detailed description of the technological background of surface haptics technologies and their actuation principle I would like to refer to Basdogan et al. (2020), Breitschaft et al. (2022a), Shultz et al. (2015) and Osgouei (2020)

High haptic fidelity experience: The haptic impression of electrostatic friction modulation can be characterized by a high fidelity and high-quality experience. Electrostatic friction modulation allows for a broad spectrum of haptic effects — from highly precise single haptic clicks to choppy or very fine textures. The almost immediate and localized haptic feeling contributes to the quality impression.

Solid-state: Electrostatic friction displays generate haptic feedback using an additional electrode layer in the technological stack. The haptic effect is not based on the vibration of a moving mass. Hence, no moving parts are required, which makes it completely solid-state. This is a massive upside as no complex mechanical integration and spring-damper system is necessary for dampening and decoupling the moving mass (something which gets extremely complex as display sizes and masses increase). It also helps to keep the tech stack reduced.

Low latency: The haptic feedback is low latency which massively contributes to the high-quality impression — in contrast to vibration-based systems (Kaaresoja, 2015; Weddle et al., 2013). "Pre-loading" the friction map with changing GUI screens as well as the lack of a physically moving actuator, which usually introduces inertia and additional ramp-up time, contribute to an instant-feeling impression ("You feel the haptic feedback where you're supposed to feel it").

Silent actuation: Variable friction displays are very silent during the interaction as they do not rely on vibration-based haptic actuators, which are often accompanied by considerable actuation noise. The absence of by-product noises is a common requirement for manufacturers as it does not interfere with the haptic impression. It also does not interfere with any additional system audio feedback and offers additional degrees of freedom for audio design.

Scalability & adaptability: The solid-state nature of electrostatic friction modulation allows for scalability and adaptability to various interface sizes and form factors while retaining a homogeneous and high-quality haptic impression within the interface but also across devices using different sizes. For example, Tanvas also implemented their electrostatic friction modulation technology to flexible AMOLED displays (Tanvas, 2022b). Scalability is an issue for vibration-based technologies as larger display sizes and asymmetrical display shapes require modification of the whole haptic system, starting from the actuator to mechanical integration.

Software-defined feedback: Another advantage is that haptic sensations are completely software-defined and adaptable. Due to the solid-state nature, the impulse design has hardly any mechanical restriction. Full programmability makes it an easy-to-handle prototyping tool during the ideation and development process. It also offers the possibility to upgrade haptic effects during series production via over-the-air updates. For example, the TanvasTouch device used in the subsequently reported studies (Mimo Monitors, 2022; Tanvas, 2022a) renders haptic effects based on black-and-white image bitmaps. The bitmaps' black and white values (0/255) correspond to the exerted friction level (Shultz, 2020). White equals the maximum possible friction level, whereas black means no additional friction. In grey areas, the exerted friction level corresponds to their RGB values (0 to 255). Haptic design is based on creating a friction map (black/white bitmap) that corresponds to visual interface elements. For example, button elements may implement a white noise pattern to augment interface elements. Once the user opens a specific graphical user interface screen, the associated (underlying) friction map is "pre-loaded" before the user interacts.

However, a crucial restriction to consider is that friction modulation is inherently based on an exploration-focused mode of interaction as it requires active tangential finger movement. As a moving finger is necessary to create a haptic sensation, recreating a typical button click impression to confirm a touch input is hardly possible. In some cases, this might restrict the range of possible interactions and become an issue once tap or push is the primary mode of confirmation in interfaces. In this case, new types of interactive movements for these "traditional" interaction metaphors need further exploration. Despite this limitation, the focus on active haptic exploration as the primary type of interaction makes friction haptics highly appropriate for search haptics.

Upon the start of experimenting (beginning of 2019) with the TanvasTouch, there were hardly any technology-specific design guidelines and insights from actual usability studies on how to design friction stimuli for this type of interface. This was mainly due to the novelty and scarce availability of the product to a broader market. Before implementing this device in search haptic applications, a primary goal was to understand the basic design principles — the essential "building blocks" of friction haptics.

3.2.1 Building Blocks of Friction Haptics

The following section documents the efforts in exploring the design space for electrostatic friction modulation displays. Some of the steps were also part of the work-in-progress contributions at the EuroHaptics 2020 conference. Surface haptics is not an entirely new technological approach. First working prototypes have been around since the late 2000's (Biet et al., 2007; Linjama & Mäkinen, 2009; Winfield et al., 2007). However, only since the very late 2010's/early 2020s surface haptics devices are available to a broader field of practitioners by companies, such as Tanvas and Hap2U (Hap2U, 2020; Tanvas, 2020b).

Various proof-of-concept studies with initial design exploration and psychophysical examinations using proofs-of-concept and complex lab-grade devices have been published throughout the 2010s. For example, Bau et al. (2010) examined subjective interpretations in their initial studies using electrovibration stimuli. Levesque et al. (2011), as well as Levesque et al. (2012), describe the exploration of the haptic design space for ultrasonic stimuli. Basdogan et al. (2020) provide an extensive overview of the current state of surface haptics, including haptic technology, rendering, human haptic perception, applications in UI/UX, and design challenges. In this context, they also describe the application of electrostatic friction modulation for different UI use cases, such as rendering virtual textures and shapes (for comparison, see Table 3 of the original contribution). Interestingly, most reported studies focus on purely psychophysical measures and neglect a more holistic approach to the user experience of electrostatic friction stimuli. Use cases like target acquisition, augmenting buttons, and slider controls using electrostatics have hardly been examined — or at least they are missing in the summary table of Basdogan et al. (2020).

The main goals of these design explorations into electrostatic friction modulation were understanding (1) the prerequisites of human haptic perception of basic stimuli (e.g., the saliency of textures, discrimination of haptic lines and textures, item size), (2) the effectiveness of surface haptics in multitask automotive UI-settings and (3) general strengths and challenges towards implementation, perception, and interaction.

In addition to functional and usability-focused parameters, another aim was to shed some light on the aesthetical impression of friction stimuli, which is essential for the initial contact as well as long-term user satisfaction. Due to its novelty within the automotive field, examining user reactions and first-hand impressions of electrostatics seemed intriguing. Ultimately, these efforts are supposed to depict a well-rounded image of the potentials and challenges of variable friction displays and provide an initial set of guiding design principles for practitioners using electrostatic devices.

The following studies were based on the first commercially available version of the TanvasTouch MimoVue Touchscreen device using SDK 2.0.1 (except Section 3.2.3, which used 1.0.13). Even though the device is still under constant development (as of February 2023) and newer software and hardware revision may potentially result in more capable devices, these studies provide a solid starting point for practitioners. A pragmatic and application-based design approach was applied by using Tanvas' black/white friction map approach. That means friction maps were created using a bitmap graphics editor instead of code — a workflow most practitioners would probably also implement. The following section will not include any technical values and parameters as this is a prototyping rather than an actual research device. Another reason is that the documentation of concrete driving parameters is subject to Tanvas' intellectual property. The friction levels refer to the levels of haptic strength the MimoVue device can deliver. In the subsequent studies, participants were not explicitly introduced to electrostatic friction. All studies included multiple test trials to accommodate for the novel haptic experience.

3.2.2 Conference Poster: Examining Detectability of Virtual Haptic Items Rendered on an Electrostatic Friction Modulation Display.

This section, including all figures, is based on:

Breitschaft, S. J., Pasthukov, A., & Carbon, C.-C. (2020b). Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.35489.84320

Abstract - Electrostatic friction modulation can be used to augment virtual user interface elements via haptic feedback, for example, to highlight interactive elements like a button. This might be especially useful in a seamless user interface, such as a display or control panel, that requires both high aesthetic quality and safe-to-use interactions. However, it is unclear which textures are best for making virtual items "stand out" while retaining a pleasant character. This study explored the impact of graphical control element size (10, 15 mm) and texture on detectability and user experience (pleasantness, quality, precision, annoyance, and fitting) of virtual elements rendered via electrostatic friction modulation. Stimuli included six different textures. Four differed in haptic strength (low/high) and spatial frequency (high/low), one only consisted of a contour, and one consisted of a homogeneous high friction patch. Participants (N=16) performed a "haptic search" task. After fixating a finger at the center of the screen, they searched for an electrostatically rendered but visually invisible target that appeared at a randomized location. Results showed that larger items were detected faster and yielded fewer errors. Size impacted user experience variables positively. Stimuli with only a contour and low strength generally yielded more errors, produced longer response times, and scored lower values on user experience variables. We describe a set of targets most suitable for "searching" virtual elements rendered via electrostatic friction modulation.

The conference poster can be found in Appendix A.7 (p. 252).

Motivation & Rationale

Current automotive touchscreens focus on a visually-driven look-and-tap-based interaction. In most production-ready cars with haptic touchscreens, haptics is mostly only implemented at the confirmation stage (see Figure 13 and Section 3.2.5) — if at all. In this case, searching and acquiring functions are still predominantly guided by brief glances (Rümelin, 2014). The feel-focused approach from traditional button interfaces might reduce visual distraction already at the search stage. Friction stimuli allow haptic search and detection of augmented interface items, such as button textures and edges.

Traditional physical button interfaces primarily focused on discontinuities, such as joints and edges, to provide search haptic cues. Also, other surface features, such as geometry and form, can enhance eyes-free interaction (Breitschaft & Carbon, 2021). Button shape and geometry play a crucial role in haptic exploration as it gives subtle haptic information on the status of the explored surface. These subtle cues are often missing in active haptic interfaces, as only the boundaries of interactive surface areas are augmented via haptic clicks. This makes it difficult for users to distinguish whether they slid on or off the element. In the context of the *Framework of Haptic Processing in Automotive User Interfaces* (see Section 1.4.2), I described that search cues should be salient and detectable. Search cues used for detection should also be distinguishable from identification cues. This differentiation from detection and identification cues is lacking if only edges are augmented. Augmenting interactive elements via textures might allow easier and faster detection of interface elements. Zhang and Harrison (2015) already pinpointed the positive effect of "fill"-texture feedback in simple 1D-drag-and-drop tasks.

Electrostatic friction displays offer various haptic sensations, from high-precision haptic clicks to different kinds of textures. Design guidelines as to which type of design parameters are optimal to enhance detection and, at the same time, provide a high-quality haptic impression are scarce. The goal of this exploration was to examine (1) which haptic features make virtual elements easier and faster to detect (button edges or textures), (2) which haptic coding optimally supports detection, (3) whether item size influences detection performance, and (4) how different textures influence aesthetic appreciation. Based on previous pilot studies, we expected a dissociation between saliency and pleasantness, meaning high-frequent/high-amplitude textures to be highly salient but somewhat unpleasant to touch.

Method & Results

Sixteen participants took part in the study. They were neither aware of the study's background nor familiar with the TanvasTouch device. The study employed a *haptic search*-paradigm similar to the methodology known from search experiments in the visual and haptic domain (Kappers & Bergmann Tiest, 2015a). Participants were asked to explore the haptic display and "search" the target item, which was augmented on the screen. Participants started the task in the center of the screen (which was indicated by a blue dot), explored the screen, and were told to "search" and activate the target element by lifting their finger upon detection of the element. The target item itself was not visible. Only the item's approximate location was indicated by visually highlighting the quadrant of the screen part it was located in. The experimental procedure is explained in Breitschaft et al. (2020b). The conference poster can be found in Appendix A.7.

The study included twelve different texture patches — six different button texture patches that vary on two different item sizes (10mm and 15mm). The texture patches were created using different variations of amplitude (i.e., haptic intensity) and frequency (i.e., number of friction changes). Four textures were constructed using a checkerboard pattern. One texture consisted of a homogeneous friction patch, and another one only augmented the contour of the target item. The friction maps of the stimuli are displayed in Figure 21 and Appendix A.7. As described earlier, the black, white, and grey values correspond to the exerted friction force on the haptic display. Each participant explored all of the 12 different textures in a randomized order. Each experimental block consisted of 12 trials with the same texture.

The analysis strategy was two-fold and included objective and subjective data. The functional evaluation of detection was based on objective performance data, including detection rates (not reported in the work-in-progress contribution) and response times (RT). After every stimulus block, participants were given a questionnaire including the following variables to assess haptic experience: Pleasantness, Annoyance, Perceived Precision, Quality, and Fitting. The study session concluded with a qualitative evaluation of the haptic impression.

In general, bigger target items yielded lower response times and higher detection rates (see Figure 21). From a subjective perspective, the 15mm targets were perceived to be more pleasant, higher quality, precise, and fitting. The detection rates were low for all stimuli. For the 10mm targets, they were below 50% each. This means the targets were only correctly detected in less than 50% of the trials. Detection rates of the 15mm targets were a bit higher (roughly 50%). The target's distance to the center did not influence the detection rate of haptic target items, i.e., targets closer to the center were not detected more often, only because they were closer.

Figure 21 depicts the subjective ratings for the different textures (averaged across item size). Results indicated that the high-frequent-high-amplitude texture patches were most fitting, pleasant, precise, and high-quality. The homogeneous high-friction patch (white only, no texture) appeared to be the second-best button texture concerning the aesthetical impression. The low-amplitude stimuli (especially the low-frequency-low-amplitude) were perceived as less fitting, pleasant, precise, and low-quality. The targets with the highlighted contour scored worse than the high-amplitude but better than the low-amplitude textures.

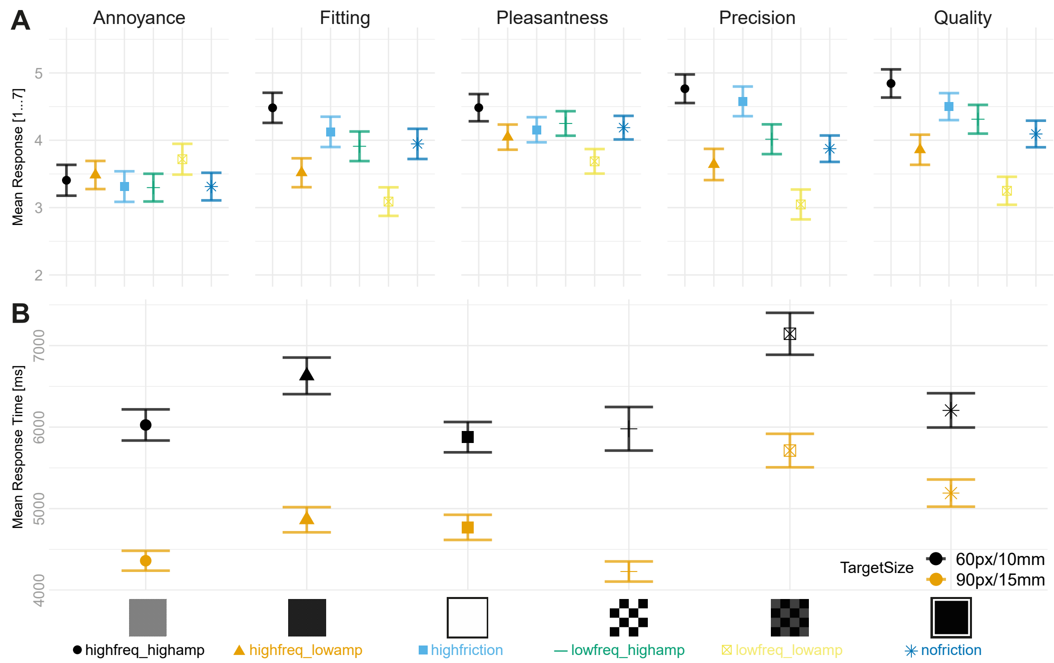


Fig. 21.: Detection performance differed for item size and texture. The graphs provide a summary of the results for (A) the UX variables and (B) the mean detection time in the *Detectability of Virtual Haptic Items* study.

Discussion

The goal of this study was to explore the impact of element size and texture on the detectability and haptic experience of virtual display elements augmented via electrostatic friction modulation. First, bigger targets (15mm vs. 10mm) seemed to be detected more effectively, which corresponds to other studies (Eren et al., 2015; Rümelin, 2014). To minimize the complexity of this design exploration, we implemented only two different item sizes. An item size of 15mm was used as the maximum size as this size is a practical rule-of-thumb among automotive interface designers. Despite big screen sizes, screen estate is also a valuable resource in digital interfaces, which is why no bigger item size was implemented. Based on previous studies, detection performance probably increases with bigger item sizes up to a certain level (Eren et al., 2015). However, studies using big item sizes often neglect design constraints in real-world settings (Tunca et al., 2018). For example, Eren et al. (2015) depict that item with a size of 140mm foster eyes-free interaction. However, 140mm items are way too big to apply in automotive interfaces.

The findings for the high-frequency-high-amplitude target were somewhat surprising. Due to their saliency, we expected that the high-frequency-high-amplitude target would be the quickest and most reliable to detect but also rather annoying and unpleasant due to their high-frequent nature. Surprisingly, this texture scored well with regard to subjective ratings compared to the other stimuli. It was the most fitting, pleasant, precise, and high-quality of all textures. The homogeneous high-friction patch was perceived to be easily detected and yielded acceptable subjective ratings, which was also reflected in some of the participants' post-study evaluations. The homogeneous high-friction patch reinforces the "my finger sticks to the target"-impression and complies with the user's association of searching and finding a control element.

It turned out that the low-amplitude stimuli (regardless of frequency) were not suitable for optimizing the augmentation of digital interface elements, which is also highlighted by the subjective experience ratings. In this case, the friction level was set to a third of the maximum available strength level. This might have been too low and resulted in a somewhat fuzzy, imprecise, and non-fitting feeling — especially as electrostatic haptic feedback was a novel experience for most participants. Even though low-amplitude stimuli are not suitable for maximizing haptic saliency, they may still be a valuable asset in augmenting other interface elements - for example, to augment elements with lower importance.

There were also some limitations to the study that I will briefly discuss. We only implemented a small but carefully selected set of stimuli. The textures were basic from a haptic design point of view — black/white checkerboards with varying sizes of squares. We chose this approach because, in earlier prototyping sessions, we found that textures using symmetrical or asymmetrical friction patterns were hard to keep apart. Future studies may examine the saliency of different electrostatic textures based on a more systematic approach, i.e., more item sizes, different strength levels, and different texture shapes. It would be interesting to see how detection performance and subjective ratings vary with a systematic approach using more stimuli.

The overall low detection rate was strikingly low. The 10mm targets were correctly activated in less than 50% of the trials. Detection rates were only slightly higher for the 15mm targets. The high error rate might be based on multiple technical and methodological limitations. While the target size may have been sufficient, the device's maximal level of haptic strength was not. The search paradigm, i.e., search-and-lift-off-to-activate, might have also been problematic for several reasons. From an interaction perspective, it does not necessarily correspond to a prototypical search-and-activate setting. Confirmation is usually performed by an additional interaction like pressing or tapping after a successful haptic exploration (also see *Framework of Haptic Processing in Automotive User Interfaces in Section 1.4.2*. It also did not allow for a multi-step search strategy as even involuntarily lifting a finger off the screen caused completion of the trial — and in many cases, probably an erroneous confirmation. The device's finger-sensing performance may have also influenced the issue of false positive trials. Even though the study was performed after a firmware update, which massively improved the accuracy of finger sensing, the device might have falsely detected a finger-off event (due to calibration or grounding issues), resulting in a false positive trial. The exploration-and-lift-off approach was primarily implemented to focus on the search phase and avoid possible confusion with the device's haptic feedback upon pressing. Unfortunately, tracking the rate of false positive trials post-study is not possible. The overall detection rate may yield more valid results by applying a different experimental haptic search paradigm, for example, by implementing an exploration till target-lift finger-tap to activate paradigm to confirm the input (similar to the process described in Section 1.4.2).

The search task was designed to focus on pure haptic exploration. The target was only augmented via a haptic texture and was not visible. However, interface elements on touchscreens are primarily augmented visually. Results from Eren et al. (2015) and also conclusions from Rümelin (2014) depicts that interaction is hardly solely eyes-free. An interesting consideration for further studies would be to investigate the influence of visual glances on detection performance and exploration behavior with electrostatic friction modulation displays.

3.2.3 Conference Poster: Semantic Differentiation of Haptic Edges Rendered on an Electrostatic Friction Modulation Display

This section, including all figures, is based on:

Breitschaft, S. J., & Carbon, C.-C. (2020b). Semantic Differentiation of Haptic Edges rendered on an Electrostatic Friction Modulation Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.34650.98245

Abstract - In recent years, there has been a staggering demand for haptic devices embedded in seamless surfaces of high aesthetic quality. This is particularly true for industries requiring innovative yet safe-to-use and aesthetically pleasing interfaces, such as premium automotive brands. Variable friction displays, especially the electrostatic type, yield specific advantages. Despite psychophysical studies, there are only a few evidence-based guidelines for electrostatic friction modulation in haptic interface design, for example, to augment discontinuities between buttons with haptic feedback. The present study aimed to examine which qualities of edges rendered on an electrostatic friction modulation display are differentiated by participants. Rendered stimuli were 5mm wide (except thin edge: 1 mm). We used nine different types of edges (wide, thin, low amplitude, trailing slope, leading slope, triangle, double, vibration, texture) as stimuli. The similarity of randomized stimuli pairs was evaluated one by one and rated on a 7-point scale by 21 participants ("How similar do both edges feel?"). Dissimilarity data was fed into a multidimensional scaling algorithm with Euclidean geometry. Results show that there seem to be four distinct qualities of haptic edges: single sharp edges (wide, thin, low amplitude wide), single slope edges (leading/trailing slope, triangle), double edges, and vibration edges (vibration, texture). We argue those qualities are highly suitable in haptic user interface design due to their highly discriminative characters. These findings can be helpful as best practices for haptic interface designers to create augmented visual touch interfaces with comprehensible yet differentiable haptic feedback elements.

The conference poster can be found in Appendix A.8 (p. 253).

Motivation & Rationale

Implementing highly distinguishable edges to augment different interface elements is the foundation of successful haptic design. Variable friction displays allow for high customizability regarding the augmentation of different interactions, such as entering or leaving an interface element and highlighting different elements via textures. In prototyping sessions, we observed that perceived haptic strength and tactile saliency of friction stimuli hardly vary as a function of line width or amplitude. It seemed that friction stimuli are either perceived or not. It also seemed challenging to differentiate texture patches with vastly different haptic images (checkerboard vs. random white noise vs. gratings with varying frequency levels). From a perceptual point of view, it seems there aren't that many levels of distinguishable textures and haptic lines for the haptic design of electrostatic stimuli. Hence, designers might need to employ other factors than simply modulating single physical factors (e.g., amplitude) to increase discrimination.

Besides multiple psychophysical studies that explore the unilateral relation of frequency, amplitude, and perceived strength, studies have hardly implemented a broader interaction- and semantic-driven approach to examine the haptic perception of electrostatic haptic feedback. Similar to the approach in the *Similarity*-Study of *Function Follows Form*-study series (see Section 2.2.2), we propose that haptic lines rendered via electrostatic friction modulation have a haptic timbre that allows for a semantic differentiation in addition to a purely perceptual differentiation. Instead of focusing on eliciting discrimination by systemically modulating only a small set of physical parameters, such as line width and amplitude, we propose to use inherently different semantic haptic qualities of edges (single solid, slope, double, vibrant, etc.). This way of discrimination might eventually facilitate more efficient interactions. The goal of this study was to explore the essential semantic qualities and the discriminability of a set of nine different electrostatic haptic lines.

Method & Results

Twenty-one participants took part in the study. The study used the same experimental procedure and statistical analysis as the *Similarity*-study of the *Function Follows Form*-study series (see Section 2.2.2). The study included nine different haptic lines (width was roughly 5mm, except the "thin" line, which was 1mm) and were rendered on a TanvsTouch MimoVue (SDK v1.0.13). The haptic edges are depicted in Figure 22. It also describes the perceptual characteristics of the haptic lines. Black areas represent low friction, whereas white areas represent the maximum available friction value. 0-255 friction changes describe the transition from the maximum available amount of friction force to no additional friction (from black to white or vice versa). Participants compared each haptic line one by one based on their perceived similarity. The similarity data was analyzed using a MDS procedure to visualize the different perceptual clusters (see Figure 22). The a-priori stress test revealed four distinct semantic clusters. A closer inspection of the friction maps revealed that edges within each cluster seem to share common perceptual characteristics. The clusters were interpreted as (A) Single Slope Edges, (B) Single Sharp Edges, (C) Double Sharp Edges, and (D) Texture Edges.

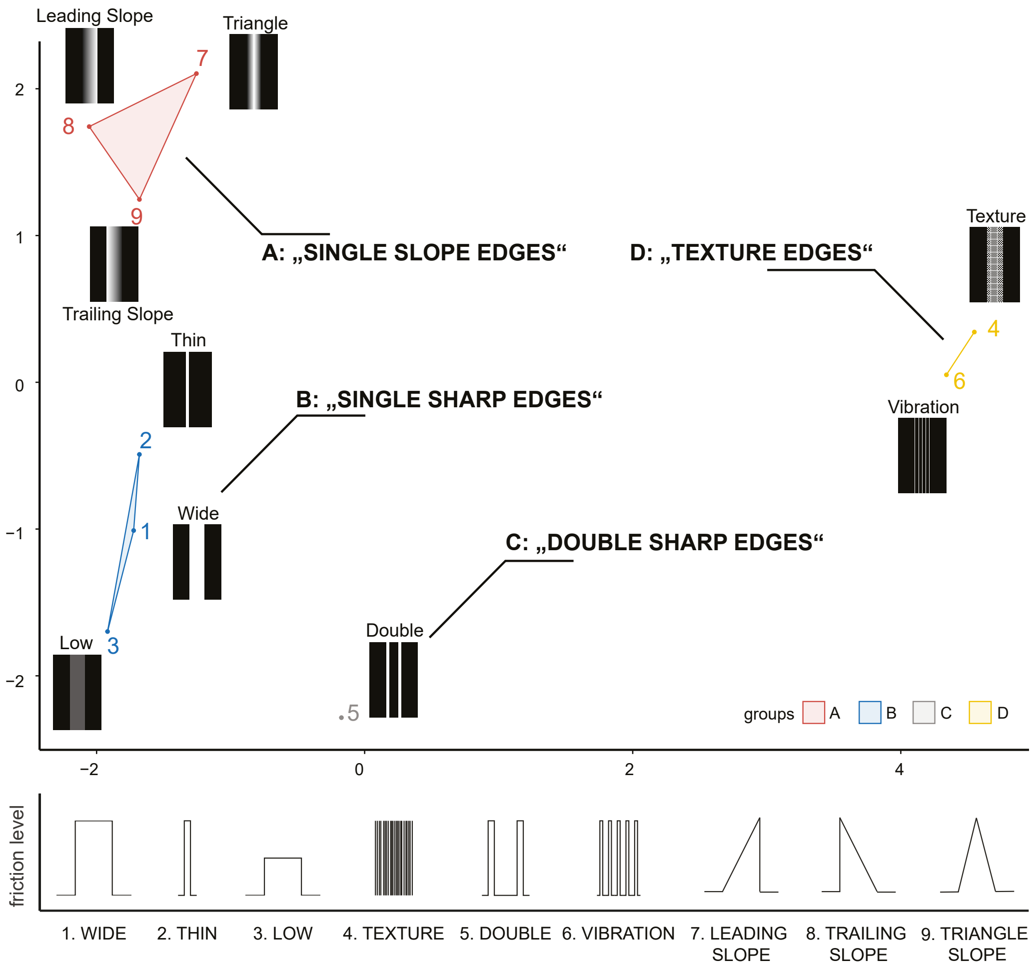


Fig. 22.: The multidimensional scaling procedure from the *Semantic Differentiation of Haptic Edges* study depicts four different perceptual clusters for friction edges: (A) single slope edges, (B) single sharp edges, (C) double sharp edges, and (D) Texture edges.

- **Slope Edges:** All lines include at least one gradual increase/decrease in friction. Line 7 Trailing Slope and 8 Leading Slope additionally include a single abrupt 255-0 friction change.
- **Single Sharp Edges:** All lines include two discrete friction changes from low-to-high and high-to-low (0-255 and 255-0), no matter the line width and amplitude.
- **Double Edge:** This line includes two discrete thin lines (comparable to Line 2) that were perceivable as two distinct lines within a single transition.
- **Texture Edge:** All lines include multiple 0-255 friction changes within a short amount of space, making it a "textural" impression no matter how the lines are designed with regards to the friction map.

Discussion

This study explored the perceived similarity of haptic edges rendered on an electrostatic friction modulation display. The goal was to describe the different semantic qualities of haptic edges. Overall, the MDS configuration indicates that electrostatic edges can be differentiated into four distinct qualities. Edges within a cluster share perceptual commonalities, for example, regarding the number of friction changes, making them somewhat less distinguishable. Based on this dissociation, we assume that edges from different clusters yield a more unique haptic and semantic impression that allows for easier discrimination of interface elements than the modulation of lines along a single perceptual factor, such as amplitude or frequency. The findings may be valuable as best practices for haptic interface designers and provide a good starting point for creating touch interfaces with easily distinguishable haptic feedback elements. This study only describes the different semantic qualities. Future studies may look deeper at their impact on difference thresholds and interaction of lines from different semantic clusters. Psychophysically-driven studies examining the difference thresholds for single physical parameters might still provide valuable insights into the perception of electrostatic stimuli.

The study only employed a limited set of transitions based on a pre-selection of stimuli — mainly to reduce the complexity and length of the experimental procedure. For example, a thin and low amplitude line was excluded as it was barely perceivable in prior evaluations. Including more types of edges might result in a different MDS configuration (e.g., more semantic clusters). It would be interesting to see the influence of a much broader and systematically designed (e.g., width) set of transitions on the MDS patterns. The experiment was conducted in late 2019. It implemented SDK v1.0.13 of Tanvas' Touch Engine Firmware and an earlier prototype hardware version of what is currently available. More recent hardware and firmware versions have introduced multiple sensing and haptic rendering improvements, which might also influence haptic perception. Especially rendering and perception of gradual friction changes were improved with later versions. This might impact the perception of wavy textures from the "slope edges"-cluster in Figure 22. Hence, revisiting the same experimental procedure with a newer soft- and hardware type may be worthwhile. Due to the prototype level of the testing device and technology-specific factors of haptic experience, our findings may not allow for a direct implementation within other technologies. Nevertheless, they might still provide a valuable starting point in creating distinguishable interface items.

3.2.4 Conference Poster: An Exploratory Evaluation of Participants' Reaction to Electrostatic Friction Modulation.

This section, including all figures, is based on:

Breitschaft, S. J., & Carbon, C.-C. (2020a). An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.14518.32327

Abstract - Electrostatic friction displays are becoming publicly available and accessible for a wide variety of practitioners. Psychophysical studies on electrostatic haptics deliver insights into the opportunities such devices can offer. But because most studies focus on tasks with low ecological validity, the important facet of the actual user experience of electrostatic friction modulation is neglected and, therefore, the suitability for application. This research summarizes data from participants' post-experimental feedback and delivers insights and recommendations based on them. Feedback in the form of verbal descriptions was given in two application-based studies incorporating friction haptics. The first study entailed a single-task haptic search paradigm, and the second study a dual-task target-selection paradigm with a prototypical lane-following task as the primary task to emulate task demands while driving a car. Using friction haptics was an unexpected and new experience for all participants. In the beginning, participants felt unsure as to what exactly they were feeling or were supposed to feel. Verbal reports indicate a highly dynamic aesthetic experience, as participants reported a change in evaluating the haptic impression throughout the session. Some reports revealed negative associations ("feels like electroshocks") that could potentially lead to acceptance issues, even after a phase of deeper familiarization with the technology. In general, participants had problems differentiating various haptic stimuli and describing their actual feeling. Soft feedback caused insecurity. Up to now, we can mainly deliver a blacklist of haptic and environmental parameters that should be prevented to reduce the chance of negative experiences with innovative haptic feedback devices.

The conference poster can be found in Appendix A.9 (p. 254).

Motivation & Rationale

Most studies, including variable friction displays, have focused on purely perceptual, psychophysical, or usability aspects. While in interaction-driven scenarios, haptic information is primarily evaluated regarding their functional content, their aesthetical impression also has a significant impact on haptic and aesthetic experience (Carbon & Jakesch, 2013). Bau et al. (2010) examined subjective descriptions within user-focused evaluations of their early TeslaTouch-Prototype. At low frequencies, the association mainly involved a *stickiness*, while high-frequency textures were characterized by roughness and smoothness descriptions. Previous studies on electrostatic friction modulation have hardly implemented an aesthetically- or experience-focused view on haptic experience (Basdogan et al., 2020).

I already stressed the importance of an association-based perspective for haptic design in Section 1.4.2, i.e., understanding how users interpret haptic stimuli. Adhering to user associations might facilitate the introduction of novel haptic technologies. Examining the subjective aesthetic impression of friction haptics is important as surface haptics has not yet been introduced to a broader market. Friction haptics is not an everyday life experience for most users and thus a still novel type of haptic feedback that users are not yet accustomed to (Bau et al., 2010). Examining first-hand impressions and ways to smoothen these first encounters seems crucial. Complying with user associations also impacts the long-term appreciation of interfaces incorporating friction haptics. Bau et al. (2010) implemented a very early prototype of an electrovibration haptic display. Now that there are commercially available electrostatic friction displays, it is worth revisiting their initial evaluation.

Figure 21 (p. 119) and the pre-study of the "Where's My Button"-study (see Section 3.2.5) which were interaction-focused studies included the possibility to gain insights on participants' first-hand experience with electrostatic haptic feedback. This contribution aimed to summarize user feedback from these studies and give insights into participants' first-hand experience with the TanvasTouch device in interactive use cases. We aimed to (1) structure user feedback and observations from the studies, (2) identify crucial aspects as well as potentials and challenges for haptic design of electrostatic friction stimuli, and (3) provide a set of initial guidelines based on these qualitative explorations.

Method & Results

The initial design conclusions were based on the user experience questionnaires, experimenter's observations, and post-study feedback from the study reported in Section 3.2.2 (Breitschaft et al., 2020b) and the pre-study described in Section 3.2.5 (Breitschaft et al., 2022b). Section 3.2.2 included a single-task haptic search experiment while Section 3.2.5 was based on an automotive dual-task target-selection-task. Both studies examined the impact of different stimuli on task performance and user experience. After every stimulus block in each study, participants were given a user experience questionnaire with the following variables: Annoyance, Fitting, Pleasantness, Prevision, and Quality. In addition to the questionnaire, both studies included an open-question post-study feedback session. At the end of each study,

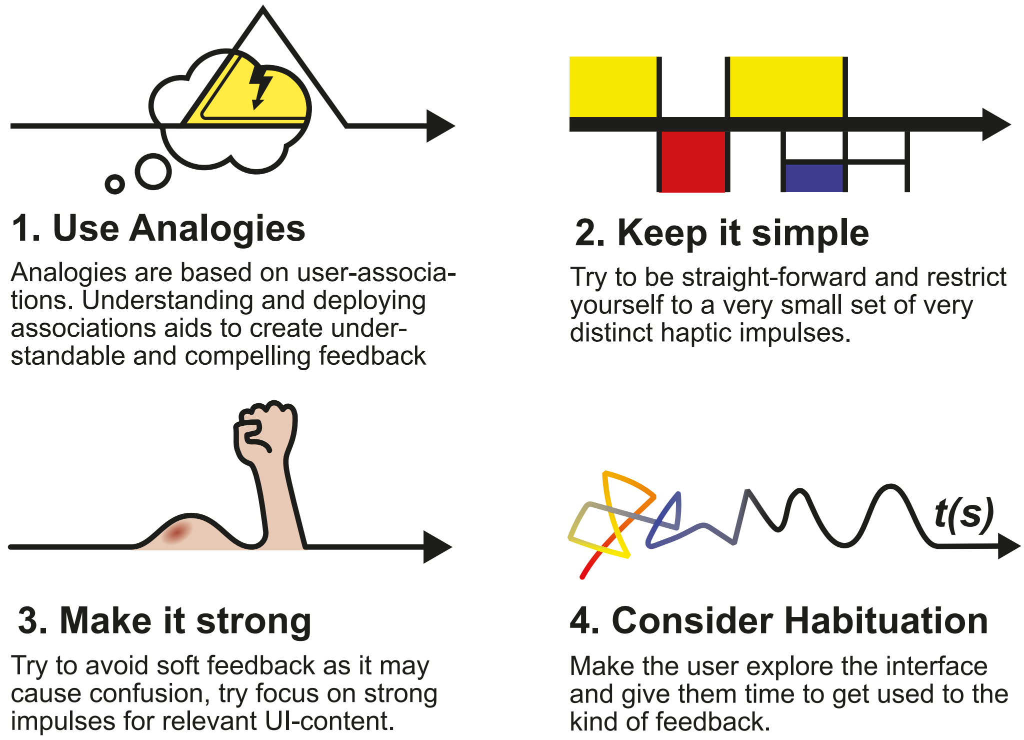


Fig. 23.: Based on the observations from the interaction-focused studies, plenty of guidelines for haptic design of electrostatic haptic devices can be drawn: Use analogies, Keep it simple, Make it strong, Consider Habituation.

participants were asked to report their general experience with the electrostatic haptic feedback. What did they like most? Was there anything they did not like? What was the most prominent feature?

The feedback was given in German and transcribed after the conclusion of the studies. No comprehensible analysis of the qualitative data was carried out, as this publication only aimed to provide an initial exploration of the participants' reactions. The verbal feedback data was structured similarly to a coding scheme to identify the most relevant and frequently mentioned aspects. We identified five basic findings from the questionnaires and observations (Breitschaft & Carbon, 2020a):

- Participants found it difficult to verbalize their haptic impressions ("I feel that there is something, but I cannot describe it") and to differentiate different haptic patterns and textures during exploration ("Everything felt the same").
- Participants described the friction haptic feedback as a novel and unfamiliar but highly innovative haptic feeling.
- The friction haptic impression seems to be subject to a highly dynamic aesthetic experience. Participants indicated that the haptic impression changed throughout the studies. For example, they reported that while they were somewhat

unsure at the beginning of the session, the haptic feedback felt much stronger towards the end of the sessions.

- Participants reported precise experience-driven associations for some of the haptic sensations ("feels like glue", "sticky"). Some associations were related to negatively connoted experiences ("feels like an electroshock").
- In general, haptic feedback was perceived as too weak. The soft impression caused insecurity when participants ought to rely on haptic feedback to perform the search and selection tasks.

Discussion

In general, the electrostatic friction modulation approach was evaluated to be an interesting yet unfamiliar approach. However, it also poses some challenges to consider during interaction design. Based on participants' experiences and observations, we derived an initial set of guidelines for the design with electrostatic friction feedback (Figure 23).

Use Analogies: Haptic stimuli have an inherent aesthetical and associative component that goes beyond a mere functional evaluation and strongly impacts the first contact and long-term appreciation of interfaces. I already described the importance of an association-based perspective in the *Function Follows Form*-studies (Section 2.2.2). Participants connected the friction stimuli to specific associations. Some of those associations have already been described by Bau et al. (2010). For example, "rough" textures were associated with an annoying and warning character. However, some high-frequent stimuli elicited negative associations ("electroshock", " dry cloth"). Participants also reported a "sticky"-impression of some of the stimuli. This "stickiness" association is highly appropriate in haptic search, selection, or adjusting use cases. It is facilitated by the fact that the finger is actually sticking to the target item on the screen through the additional friction feedback. Designers need to consider such conflicts during haptic design. Enriching interfaces with signifying and semantic content makes them potentially easier to use (Norman, 2008) and facilitates habituation with variable friction displays.

Keep it simple: Participants found it challenging to describe the haptic feeling when exploring different friction edges and textures. Observations from the studies indicate that participants hardly distinguish textures and lines even though underlying friction patterns widely differ. Participants seem to be highly sensitive to friction changes, but the detection threshold appears rather big, resulting in a small number of usable design parameters. Also, following the notions from Section 3.2.3

designers should focus on deploying a set of basic but highly distinguishable design elements (i.e., textures, transitions, etc.) instead of implementing artistically crafted friction maps.

Make it Strong: The friction stimuli were perceived as too weak was a common observation from all multitask interaction-focused studies. This is also discussed in Section 3.2.5. The reasons may be manifold. The friction stimuli were a novel experience for almost all participants. Some participants did not really know what to expect. Some confused the friction impulse with grease on the display. Others reported familiarity with other haptic-enabled devices and expected strong vibrational impulses. Also, context effects, such as environmental vibrations or mental load due to multitasking settings, might have impeded haptic strength. Despite technical limitations, practitioners must maximize the perceived strength of haptic stimuli to avoid confusion and overcome initial uncertainty.

Consider Habituation: Friction haptic feedback was a novel experience that broke participants' perceptual habits (Carbon, 2019). Participants reported they became increasingly familiar with the type of haptic feedback during a single test session (roughly 45 minutes). Most prominently, they reported that the perceived strength of the haptic impression increased over time. Especially for new and innovative technology, habituation is an essential part of product release. Even though users will eventually get used to the type of haptic feedback through repeated interaction, habituation can mindfully be facilitated in multiple ways. Practitioners could provide a tutorial that introduces friction haptics via elaboration-based paradigms, for example, the *Repeated Evaluation Technique* by Carbon and Leder (2005). Also, adapting profiles that comfort user associations, expectations, and experiences might foster habituation, e.g., using a rough, warning-like texture to indicate that a function is not available. An intentionally higher haptic strength which is tuned to a more reasonable haptic strength after familiarization, could also be used to avoid uncertainty.

Besides haptic design, habituation and user associations are essential when evaluating innovative haptic interaction concepts. Even though first-hand experiences may be interesting, most products are designed with long-term user appreciation in mind. Hence, experiments need to incorporate an appropriate amount of habituation so that users can get to know the haptic system's ins and outs (Carbon, 2019). This seems especially important for novel haptic experiences like electrostatic friction modulation. Furthermore, the effect of user age on interaction should be considered due to changing perceptual characteristics during the human lifetime. The described results and best practices only include qualitative data from two interaction-focused studies and can thus only be seen as a starting point. Only a few studies have started to describe very confined sets of best practices for specific design parameters of friction stimuli, for example, Palani and Giudice (2016) and Basdogan et al. (2020). As friction haptic devices become more accessible to practitioners, future studies and efforts may be taken to consolidate design practices.

Application of Friction Haptics in Automotive Search Haptics

The studies mentioned above describe the building blocks of friction haptics but have not yet examined the effectiveness of friction haptics in an applied automotive context. The following study was part of a research project which aimed to explore and examine the application of electrostatic friction modulation in an automotive search haptic use case using a dual-task driving scenario. Instead of choosing a single interior location and exploring the breadth of different possible use cases, we chose to use a single interaction use case (2D target selection) that was applied to three different but highly relevant interior locations: (1) a remote control in a steering wheel, (2) a remote touchpad in a center console, and (3) a direct touchscreen control in the center stack. All studies employed a similar dual-task experimental setup with a 2D-target-selection task in which a variable friction display was used to augment transitions between different items in the matrix. Only the results from the direct touchscreen study are subject to this dissertation project and reported subsequently.

3.2.5 Journal Article: Where's my Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces

This section, including all figures, is based on:

Breitschaft, S. J., Pastukhov, A., & Carbon, C.-C. (2022b). Where's My Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces [Journal Article]. *IEEE Transactions on Haptics*, *15*(2), 292–303. https://doi.org/10.1109/TOH.2021.3131058 ©2022 IEEE

Abstract - Advancements in user interface technologies and demands of design engineering led to increasing implementation of large and mostly flat interactive surfaces in automotive. Recent discussions in the context of in-vehicle usage of touchscreens advocate for using haptic feedback to restore the explore- and feel-qualities typically experienced in traditional physical button interfaces that contribute to intuitive, eyes-free, and tactually rich interactions. Haptic technologies with a friction modulation approach seem especially promising to convey a high-quality feeling. This research reports an experience-oriented evaluation of an electrostatic friction haptic display in an in-vehicle direct touch interaction context. The evaluation was based on an automotive multitask setting (primary driving-task and secondary target-selection-task) with a 2×2 feedback modality design (factors haptic/audio with levels absent/present). The objective variables (response time, errors, and performance on the primary task) did not differ between feedback modalities. Any additional feedback to a visual baseline enhanced the user experience, with the multimodal feedback being preferred by most participants. Surface haptics was perceived as a novel yet unexpected type of haptic feedback. We discuss the implications for the haptic design of programmable friction displays and provide an initial set of guidelines for this innovative technology.

The journal article can be found in Appendix A.10 (p. 255).

Motivation & Rationale

Implementing featureless tangible user interfaces like touchscreens and flat control panels affords a highly visual interaction. They mostly lack search haptic cues that allow effortless haptic exploration and detection of control elements while driving. Even though multiple automotive manufacturers have already integrated active haptic feedback into featureless control panels and touchscreens, haptic feedback is mainly restricted to pressure-based confirmation haptic input (i.e., the goal of the technology is to create a mechanical button click). Acquiring interactive elements remains a visually-focused and distracting task.

Surface haptic technologies, such as electrostatic friction modulation, are potentially highly beneficial for automotive design. They reintroduce tactility to featureless surfaces and focus on haptic augmentation of explore-and-feel-focused interactions. Compared to the majority of confirmation-focused applications of active haptics, electrostatic friction modulation focuses more on the search-phase of the interaction (see *Haptic Framework of Haptic Processing in Automotive Interfaces*, Figure 13, p. 74). From a technical perspective, electrostatic friction modulation seems to "solve" plenty of technical challenges introduced with haptic feedback on large, heavy, or asymmetrically shaped displays. Large panel-sized electrostatics enables high-fidelity, fully software-defined, low noise, and low latency haptic sensations (for more information, see Chapter 3.2). Electrostatic friction modulation is also highly interesting from an experience-centered point of view. The electroadhesion principle is based on physically attracting the moving finger. This "sticky" sensation nourished the association of "clinging to a button". This feel-focused interaction might eventually reduce visual distraction as it omits the "search view" (Rümelin, 2014) and potentially allows the user to navigate within interfaces and detect interactive elements eyes-free.

Tanvas already presented an automotive-grade display with electrostatic friction modulation (Klein, 2022; Tanvas, 2020a). To my knowledge, no published study has examined the influence of electrostatic friction modulation in an automotive dual-task setting. Despite plenty of studies examining the effect of haptic feedback in automotive interaction contexts[24] and multiple studies examining perceptual aspects of friction stimuli, the transfer of currently available literature to electrostatic friction displays is limited. This mainly comes down to two major aspects: (1) **technology** and (2) **scenario**.

First, most UI studies have implemented low- to medium-fidelity vibration-based (e.g., ERM-, Solenoid- and VCA-type) actuators. Those actuators shake the entire display rather than providing localized haptic feedback. Due to technical limitations, such as system latency, rise-time of the actuator, dampening, moving mass, etc., vibration-based systems are mainly geared towards recreating a mechanical button press feedback for confirmation. Even though vibration-based actuators can be used for search haptic use cases, the haptic impression is mostly medium-fidelity. Also, most UI studies in the context of in-vehicle haptic feedback, as reported in Breitschaft et al. (2022b), have employed vibration-type actuators, limiting the conclusions for friction-based haptic devices.

[24] For an in-depth overview, see Breitschaft et al. (2022b)

Secondly, even though there is a solid basis of studies examining the psychophysical parameters of variable friction displays and exploring their design space in different interaction design contexts (Basdogan et al., 2020; Levesque et al., 2011, 2012) results can hardly be transferred to the application in a multitask automotive context. This is because these studies were primarily conducted in generic single-task lab environments, which neglected the influence of contextual factors, such as multitask settings, on haptic perception (Jakesch et al., 2011). In the case of automotive, a highly demanding dual-task setting, the influence of context on haptic perception of friction stimuli is not clear yet. Previous studies indicate that designers must follow some specific design considerations for friction haptics due to the novelty of the haptic impression.

The main goal of this study was to evaluate the effectiveness and user experience of electrostatic friction modulation in an appropriate automotive dual-task setting (primary driving task and secondary 2D-target selection task) by comparing different feedback modalities. One of the main drivers were the following questions: "Is electrostatic friction modulation suitable to augment search haptic cues in an automotive context at all?", "Is there an added benefit for the customer? And if so, what is the added benefit?", "How does friction haptics compare to other benchmark feedback modalities?". We did collect objective data on task performance (time, error, driving performance). We were mainly interested in the haptic experience, which is why we focused on gathering and evaluating subjective user reactions and user experience variables. As this has been one of the first studies to include electrostatic friction modulation in an automotive context, we aimed to discuss the potential and challenges of implementing friction haptics into automotive user interaction and extend the already existing set of guidelines (see Section 3.2.4).

Method

The study set out to explore the user experience of electrostatic friction modulation in the context of an automotive-related dual-task setting that incorporated a primary driving task and a secondary touchscreen-focused target-selection task. We aimed to evaluate the effectiveness of the friction haptic feedback based on a comparison with other sensory feedback modalities (visual, visual-haptic, visual-audio, visual-haptic-audio). The following section provides a brief overview of the implemented methodology. See Breitschaft et al. (2022b) for a detailed description.

Participants & Apparatus: 32 participants took part in the study. Twenty-eight were right-handed and 20 were male. Participants were, on average, 33.2 years old (range:

20 - 60 years). All participants worked in the automotive sector. However, none of them was familiar with the background of the study or received specialized training in haptic perception. The study took place in a stationary medium-fidelity seating buck consisting of a car seat, a real steering wheel, a primary screen that displays the driving task, and a secondary screen in a center stack position, which was used to perform the secondary task. While not being a complete automotive interior, the seating buck entailed the most relevant context features (seating position, steering wheel, front screen, and central information display) to ensure an immersive automotive scenario. We used the MimoVue TanvasTouch 10.1-inch Monitor to display the haptic friction feedback and the secondary selection task. Technical specifications of the TanvasTouch display can be found in Klein (2022), LoPresti (2020), Shultz (2020), and Tanvas (2020b).

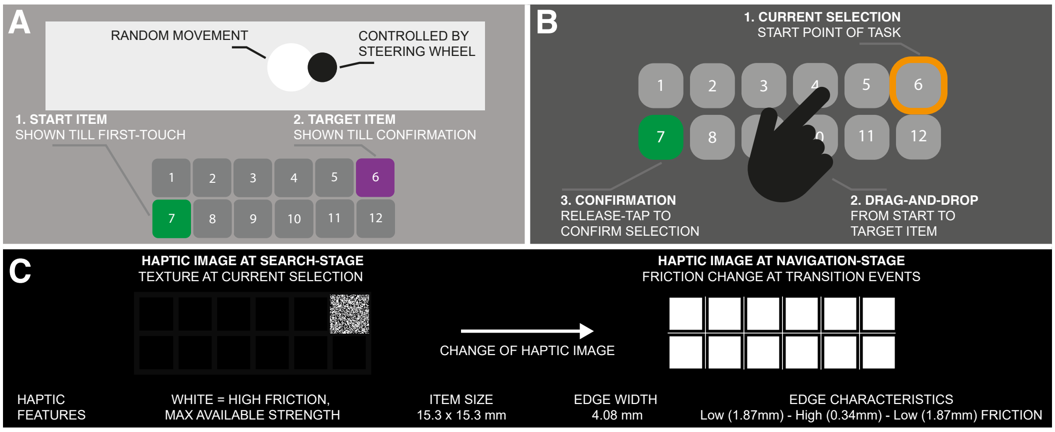


Fig. 24.: The experimental procedure in *Where's my Button?* included a two-stage "search-and-navigate" experimental procedure embedded in an automotive dual-task setting. ©2021 IEEE

Feedback Modalities: Similar to other studies in the field of automotive haptic feedback design, the study included a 2×2 feedback modality design. There was a visual-only, visual-haptic, visual-audio, and multimodal visual-haptic-audio condition. The visual feedback was always present. We figured there is always visual feedback in real-life automotive use cases, which the user will always use for orientation in interfaces (Rümelin, 2014). Even though assessing the influence of a haptic-only or audio-only condition might have been intriguing, we excluded these conditions as they seemed not relevant for real-life applications.

The visual feedback consisted of an orange cursor that indicated the currently selected item in the matrix. The visual feedback was used as the baseline condition. The start item and transitions within the grid were augmented with additional haptic and/or audio feedback. The audio feedback consisted of a "poc"-sound used in current BMW production cars during touchscreen interaction. The audio feedback was played at every item change. Also, the start item was indicated via the "poc"-sound when acquired. The haptic feedback, more precisely the friction maps, is depicted in Figure 24. A white-noise friction texture augmented the start item. The matrix-items included high-friction patches (item size = 15.3mm / 90px) with low-high-low friction transitions (4.08mm / 24px) between the matrix elements. The haptic design of the matrix was based on insights from previous studies and prototyping sessions. The high-friction-item-low-friction-transition approach was chosen as it best supported haptic interaction in a pre-study (n=16), which examined different haptic matrix designs and incorporated the same experimental procedure. The pre-study is described in Section 3.2.4 as well as the supplementary material of Breitschaft et al. (2022b) (see A.10). Another reason we chose this kind of haptic design is because it creates the impression that participants "stick" to the matrix items while "falling from one to another" when sliding. In pilot studies, we experienced that participants sometimes had trouble feeling the haptic feedback. Insights from pilot studies examining the impact of line width and the number of friction changes within transitions on haptic strength and observations during the prototyping phase with the device were implemented to maximize perceived haptic strength.

Dual-Task Setting: Figure 24 depicts the dual-task design of the primary and secondary tasks. The primary task consisted of a dot-following task presented on the display in front of the participants. It can be described as an abstract version of a continuous lane-following task. The participants' task was to continuously align a black dot manipulated via turning the steering wheel and a white dot randomly moving on a horizontal axis. We implemented this rather abstract primary task as it allowed for a less complex but highly controllable experimental design. The secondary task consisted of a 2D-target-selection paradigm which participants performed during the primary driving task. It resembled a typical touchscreen interaction while driving. The task involved a drag-and-drop paradigm. That means the participants' task was to select a target item in a 6×2 matrix by dragging a cursor from the start to the target element. The input was confirmed by releasing and tapping the selected item. The start item was randomized across all trials and indicated either via visual, visual-haptic, visual-audio, or visual-haptic-audio-feedback. Feedback (visual, haptic, or audio) indicated the item changes within the grid. This search-and-navigate paradigm enabled participants to complete the task (finding the start element and selecting the target item) eyes-free. In contrast to a "typical" touchscreen interaction where participants would be able to tap the desired item (which was not possible in this study), we included a "feel-and-navigate"-paradigm to systematize all experimental conditions. The friction haptics requires finger movement to provide haptics feedback. Allowing participants to tap the item directly might have skipped the "search"-phase.

Dependent Variables: We implemented a two-fold data collection strategy based on objective and subjective variables to assess performance and user experience. The objective variables included task completion times, erroneous confirmations, and performance in the primary task. The task completion time consists of the response time from the initial contact of the secondary screen till the activation of the correct matrix item. Erroneous confirmation included the number of false target item selections. The primary task performance included the mean squared deviation of the black and white dots in the dot-following task. The subjective variable set included a post-feedback-block UX questionnaire, a post-study modality preference ranking, and a post-session feedback interview. The UX questionnaire participants completed for every type of feedback entailed the following UX aspects: *Annoyance*, *Fitting*, *Pleasantness*, *Precision*, *Perceived Quality*, *Difficulty of Secondary Task*, *Perceived Visual Distraction*, *Interference of Secondary Task with Primary Task*, and *Enhancement of UX*. The post-experimental questionnaire included a modality preference ranking and general feedback on the study.

Procedure: The study included multiple blocks. The experimental block started with an introduction block. Participants were introduced to the goal of the study and the procedure of the experimental trials. They were told that this study explores a novel haptic feedback technology in a realistic driving scenario. In several training trials, they could familiarize themselves with the experimental task and the haptic feedback. Even though the training trials included haptic feedback, participants were not explicitly introduced to the feeling of the electrostatic feedback. Participants performed the driving task in a reference block to gather a baseline for the driving performance. The experimental conditions included a total of eight feedback blocks. Every feedback block (visual-only, visual-haptic, visual-audio, visual-haptic-audio) was presented twice in a randomized but reserved systematic order (i.e., ABCDDCBA). After every feedback block, the UX questionnaire was given to participants. Each block consisted of 12 trials. The experimental blocks were concluded by another baseline block and a post-experimental block, including the post-study questionnaire.

Results

Figure 25 summarizes the results for the objective and subjective variables. A detailed description of the results, especially the inferential statistics, can be found in Breitschaft et al. (2022b). Overall, there were no consistent differences between feedback modalities for all the objective variables, only for specific comparisons. Performance of the primary task differed significantly from the baseline (driving only blocks) for every feedback task, indicating that mere interaction is distracting. Task completion time, error rate, and performance in the primary driving task did not seem to vary based on the type of feedback in the selection task.

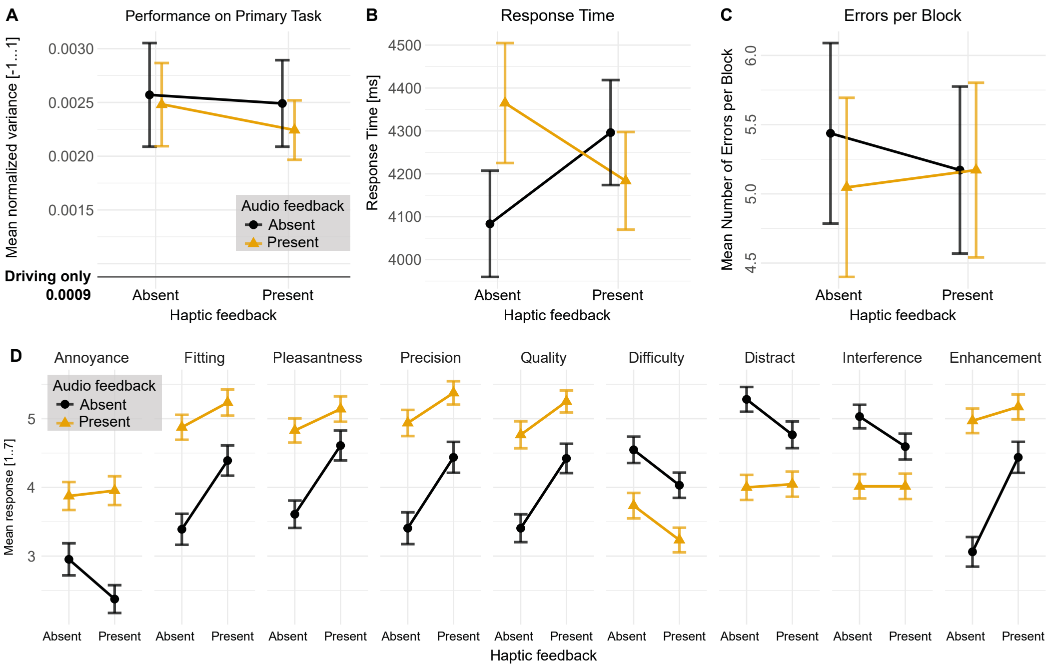


Fig. 25.: Results for objective (primary and secondary task performance) and subjective UX-variables of the *Where's my Button?* study. ©2021 IEEE

Differences between feedback modalities seem to be mostly based on user experience variables. Any additional feedback to a visual baseline (visual-haptic, visual-audio, or visual-haptic-audio) was perceived as superior (more fitting, precise, high-quality, pleasant, etc.) than mere visual feedback. The multimodal condition scored the best values in almost all user experience categories and was preferred by most participants in the preference ranking. One of the participants described the multisensory feeling as "creating a sense of engagement and involvement" with the car. The *AudioPresent* conditions were rated better than the *AudioAbsent* conditions in almost all categories except for the Annoyance-variable. Based on the results, the additional audio feedback seemed to have a bigger positive impact on user experience than the electrostatic haptic feedback. However, the continuous sound impulses (even in the multisensory condition) seemed annoying to participants.

Discussion

The study's main goal was to evaluate the user experience of electrostatic friction modulation in an automotive-related dual-task setting. As this is one of the first studies that examined electrostatic friction modulation in a dual-task context, we also focused on exploring the potentials and challenges of implementing friction stimuli in user interfaces.

The results indicate that the feedback condition did not consistently affect primary and secondary task performance. Participants were not consistently quicker or slower regarding a primary or secondary task or did not make fewer or more mistakes by having additional haptic and/or audio feedback. This seems surprising at first but partly supports the findings from previous literature. Similar studies that evaluated the user experience of haptic-enabled automotive interfaces (but employed a variety of primary driving and secondary task approaches) also do not report a consistent positive influence of feedback modality on objective performance measures, such as task completion time, error rates, and driving performance. The study setup did not allow to validly and objectively measure the influence of additional feedback on visual distraction, such as eyes-off-road time (also see the end of this section). For a more detailed description, see Table 5 and Breitschaft et al. (2022b). This demonstrates the dilemma for haptic advocates trying to incorporate haptic feedback in highly cost-driven settings. On the one hand, the haptic experience is highly innovative, but on the other hand, it "fails" to prove its effectiveness in terms of task performance. Even though some studies, such as Tunca et al. (2018) do report a significant influence of haptic feedback on task performance, we argue the outcomes vary as a function of methodology and haptic design. For example, in the case of Tunca et al. (2018), the interface consisted of four large-sized buttons that can hardly be implemented in real-life applications.

The fact that haptic feedback does not seem to have a consistent impact across multiple studies might incline to support the claim that haptic feedback does not support interaction, increase usability, or have added value for the customer. From a psychological and user-centric perspective, this seems a rather blunt and overly simplified way of interpreting the findings. Interaction is based on a person's experiences, so users might feel more immersed and confident in having an additional feedback channel even if they do not perform a task faster or with fewer errors. This engineering-driven view on precisely measurable performance neglects the fundamental importance of user experience and aesthetical appreciation. It is often used as a convenient excuse in the face of cost-intensive haptic technologies. The impact of haptic and multisensory feedback is much more multi-faceted than what purely objective usability measures indicate. Already minor effects and improvements on distraction might save multiple lives. Given the results from previous studies, haptic feedback's true impact on usability and user experience can only be evaluated by additionally implementing and focusing on experience-based measures.

Overall, any additional feedback was perceived superior to mere visual feedback. Yet, multisensory feedback seemed to enhance UX the most, which is also consistent with previous literature. Feedback conveyed via multiple perceptual channels provides redundancy and reinforcement in cognitively demanding contexts, such as driving a car. The results (see Figure 25) indicate that the audio feedback might have a more significant impact on user experience than the friction haptic feedback. Some participants were surprised by how well the audio clicks supported their interaction. Participants traced it back to the audio signal's prominence compared to the generally weak haptic impression. Even though the haptic design of the friction haptic stimuli was based on insights and observations from multiple pilot studies whose goal was to maximize haptic strength, the friction stimuli seemed to be perceived as too weak in the context of the experiment. Tactile saliency is a detrimental factor for the effectiveness of haptic feedback in general (MacLean, 2008; MacLean & Hayward, 2008). Friction haptic impulses must have a distinct impression when implemented in automotive interfaces. Other automotive studies report similar issues concerning perceived haptic strength (Pitts et al., 2012b). Friction haptic impulses have previously only been implemented in single-task lab-like studies, which do not fully consider the influence of complex multitask-scenario on perception. While stimuli are highly perceivable in single-task use cases, their perceptual character differs in dual-task scenarios. Multiple explanations exist for this study's relatively low perceived strength of the friction stimuli, which needs to be considered in future implementations. Follow-up studies (not part of this thesis) implementing friction feedback at a steering wheel touchpad position indicate that haptic strength is even more critical when perceived with the thumb. Explanations for the weak friction haptic strength include:

- **Hardware Limitations:** The prototype status of the hardware might have limited the perceived intensity. Especially with the TanvasTouch device, some participants reported issues with finger sensing. Similar studies also discussed the study results concerning the prototype status of the experimental device (Pitts et al., 2012b). Surface haptic devices are a novel kind of technology that are in constant development. Further developed devices might yield a much more robust and prominent haptic feeling.

- **Novelty:** The friction haptic feedback was a novel experience for almost all users. Participants were not explicitly introduced to the type of haptic feedback. Some confused the friction stimuli with the grease on the display. Not knowing exactly what to expect from the haptic feedback might have impeded perceived intensity. Participants might have required more habituation to fully get accustomed to and appreciate the aesthetical impression of the friction stimuli.

- **Mental Load:** While almost all participants reported feeling the haptics once they had the chance to explore the demo use cases without any multitask influences, the dual-task "forced" participants to shift their attention to the primary task. Especially in conjunction with the novel character of the friction stimuli, the divided attention might have hindered the appropriate perception of the friction stimuli.

- **Expectations:** Participants were told that this study examines the effectiveness of novel haptic feedback technologies. Most participants were familiar with haptic feedback in the context of user interaction. They were surprised by the unfamiliar and generally too soft friction impression. Some participants reported that they expected a strong vibration impulse (similar to haptic clicks they already know from other haptic touchscreens and their phones).

- **Influence of Age:** Elderly participants reported having slightly more issues feeling the haptic feedback. This is unsurprising as tactile sensitivity deteriorates with age (Thornbury & Mistretta, 1981; Tremblay & Master, 2015). Elderly participants also seem to have more issues with the sensing performance of the TanvasTouch Device. However, there is hardly any evidence of the influence of aging on the perception of surface haptic impulses. During the design process, it is essential to keep the age-related haptic performance of the target group in mind.

- **Dominance of Audio:** The volume of the audio feedback can easily be adjusted and was set to an appropriate volume level during the experiment. The prominence of the audio impression might have "outshined" the haptic impression. This might have led participants to assess the friction stimuli as not "appropriate" or "trustworthy" enough to be used as a feedback modality (Ernst & Banks, 2002; MacLean, 2008; Welch & Warren, 1980).

- **Familiarity of Audio:** While screen devices that implement haptic feedback upon slider interactions are still a relatively unfamiliar type of interaction for most participants, audio feedback has been an integral part of user interfaces for many years now. This means users are familiar with having sounds displaying system information. Haptic feedback, especially friction modulation, potentially breaks everyday perceptual habits because "a touch display does not have any haptic feedback".

Audio feedback seems to yield an interesting compromise in case of costs for a haptic system are an issue. Nevertheless, adding haptic feedback enhances user interaction beyond visual-audio feedback. The audio feedback (also in the multimodal condition) was perceived to be more annoying than the haptic feedback, which participants attributed to the continuous "poc"-sound during the exploration-based target-selection task. This is important to consider as it may deteriorate overall product quality. Annoyance is especially important in interaction use cases that include longer chains of micro-interactions and continuous feedback sounds, for example, when adjusting the volume or typing on a virtual keyboard. It is often disregarded that the feedback is only really needed by the driver, which makes additional audio feedback even more annoying for passengers. Due to its private and direct nature (see Section 1.1.2), friction stimuli support interaction in cases where the audio feedback might be too annoying, or information is only intended for the driver.

Despite the impression that the audio feedback might have outperformed the friction stimuli, haptic feedback is still a valuable resource in interaction. As driving is visually and acoustically engaging, haptics might facilitate interaction by providing relevant cues via a perceptually "less occupied" channel. The study results must be considered in the context of the current hardware version and user expectations. Most participants described friction modulation as an innovative haptic technology that might make touchscreen interaction safer. Adding haptic feedback to a touchscreen has a certain "wow factor" and makes the otherwise dead glass surface come to life. Once haptics becomes an inherent part of user interaction in everyday consumer electronic devices, user expectations will also change towards automotive touchscreen interactions. Replicating this study in a few years (with state-of-the-art hardware) might yield different results.

One major limitation of the study is that we should have included an objective measure of gaze behavior. This was mainly due to the complexity of the experimental setup and the lack of appropriate data collection equipment. The study included a "Perceived Visual Distraction" variable that tried to provide insights into how participants perceived the support of the different feedback modalities concerning visual distraction. The results indicate that every additional feedback minimizes perceived visual distraction compared to the visual baseline. Previous studies suggest that haptic feedback in in-vehicle interactions alleviates visual demand and reduces the total glance time on secondary screen devices (Beruscha et al., 2017; Mullenbach et al., 2013a; Pitts et al., 2012a) during driving tasks. Future studies should explore the influence of electrostatic friction modulation using appropriate measures to capture visual distraction. Other limitations, which are also discussed in more detail in the full publication, refer to the hardware version of the TanvasTouch touchscreen device (and its currently limited capability with regard to haptic strength), the grade of fidelity of the seating buck, and the application of the primary and secondary task.

Conclusion

There are a couple of "takeaways" concerning opportunities and challenges for implementing electrostatic friction modulation in automotive. There is a fine line between supportive and bad haptic design. Novel and innovative haptic technologies are not a universal remedy for visual distraction but require careful consideration and implementation. Especially because haptic feedback during exploration-based screen interactions is yet unfamiliar to many users. Friction haptics requires habituation to compensate for the effect of novelty. Also, technology-specific experiences should be taken into account. For example, a few participants (roughly 10%) deliberately reported negative associations in conjunction with the friction stimuli ("feels like going over sharp knives", "electroshock", and "the sticky feeling hinders smooth movement"), which need to be carefully reviewed during implementation. Age-related issues are also essential to consider. Despite abundant studies and demonstrators using surface haptics, most of these demonstrations have not yet been tested in user-centered studies. There is a necessity for more experience-driven evaluations of haptic feedback in user interfaces among stakeholders during the design process. A purely performance-focused assessment neglects the positive impact on user experience. Also, results from our study are limited as we only examined friction haptics in the context of a 2D-target-selection interaction. Conclusions differ for other use cases, such as haptic search tasks. Other challenges refer to the possibility of implementing a "button" click for confirmation.

On the other hand, I see electrostatic friction modulation haptics as an excellent opportunity to create search haptic on otherwise completely flat interfaces. Friction modulation allows augmenting a wide variety of exploration-focused use cases, such as sliders, rotary dials, toggle switches, etc. Levesque et al. (2011, 2012) and Levesque et al. (2012) explored the interaction design space of ultrasonic friction stimuli and describe that friction stimuli pose the potential to enhance interaction for various exploration-focused use cases. Tanvas (2020a) has already demonstrated how its technology integrates with automotive screens and augments user interaction. Besides user experience-related issues, electrostatic friction modulation has some technical advantages over vibration-based technologies, such as the solid-state and fully software-defined design approach, low-noise, and low-latency actuation. This study indicates that additional feedback (haptic or/and audio) enhances user experience beyond mere visual feedback. More importantly, it is an innovative approach to haptic feedback with a certain "wow factor". Participants were impressed by the technology as it made the touchscreen feel alive. In this sense, it poses a massive potential for automotive manufacturers to create a brand-specific haptic language on seamless control surfaces.

Part 4

RÉSUMÉ

4.1 What is "Good" Search Haptics?

> *No haptics is still better than bad haptics.*
>
> **— Common design practice**

The previous chapters (mainly Parts 2 & 3) carefully laid out various aspects of search haptics design in automotive. Given all this input, some questions remain: How can good search haptics be described and defined? What are the guiding design principles? Is there something like good search haptics for active haptic technologies? Should search haptic primarily be designed with passive haptics cues? What are the ingredients to make interfaces controllable eyes-free? In short: it depends. The fundamental premises of this thesis were to explore how haptic feedback should be adapted to design easily accessible and high-quality interfaces and to lay out basic design premises. The following section provides a résumé on how haptic technologies may be implemented to provide "good search haptics".

4.1.1 It's a Matter of Technology

There is a fine line between good haptic design and really bad haptic design. Good search haptic design depends on a seamless symbiosis of technological implementation, context, and use cases. Practitioners should be aware that haptics is not a mere nice-to-have "add-on" and be implemented for the sake of innovativeness. Once implemented, haptic feedback becomes a fundamental part of product interaction and user experience. Hence, stakeholders should carefully consider the interaction use cases they are designing for. Search haptic cues require different perceptual prerequisites than confirmation haptics, as the modes of interaction differ fundamentally. Some technologies are more suitable for search haptics based on their technical and, thus also, perceptual prerequisites, while other technologies tend more toward confirmation. For example, surface textures and geometries provide easily accessible search haptic cues as they rely on haptic exploration. This is also reflected in the *Haptic Fidelity Framework*, which proposes that practitioners should choose their actuators based on their **appropriateness** for the desired task.

This especially applies to active haptic technologies. The different technological approaches to automotive haptics — vibration- and friction-based — target different modes of interaction. Even though vibration-based (or inertia-based, e.g., solenoid, voice coil, and piezo) technologies have already been implemented to augment exploration-based interactions, their main purpose has been to provide confirmation haptics primarily by simulating mechanical button clicks. Even though there are vibration-bsuiased actuators with low latency and rise times (<1ms, e.g., piezo, etc.), the integration into GUI-based systems (e.g., due to touch- or force-sensing, system-internal communication with a central processing unit, etc.) often adds latency which is detrimental to haptics performance. The actuator will only be triggered once the user crosses a particular location or threshold. In practice, this means it is difficult to sync the visual, audio, and haptic impression during the interaction as the haptic impression is always perceived slightly too late if no countermeasures are implemented. Results from Kaaresoja (2015) indicate that the haptic sense seems more sensitive toward latency and perceived simultaneity (or asynchronicity) of input action and output feedback than the visual and auditive senses. Vibration-based systems do not necessarily require active movement to convey feedback and usually actuate the entire interactive surface, meaning they introduce inertia to the system, which requires dampening. On the other hand, friction-based approaches, such as electrostatic friction modulation, require active movement to convey the haptic impression — in a sense, they are geared toward a feel-and-exploration-focused interaction approach. Haptic stimuli are created by friction maps that are "pre-loaded" depending on the currently visible screen. Similarly to passive haptics, detents, ridges, and other surface features are already "laid out" and do not need to be triggered. It seems surface haptic technologies are much more suitable for feel-and-navigation-based modes of interaction as they "localize" the haptic impression without moving the entire surface. Localized and "instant" feedback, as well as the involvement of active movement, are some of the fundamental factors of search haptics. If stakeholders are eager to increase the ability of blind operation of visually-driven interfaces via active haptics, they should implement technologies that are geared towards a more feel-focused approach, such as surface haptics and friction-based technologies.

The question "*How can "good" search haptic cues in active haptics system be characterized and parameterized?*" cannot be answered in a general way. Different technological approaches entail different requirements and prerequisites towards perception — as already discussed within the *Haptic Fidelity Framework*. Proposing sets of parameters isn't expedient simply because different haptic technologies use different sets of parameters and are embedded in different haptic systems. Also, technologies with the same actuation principle might employ different design principles and parameters if supplied by different manufacturers or implemented in different haptic systems. For example, all studies described in Chapter 3.2 were performed using the Tanvas MimoVue Haptic Touchscreen. This unit is still in constant development, so even different software and hardware versions might result in using different friction maps. In the end, iterative user-focused studies need to be carried out using a (near production-ready version) device in which the haptic feedback should be implemented to define the proper set of parameters to achieve the desired haptic stimuli.

4.1.2 Active vs. Passive Search Haptics

A verdict from the studies and personal experience during the research phase of this PhD project is that active haptics will possibly never be able to fully replace passive search haptics in terms of usability, haptic quality, and their potential for eyes-free operation. In the previous sections, I pinpointed the fact of appropriateness. Previous "traditional button interface" car generations and the *Function Follows Form* studies have depicted that passive haptic forms and surface features allow for easily accessible haptic interfaces. In recent years some automotive carmakers are deliberately switching back from featureless capacitive surfaces to (or keeping) real passive haptics buttons (Day, 2023; Halvorson, 2019; Tsui, 2020; Zipper, 2023) due to driving safety and customer acceptance. When it comes to search haptics, it feels like passive haptic cues are more appropriate than active haptics, which boils down to several observations during my research period:

Association & Saliency: Users have gotten used to the subtle passive haptic qualities that have guided haptic exploration in car interiors over several automotive generations. Due to the context of "searching buttons and functions", already small surface bumps provide a strong enough haptic saliency to activate deeply rooted interactive metaphors ("There is something I can press"). Active haptic impulses upon sliding interactions on seamless (and screen) interfaces have not been fully integrated into users' perceptual habits, as real-world examples are still scarce. Users might be surprised at initial contact even though actively augmented click feedback might foster the search haptic impression. The unfamiliar impression might change with the more mainstream integration of active haptics into consumer and automotive products.

Temporal & Spatial Continuity: Another reason is the temporal and spatial permanency of passive haptics. Passive cues are independent of the current interface status. This allows users to establish a clear mental model of the interface. The location of buttons and how they "feel" remains constant, even after system updates. Actively changing interfaces that result in constantly changing haptic patterns (depending on the screen and system state) might confuse users. With ubiquitous touchscreen interfaces and over-the-air upgrade capabilities nowadays, car manufacturers can and already do change the complete GUI layout via software updates (van de Bruggen, 2022). The fact that passive haptic cues are physically anchored makes them a strong reference for haptic exploration, as continuous edges pose the potential to guide haptic interaction. This is something that could be observed in the Main Study of the *Function Follows Form* study series (see Section 2.2.2). Participants reported that the simple straight raised-line bars are a perfect finger guidance and reference frame for interaction.

Discrimination of Search and Confirmation Haptics: One of the central notions of the *Framework of Haptic Processing in Automotive User interfaces* is that different haptic cues serve different purposes in interaction — search and confirmation haptics. The previously mentioned notion of appropriateness also applies here. Some haptic cues are more suitable (or associated) for being used as search cues, while others are more related to confirmation cues. "Traditional" car interiors implemented discrete buttons with edges, seams, and specific button geometries to allow for eyes-free operation, which is why surface features, such as seams, textures, and 3D features, are still primarily associated with search haptic cues. In contrast, button click events (accompanied by surface displacement and a unique force-travel characteristic) are almost exclusively associated with confirmation haptics. In the context of passive haptic interfaces, the haptic impression of search and confirmation cues inherently differs from a perceptual point-of-view. Hence, they can easily be discriminated during interaction — an asset not to be underestimated in haptic design. This "natural" discrimination is somewhat different for active haptic technologies. Even though active haptic impulses may differ concerning frequency, amplitude, duration, etc., the haptic sensation (i.e., creation of the haptic via vibration) remains similar. This might be confusing if haptic feedback is used for different interaction use cases. Designers need to maximize the difference regarding the perceptual qualities of search and confirmation cues in active haptic devices. This can easily be implemented using different haptic technologies for search and confirmation haptics.

Discrimination of Detection and Identification: Also, in the context of search haptics, haptic cues may not only be used for detection but also for identification of control elements (Breitschaft & Carbon, 2021; Götz, 2007). Passive haptic interfaces often inherently entail a strong search haptic impression as the haptic experience of detection and identification cues widely differ (i.e., cues that allow discriminating design and interactive surfaces and, even more precisely, the exact button). For example, the control panel has different materiality than the circumferential decor parts or a design clasp surrounds the component. Buttons, levers, or rotary dials can also have a distinct and iconic geometrical shape that is completely lacking in flat interfaces. Section 2.2.2 concludes that form is a strong communicator of saliency and functionality. The strong impression and impact of control elements, such as BMW's iDrive controller, can hardly be reproduced with active haptics. Instead of mere virtual clicks, designers and engineers might want to introduce a "natural" haptic distinction by applying a multi-step *search-and-selection* approach in active haptics. This approach incorporates vastly different haptic patterns for search (detection) and selection (identification) cues (Figure 26). It can be described as a coarse-to-precise interaction. During *exploration*, in which the user's main goal is to separate interactive from non-interactive areas, a textural impression across the complete interactive area augments interaction. Once the user "found" the interactive area using the textural pattern, haptic feedback upon transitions between different interface elements allows the user to *navigate* and perform a finer selection. This approach has already been employed as an experimental procedure in (Breitschaft et al., 2022b)

4.1.3 A Two-Stage Approach to Search Haptics: Detection vs. Identification

Building on the *Framework of Haptic Processing in Automotive User Interfaces*, there are basically two major modes that constitute the search haptic impression: (1) Detection and (2) Identification[25]. Detection means acquiring interactive surfaces and buttons within non-interactive areas of the interior. Identification means the discrimination of the different button areas within a single interface to select the desired functionality, i.e., haptic cues like ridges that separate adjacent buttons within a button bar. For a detailed discussion on haptic cues, see Figure 13 (p. 74). A major design principle described in the framework is *Discriminability*. This means that haptic cues should be distinct enough so that each type of feedback indicates the stage of interaction — or described in another way: every stage should be

[25]The first stage of the *Framework of Haptic Processing in Automotive User Interfaces* includes *Exploration* as the initial stage as it provides a first haptic glance of the interface and sets up the starting point for further and more detailed exploration

represented by a specific kind of haptic impression. Appropriate search haptic cues depend on the particular use case (e.g., detection of single elements, navigating between different items, etc.) and mode of interaction. Figure 26 (p. 151) describes how the *Detection* and *Identification* approach can be combined to enhance search haptics in active haptic devices.

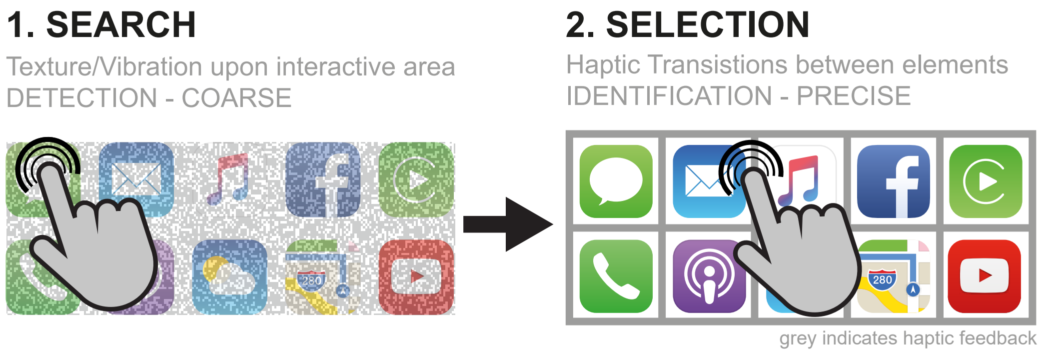


Fig. 26.: A two-stage "search-and-selection" that combines textures to ease the detection of interactive surface and haptic transitions between elements for finer and more precise interaction might facilitate search haptic design.

Detection/Search - Single elements: Provide feedback on the element itself and make it different from confirmation haptic feedback. Single elements may best be augmented via textures, form, or other salient surface features. Section 2.2.2 describes how passive haptic forms communicate functionality via haptic exploration. It also details specific form-functionality associations. The notion of using textures also applies to active haptics. In the context of electroadhesion, having friction patches upon interactive areas fosters the illusion of "sticking to the button". Only using single haptic clicks to indicate virtual edges may potentially confuse participants as they do not know whether they are sliding on or off the button. Conclusions from research in the context of *haptic saliency* and *haptic search* might be applied here with regard to the detectability of interactive items. For example, Breitschaft et al. (2020b) indicate that items with highly frequent friction change patterns (using electrostatic rendering) seem easily detectable. Despite being highly detectable, high-frequency haptic patterns pose the risk of being unpleasant and annoying in prolonged interaction — this equally applies to friction- and vibration-based systems (Breitschaft & Carbon, 2020a; Petermeijer et al., 2015).

Identification/Selection - Multiple adjacent elements: Provide clear feedback between transitions from one element to another. If buttons within a control panel are directly placed next to each other, they should preferably be augmented via short and demarcated haptic events, such as edges, seams, ridges, discontinuities, or property changes, to help navigation within the interface[26]. Maintaining a high figure-ground contrast between the buttons and transitions is essential. Observations from the studies described in Chapter 3.1 indicate that it's secondary for friction haptic feedback, whether the elements or the transitions contain the high or low friction impression. What's important is a strong friction change impression upon the transition. Textures upon the elements should be avoided in this context as they potentially mask transition feedback (Vardar, 2020). These design principles might also apply to passive haptic interfaces. For electrostatics, it seems that sudden friction changes and line width modulate the detection of haptic edges. For exploration with the index finger, we found 4mm lines with multiple friction changes to yield the highest saliency while retaining a non-annoying character[27]. Also, the general haptic line appearance (line, vibrational, slope, etc.) probably influences discrimination (Breitschaft & Carbon, 2020b).

4.1.4 An Approach Towards a Qualitative Definition of "Good" Search Haptics

It might not be expedient to precisely characterize the technical parameters of search haptic feedback. Every haptic device would require a specific basic haptic parameter set due to the differences in the actuation principle of the actuator, mass-damper-system, moving mass etc. (Breitschaft et al., 2022a). Nevertheless, following the notion of the *Haptic Fidelity Framework* and describing the haptic experience, which fosters search haptics is immensely valuable for practitioners. Based on results from the studies and personal observations, there seem to be some essential qualities that constitute "good" search haptics, i.e., for exploration, detection, and identification (see *Framework of Haptic Processing in Automotive User Interfaces* in Section 1.4.2).

First, interfaces need to support and **invite search haptic** interactions. To put it in the words of Klatzky and Peck (2012): surfaces need to have a certain *touch-ability*. Moreover, to put it in the words of Norman (2013): interfaces need to afford haptic exploration. As mentioned earlier, designers need to implement haptic (in the form of surface shapes or button layout), visual (in the form of GUI elements), or interaction-related cues that indicate the interface can potentially be operated

[26]A demarcated event can mean different things for different technologies. For example, on a vibration-based system, it could be a short vibrational click pattern; on textile interfaces, it could be stichting; on a variable friction interface, it could be a friction change; on a passive haptic interface, it could be a change in surface friction, etc.

[27]The line width is based on the Tanvas MimoVue device used in all the studies from Chapter 3.2 with maximum available strength

using only search haptic impressions. Haptic and visual cues already communicate functionality beyond a mere detection (Breitschaft & Carbon, 2021; Götz, 2007).

Another basic denominator of detection is **tactile saliency**. This means the figure-ground contrast for haptic stimuli needs to be sufficient to be detected in the demanding multitask automotive context. Multiple studies suggest that perceived haptic strength is crucial to a device's effectiveness (Breitschaft et al., 2022b; MacLean, 2008; MacLean & Hayward, 2008; Pitts et al., 2012a). This is especially essential for critical interactions in the context of blind operation (i.e., the user is supposed not to look at a screen while interacting). As described previously, tactually salient impulses need to be defined using the final haptic system as it is technology-specific how saliency is characterized. As a general rule of thumb, one can only say, "perceived haptic strength needs to be high enough to robustly perceived the haptic feedback when different contextual factors are factored in".

Even though overall haptic strength is essential, designers should focus on more than just objective performance-based parameters when evaluating haptic stimuli. They should also look at how haptic stimuli are perceived from an **haptic experience perspective**. Strong impulses might not necessarily be pleasant to use. Hence, haptic design requires a trade-off between strength and haptic experience. For example, even though the high-frequent-high-strength texture patches in Section 3.2.2 yielded positive subjective evaluation regarding pleasantness and detectability of interactive items, other studies indicate prolonged haptic textures and vibrations might cause annoyance (Heijboer et al., 2019a; Petermeijer et al., 2015).

Current search haptic implementations, such as OEM products, supplier prototypes, and haptic literature (e.g., Kaaresoja (2015)) indicate that the haptic **latency** to the interaction significantly influences the effectiveness of search haptics. As already described, the haptic sense seems more sensitive toward latency than the visual counterpart concerning perceived simultaneity and quality of perceptual events. Search haptic cues need to be "zero to low latency". Due to the active and dynamic nature of exploration, haptic responses while sliding need to be "instantaneous" so that the visual and haptic impressions of system changes do not fall apart. This is somewhat different from press interaction which requires prolonged (through the orthogonal press movement) and stationary contact between finger and surface. This "instant" haptic impression is difficult for vibration-based technologies (due to latency introduced by sensing, electronic communication, and actuator start-up time). The low-latency nature makes passive haptic and friction haptic technologies highly appropriate for search haptics.

Item size is another decisive denominator for "good" search haptics — even though it is not exclusively related to the haptic feedback impression itself. As a rule of thumb, the bigger the target, the better the detection performance. Results from Breitschaft et al. (2020b) indicate that detection performance is related to item size. The 15×15mm items were detected easier and faster than the 10x10mm items. Other studies also report that usability and driving performance increase with bigger item sizes (Kim et al., 2014; Rümelin & Butz, 2013). The relationship between item size (and distance) can be described and modeled using Fitt's Law (Budiu, 2022; Fitts, 1954). Even though very large items massively reduce visual distraction, they will never be fully glance-free as short glances might still be used for quick localization and confirmation of hand positions (Rümelin, 2014, p. 57). Eren et al. (2015) concluded that roughly 50% of single press button interactions could be performed eyes-free when item size is 140×140mm[28]. Similar to limited space in hardware package size, screen and interface real estate is scarce.

Haptic feedback can be manifold and support different stages of the interaction process — from search to confirmation haptics. Most importantly, search haptic cues need to meet **user expectations** and be consistent in the context of product interaction. This is interconnected with all points mentioned above. For example, haptic cues should be strong enough, and interfaces should already invite a feel-focused interaction. If the interface includes search and confirmation haptics, both types of cues need to be distinct enough to avoid any potential confusion, for example, by applying texture and shape during the search phase and demarcated haptic clicks upon confirmation. The same applies to the mapping of haptic strength. Even though haptic cues must be strong enough to be perceived, the strength should match their relevance during the interaction, i.e., search haptic impulses indicating a single list entry (in a list of 50 elements) may not be as intense as the transition between two distinct buttons. In addition, haptic cues during the search phase might already employ different perceptual qualities, i.e., mere search cues or cues that already implicate a specific function due to their associative character.

[28] As digital screen real estate is restricted, an item size of 140×140mm is already too large to be implemented in in-vehicle GUIs from a practical point of view.

4.1.5 Haptics is no Omnipotent Remedy to Visual Distraction

Despite widespread marketing claims, haptic feedback is no omnipotent remedy to avoid visual distraction, which is one of the main challenges in automotive interaction design. Even though users become safer with increasing driving experience, the primary driving tasks will remain highly demanding and require lots of attention. Pitts et al. (2012a) indicate that the mere introduction of a secondary driving-related task (e.g., controlling car functions via interior interfaces) already introduces additional mental and visual distraction — and so might do the mere existence of a touchscreen (Engström et al., 2005).

Interestingly, previous literature and the *Where's My Button* study indicate no consistent influence of haptic feedback on objective performance measures, such as response times, interaction errors, and driving performance. Study outcomes may vary as a function of experimental and haptic design. Nevertheless, haptic feedback increasingly becomes a decisive factor in seamless tangible user interfaces as it has a massive impact on the user and product experience. Even though users are not quicker, make fewer errors, and generally perform better, they seem to feel more confident and safer with haptic feedback. Also, haptic-enabled interfaces have been more preferred and accepted than their non-haptic counterparts. Studies also indicate that haptic feedback, especially in the context of exploration and detection, possibly reduces visual distraction, which can be measured using gaze-related measures, such as eyes-off-road times (see Table 5).

Interfaces that are visually inherently distracting, such as screens and large, flat tangible interfaces, cannot be turned into non-distracting alternatives simply by adding haptic feedback to interaction. Rümelin (2014) explored how to make large interactive surfaces easier accessible during driving and concluded that adding haptics to create visually less distracting interfaces is one part of the puzzle. There are other and potentially more effective methods to foster eyes-free interaction in case haptic feedback may not be an option:

Increase item size: Item size does influence targeting performance. Larger items require less time to be detected and selected (Rümelin, 2014). Eren et al. (2015) describe that target items with a size of 140$\times$140mm required zero visual demand in half of the cases.

Employ spatial memory: Increasing item size or locating buttons at consistent locations in the interface supports haptic exploration through spatial information in the form of kinesthetic cues (e.g., arm posture) supports haptic exploration. In addition to tactile cues, kinesthetic information that employs spatial (and muscle) memory provides subtle feedback on interaction (Rümelin, 2014; Wigdor & Wixon, 2011). More concretely, interfaces should not only employ the *What* but also the *Where* system of haptic perception (Lederman & Klatzky, 2009). For example, the DS *Smart Touch* System (DS Automobiles, 2022) employs spatial information to confirm user input. Six shortcut elements in a 3×2 matrix on the central information screen are controlled via simple swipe gestures on the touchpad. For example, swiping left and up activates the upper right shortcut. Swiping down activates the lower center shortcut. In this case, there is no tactile feedback from the touchpad. The kinesthetic information provided via the interaction movement is the basis of user feedback.

Simple Touch, Complex Speech: Designers should align the general type of interaction with the task prerequisites. Simple interactions (i.e., interactions that only require a small number of touch-points to reach the desired output), like opening/closing windows or switching on/off the seat heating, may be performed by simply pressing a button. Complex and prolonged interactions, like entering a navigation destination, benefit from speech input. In this case, a touchscreen might also be more suitable than a remote controller or touchpad, which, for example, are restricted to a sequential input of characters (ADAC, 2022; Breitschaft et al., 2022b). Voice interaction may prevent prolonged visual and manual distraction through haptic exploration and interaction, as users can keep their eyes on the road and hands on the wheel during the interaction. Speech interfaces are increasingly becoming more advanced, powerful, and accurate, which means that the hurdles of early speech interfaces (e.g., the obligation to use a phrase like "navigate to" to enter the navigation menu) are becoming smaller. Nevertheless, designers should also take user preferences into account. A survey by mobile.de (2020) showed that users might still have preconceptions about using voice interfaces. Even though voice interfaces can control many functions, there are still highly safety-relevant car functions that require tactile input or functions that users prefer to activate via a simple press because the interaction is short and confined.

Focus on information hierarchy: Blind operation may also be facilitated by focusing on and optimizing the information hierarchy of control panels. Designers should first focus on minimizing the general task demands before implementing haptics. This means that frequently used functionalities, such as climate functions, should not be embedded in GUI-submenus but be made easily accessible via direct touch hard keys as this might minimize the operation time and complexity of the manual operation. In the context of more touchscreen-focused interactions, designers should strongly evaluate how they lay out information in the different layers of the GUI.

For example, Mercedes tries to tackle this issue by applying a *zero-layer* approach in their second-generation MBUX touchscreen UI. All situation-relevant information and functionalities are directly accessible on the main screen (Daimler AG, 2021a). In addition, the system is "learning" interactive patterns and continuously adapts the interface accordingly. Using artificial intelligence to implement more proactive systems, i.e., systems that actively and context-dependent propose UI functionality based on previously learned user behavior, could also foster blind operation.

Integrate favorite functions: Automatizing interaction by providing the possibility to store and recall certain user-favorite UI functionalities via the press of a single button (e.g., setting a certain navigation address, setting a specific climate setting) may reduce mental load and required interaction time. For example, BMW has introduced so-called "functional bookmarks" that can be programmed to access almost any system functionality (BMW Group, 2013).

Remote vs. direct interaction: Another option to minimize visual and manual distraction is to reconsider the primary mode of operation and adapt the GUI-Layout accordingly. Current generation UI systems are heavily geared toward direct interaction upon touchscreens. Touchscreens are primarily located in the center stack. Even though they are often positioned in a so-called "touch-optimized position" with respect to the driver's seat, users often cannot rest their arm on the center console during the interaction. It is visually and physically demanding as users constantly need to uphold and adjust their arm position to select and activate functions. Touchscreen interaction is often ergonomically challenging from a kinesthetic point of view, especially when screen elements are small (ADAC, 2022; Budiu, 2019). Remote interaction decouples the input and output locations. Information is not directly manipulated at the screen but via a secondary touchpad or rotary dial. This allows for an ergonomically perfect layout of input and output devices. Especially remote elements like Push-Turn-Tilt dials (such as BMW's iDrive) can facilitate eyes-free operation as they entail a powerful and affording haptic character. Remote elements (1) provide a visual and haptic anchor for interaction, (2) give orientation for haptic exploration, and (3) "predefine" the types of interaction, like pushing, turning, and tilting through their haptic appearance. On the other hand, touchscreens (and thus direct interaction) are en vogue and meet customer expectations towards screen interactions. Also, some types of interactions, such as inputting a navigation destination or zooming on a map, may be easier and quicker than on remote controls. Nevertheless, the choice of a remote- or direct-focused interaction has a massive impact on the layout of the GUI. If a direct interaction-focused approach is applied, it can be designed more like a familiar smartphone interface. If a remote controller is the center of interaction, the graphical interface needs to accommodate the degrees of freedom the remote controller offers, e.g., by relying on a list-based UI for rotary dials or a matrix-based UI for touchpads.

Position-independent controls: Rümelin (2014) also proposes the implementation of position-independent gestures, such as long-press or multiple-finger-interactions, for eyes-free interaction. Avoiding the requirement to "search" the correct control element could potentially facilitate visual and manual distraction. Users could tap and swipe anywhere in a confined touch-sensitive area to interact. The DS *Smart Touch* Touchpad integrates position-independent touch commands corresponding to specific user interactions (DS Automobiles, 2022). For example, swiping from the touchpad's right to the left border corresponds to confirmation. Also, pinch-to-zoom anywhere on the touchpad zooms in or out when in navigation mode. The exact interaction starting point on the touchpad is not relevant. A downside of position-independent gestures is that there is no apparent relationship between gesture and output. As long as there are no universal touch commands, it will require learning and training.

4.2 Design Principles for Automotive (Search) Haptics

> *There's a fine line between genius and [really bad design]*
>
> **— Oscar Levant (1959, adapted)**

This thesis revolves around the question of how to design search haptics cues to maximize their impact on eyes-free interaction. All research activities within this thesis already provide insights for search haptic design in the specific sections or published contributions. However, there are further "lessons learned" through personal experiences, prototyping sessions, and discussions on haptic design that are not reported in detail. This concluding section will summarize all these insights and provide a set of (general and also search haptic specific) guiding design principles for practitioners. This set will also build upon the abundance of already existing but mostly more general types of haptic design guidelines (see Table 6, p. 167).

Employ analogies & metaphors: Perception and aesthetic appreciation are driven by previous experiences, expectations, and user associations (Carbon, 2019). Employing characteristic user associations can facilitate interaction. Haptic forms and surface features have an implicit functional character (Breitschaft & Carbon, 2021). Also, vibration-based active haptic impulses seem to employ perceptual associations. For example, longer vibration impulses tend to elicit associations with regards to "warning" and "danger" (Heijboer et al., 2019a) but also annoyance. This might be especially useful when novel types of haptic feedback are put in place. Try to facilitate interaction with metaphors the user is already familiar with.

Consider context: The context in which interaction takes place has a massive influence on aesthetic and functional evaluation (Carbon & Jakesch, 2013; Jakesch & Carbon, 2011). This is especially important to consider for novel-type haptic devices. Even though the haptic feedback might provide a strong and detectable haptic sensation in table-top use cases, the haptic impression might drastically change once context information, like the multitask and multimodal nature of driving, is introduced (Breitschaft et al., 2022b; Pitts et al., 2012a). Also, how users

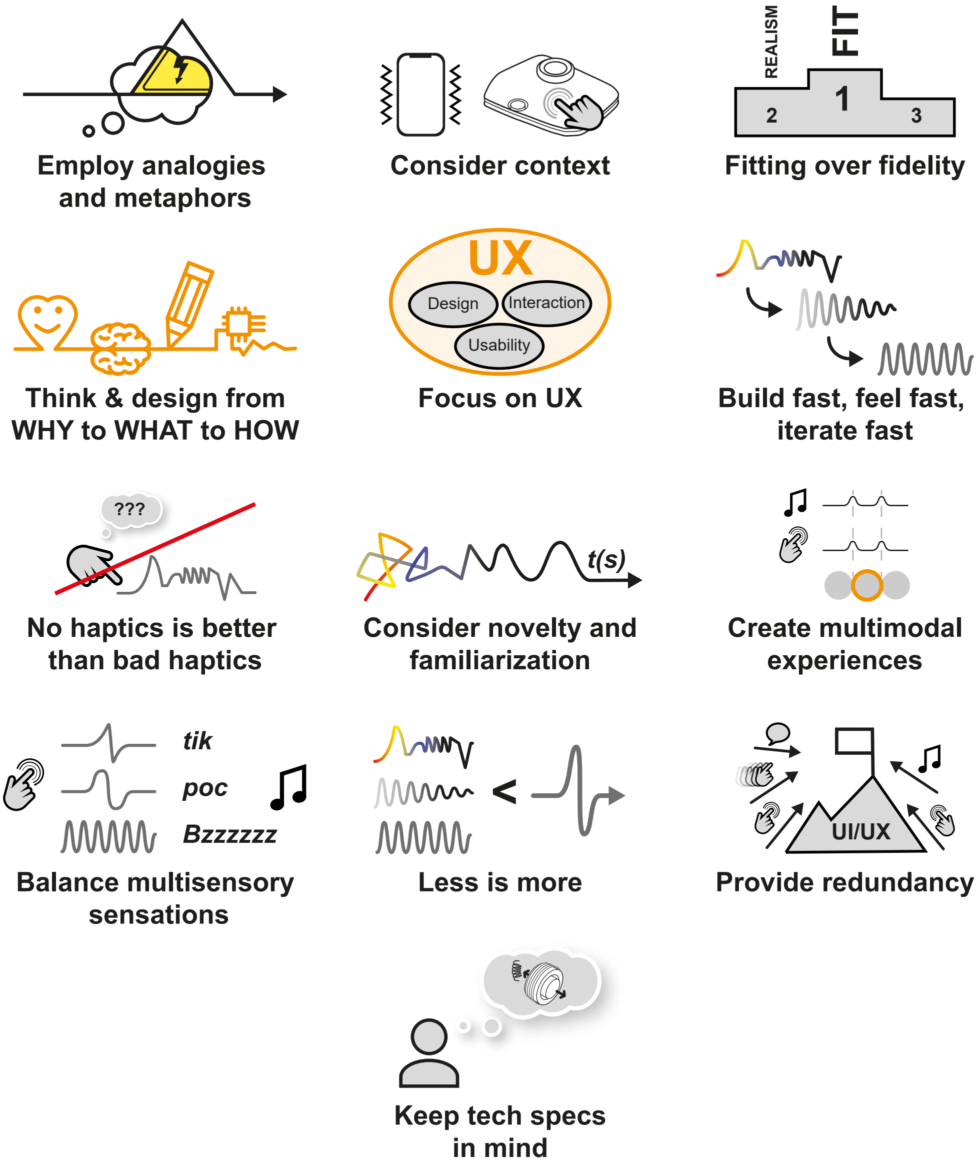


Fig. 27.: Summary of general design guidelines for haptic feedback in user interaction.

interact and feel the haptic feedback impacts the impression — e.g., feedback on a mobile phone that users hold in their hand vs. feedback in an automotive control panel which is only delivered through the fingertip. Especially real-world influences, such as environmental and road conditions, might require factoring in a stronger haptic impression during the design process[29].

Fitting over fidelity: Focus on providing a haptic experience that fits the overall interaction rather than the fidelity of the sensation. This is especially important

[29]For a more detailed discussion on the automotive context, see Chapter 1.4

when designing with novel technologies that users are unfamiliar with. For example, a physical edge is a salient passive search haptic cue to augment interactive elements. Even though active haptic technologies can replicate the impression of a physical edge, other impulses, such as prolonged vibration, might be more appropriate in the context of augmenting interactive interface elements. Different technologies do pose different technical requirements and haptic timbre. In order to create appropriate experiences (or choose appropriate technologies), practitioners are required to "match" user prerequisites, interaction requirements, and technical characteristics. The *Framework of Haptic Processing in Automotive User Interfaces* (Section 1.4.2, p. 69) and the *Haptic Fidelity Framework* (Section 1.3.2, p. 51) provide a framework to match tech specs and user requirements in the context of search haptics. Section 2.2.2 (p. 87) describes the appropriateness of various haptic forms to communicate specific functionalities. Figure 11 (p. 58) provides a subjective classification of active haptic technologies and their suitability for particular interaction use cases.

Think & design holistically from Why to What to How: Do not simply implement haptics for the sake of innovation and technology. The question "Why do I want to integrate haptic feedback" (e.g., to reduce visual distraction and support eyes-free interaction) should be the starting point and foundation of the design process as opposed to starting with the applied technology. From why haptics is integrated, one should define the context of interaction, perceptual prerequisites, and user requirements. Based on these preliminary considerations, sketch the haptic experiences you want to convey. Only once you defined the *Why* and *What* think about *How* to implement haptics — i.e., which technologies are most appropriate for the type of interactions (also see Figure 9, p. 50).

Focus on UX: Do not only focus on pure functionality and performance but on how haptic feedback is implemented in the greater scheme of interaction and user experience. The overview on automotive haptic studies in Breitschaft et al. (2022b) indicates that the main differentiating factor of haptic feedback is its positive impact on user experience. For example, high-frequent friction textures are highly salient for search haptics but might be annoying and potentially deteriorate perceived quality in long-term interaction (Breitschaft et al., 2020b).

Build fast, feel fast, iterate fast: Build, test, evaluate and iterate your haptic design. It might be beneficial to prioritize low-fidelity prototypes and fast iterations over high-fidelity prototypes in the early stages of development. Hardware sketching, i.e., early prototyping and iterating ideas, might be a valuable source of inspiration (Moussette, 2012). Even though a pre-selection of stimuli can be done on generic prototype-level devices, the final tuning needs to be done on a nearly final haptic system as the system implementation itself (i.e., the interaction of moving mass, actuator, spring damper system, etc.) has an impact on the haptic experience and which experiences can be created in the first place. This also entails the implementation of context (see above). Many haptic studies depict that although haptic impulses have been evaluated beforehand, they still fail to convey a strong impression in the multitask main study (Breitschaft et al., 2022b; Pitts et al., 2012a).

No haptics is better than bad haptics: If the haptic feedback feels too weak, unexpected, inappropriate, inconsistent and out of place, or not properly done due to the technology or implementation, it can have a detrimental impact on user experience and overall quality. For example, when search haptics cues are only felt with a slight delay. In the automotive context, poorly designed impulses may be confusing and pose a safety risk rather than being helpful. If the haptic feedback feels inadequate, it might be better to leave out the haptic modality.

Consider novelty & familiarization: Even though haptic feedback has existed for several decades, higher fidelity haptic technologies and experiences have only started emerging in consumer electronics products. Plenty of users may still not have fully adapted to how novel interface technologies "feel". Also, haptic feedback applied to touchscreen interaction might still be unfamiliar for a lot of users (e.g., that there is a haptic click upon scrolling through a list, toggling between different items or a feelable texture) as they do not yet expect a touchscreen to vibrate or provide haptic feedback. This expectation might change in the coming years. Smoothen the transition by providing easy, clear, and strong feedback. Help users get accustomed to the novel type of experience (see Section 3.2.5).

Create multimodal experiences: Use multisensory feedback whenever possible (MacLean, 2008; MacLean & Hayward, 2008; Moreno & Weddle, 2013). Various UI studies (see Table 5, p. 64) depict that even though haptic and audio feedback already enhance user experience compared to a visual baseline, users still mostly prefer a multisensory experience as it creates a sense of involvement. This is also indicated by the *Where's My Button*-study (see Table 5, p. 64).

Balance multisensory sensations: When designing multimodal experiences, choose appropriate sensory modalities to convey system information to the users. Make sure visual, audio and haptic feedback are well balanced. For example, a hazardous situation may be displayed via vibration in the seat and steering wheel or loud noises that the user cannot miss, even in busy situations. Haptics can be used for private communication in case information only need to be delivered to the driver or passenger. Balancing means providing an appropriate level of strength for each feedback modality. The *Where's my Button*-study indicates that audio feedback "overshadowed" the haptic impression, which might cause confusion and deteriorate user experience. On the other hand, different audio-haptic interferences may explicitly be used to modulate the haptic impression (Tikka & Laitinen, 2006). Impressions from different modalities need to "fit" together — not only from a perceptual point of view regarding latency and strength but also from an aesthetical perspective. For example, in the context of the *Where's my Button*-study, participants reported that the haptics impression was not "on point" as some participants associated the friction stimuli with a negative impression which did not fit the neutral and dull-sounding acoustics.

Less is more: Try not to overthink haptic feedback, and don't get lost in technical details. Instead, concentrate on what is important from a user's perspective — this is related to designing from Why to How. Instead of implementing highly complex rendering and driving algorithms, focus on providing a strong and clearly defined haptic experience. Restrict yourself from using too many haptic stimuli within the interface, as it might confuse users. Especially in multitask settings, where users cannot entirely focus on the haptic feedback, perception thresholds may be higher than expected. For example, the *Perception*-study from Breitschaft and Carbon (2021) indicates that the amount of different haptic forms is restricted. Also, early iterations from the *Semantic Differentiation*-study (Breitschaft & Carbon, 2020b) and *Where's my Button study* (Breitschaft & Carbon, 2020a; Breitschaft et al., 2022b) indicate that perception thresholds for friction textures are reasonably big in interaction contexts, i.e., users can only differentiate a small number of textures.

Provide redundancy: Design for redundancy whenever possible (MacLean & Hayward, 2008). In the context of interaction, redundancy can mean various things. Redundant multisensory information reinforces task demands and supports interaction. But also redundant input methods, such as touchscreens accessible via remote controls or additional voice control, provide fallback solutions and enable the user to interact to their liking.

Keep tech specs in mind: Every type of technology conveys a tech-specific haptic *timbre* (Kim & Schneider, 2020). It comes with a specific set of experiences it can deliver by design (Breitschaft et al., 2022a) — also see 1.3.2. This means that for every haptic system, there are technological boundaries for haptic design. Define the experiences you want to convey and choose the appropriate technology accordingly (Breitschaft et al., 2022a).

Some of the guidelines refer more concretely to search haptic feedback, i.e., how to make interfaces easier to operate eyes-free:

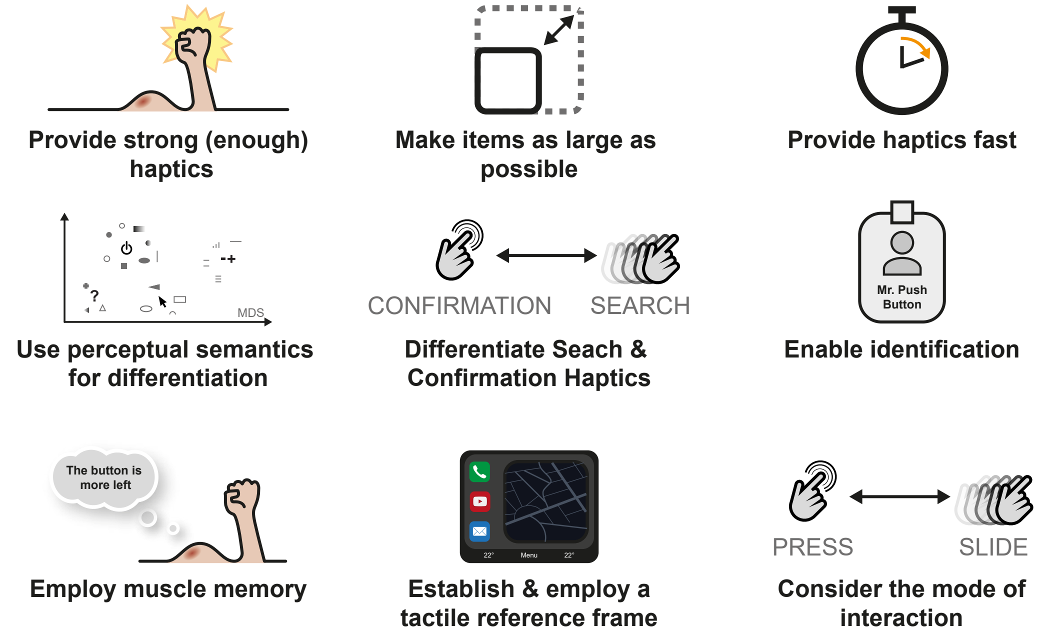


Fig. 28.: Summary of specific guidelines for the design of search haptic stimuli.

Provide strong (enough) haptics: Haptic impulses should be strong enough to be perceived. There is no use in haptics the user doesn't feel. There is no general answer to what strong haptics means as it is highly technology-, system, and use case-specific. Double-check and iterate perceived haptic strength before implementation. Consider adjusting the haptic strength to the context as well. For example, the studies described in Chapter 3.1 indicate that while the friction haptic feedback was highly perceivable in single-task settings, haptic strength was too weak in a cognitively demanding dual-task setting. Novel technologies that users are not yet used to may require a stronger haptic feeling to overcome uncertainty and support familiarization. Especially in automotive, environmental influences, such as bumpy roads, need to be considered.

Make items as large as possible: Studies indicate that target performance increases with item size in haptic search tasks (Breitschaft et al., 2020b; Eren et al., 2015; Kim et al., 2014; Rümelin & Butz, 2013). Try to maximize target sizes, even though screen real estate may often be limited.

Provide haptics fast: The haptic sense is very sensitive to input action and feedback latency. Stimuli with a delay of more than 20-50ms with respect to the input interaction are not perceived as simultaneous anymore (Kaaresoja, 2015). Tactile feedback stimuli following an input action with a delay of more than 70-100ms already seem to have a massive impact on perceived quality and user experience

(Kaaresoja, 2015). Especially in the context of an exploration-based search haptic impression, an "instantaneous" sensation is fundamental (a more detailed discussion, see Section 4.1.4). Haptic feedback should be provided within 55ms in visuo-actile and within 25ms in tactile-audio scenarios (Kaaresoja, 2015). The guidelines provided by Kaaresoja (2015) have been carried out in a mobile context. They might change with a different interaction context. Future expectations towards latency may adapt even further with more capable and responsive devices.

Use perceptual semantics for differentiation: Different haptic sensations and interactions within components must be distinguishable. In addition to distinguishing stimuli by modulating them on a singular dimension, such as amplitude and strength, applying semantically different haptic patterns, such as single-solid or vibrant patterns (Breitschaft & Carbon, 2020b), might facilitate differentiation. Furthermore, it might already allow the identification of specific transitions upon multiple repetitions.

Differentiate Search and Confirmation Haptics: Haptics can be implemented to augment various use cases in interaction. Using similar stimuli and sensations for different types of interactions (search and confirmation) may confuse users. Differentiate the haptic impressions for search and confirmation haptics as much as possible (Breitschaft et al., 2019a). In the context of passive haptics, this might include using surface textures and geometries to enable haptic exploration and force-travel parameters to indicate confirmation. In the context of active haptics, this might include a double-step approach with textures upon interactive elements for search haptics and singular haptic clicks for confirmation haptics (see Section 4.1.2 and Figure 26, p. 151). Table 6 (p. 167) gives an overview of further best practices in haptic user experience design. A combination of passive haptics for search cues and active haptics might yield even better results due to their distinct perceptual character and appropriateness of passive and active haptics cues to convey search and confirmation haptic information (also see Section 4.1.2).

Enable identification: Implementing haptic forms and vibrational patterns that employ user associations and communicate functionality (e.g., a protruded circular shape to represent a push button) may enhance interface design as they augment system information beyond a mere detection (Breitschaft & Carbon, 2021). This might allow for an even finer, yet easy-to-understand, discrimination between haptic search and navigation (see Section 4.1.3).

Employ muscle memory: Involve the subtle power of kinesthetic cues in search haptic design. If interface dimensions are no issue, place interface elements at different, distant locations. Functions might already be identified by their location in the interface through kinesthetic information. This gives (1) more degrees of freedom with respect to haptic design and (2) employs kinesthetic information, which is included in the search haptic context.

Establish & employ a tactile reference frame: Embed subtle haptic cues of the interface's surroundings to support search haptics interactions. For example, locating buttons at the edge of the interface (e.g., a button bar with frequently used functions on the right or bottom side of a touchscreen or touchpad interface) might already provide a subtle but strong tactile reference frame as users may use the edge of the interface as an anchor, reference or starting point for haptic exploration. This might already substitute the necessity of implementing further search haptic feedback (Rümelin, 2014). Especially in screen interfaces locating driving-relevant items close to the driver (in most cases more towards the left side of the screen) might also facilitate interaction as it alleviates kinesthetic effort (Budiu, 2019). Implementing highly affordant and salient surface geometries and shapes might foster the implementation of a tactile reference frame, as these salient surface features serve as a reference point for interaction. For example, in the current generation of BMW iDrive controllers, multiple functions are placed around the rotary controller itself. While the hand rests on the controller, push functions can be located and activated effortlessly — in this case, a function might already be distinguished by its distinct location in relation to the controller, e.g., top center or bottom center. Users will familiarize themselves with the locations of functions and employ this *tactile reference frame* in their behavioral patterns. Hence, it is essential to **keep locations of functions consistent** across interface iterations. While this might be less relevant for passive haptics interfaces (where buttons are fixed), it is important to consider for screen-based interfaces where the GUI can be updated over the air. While this allows to "modernize" and "keep interfaces fresh" over a complete product cycle, changing the interaction "on the fly" poses a potential safety risk as users may be required to "relearn" how to use their previously familiarized interface.

Consider the mode of interaction: The primary mode of interaction tremendously influences which technology should be implemented. For example, if the interface integrates a tap- and press-focused mode of interaction, vibration-based technologies might be a good choice. If it follows a feel-focused approach surface, haptic technologies might be a better option (see also Figure 11, p. 58). This is described in more detail in the *Haptic Fidelity Framework* in Section 1.3.2 (Breitschaft et al., 2022a).

Tab. 6.: Overview of sources for general best practice haptic experience design guidelines.

Category	Guidelines
General	*Human Interface Guidelines* (Apple, 2020a)
General	*Android Haptics* (Google Inc., 2020)
General	*Haptic UX — The Design Guide for Building Touch Experiences* (Baker, 2019)
General	*Designing For The Tactile Experience* (Kolesárová, 2018)
General	*The Tactile Era: 10 Principles for Haptic Design* (Punchcut, 2020)
General	*Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX* (Kim & Schneider, 2020)
General	*Design Guidelines for Schematizing and Rendering Haptically Perceivable Graphical Elements on Touchscreen Devices* (Palani et al., 2020)
Automotive	*User experience and expectations of haptic feedback in in-car interaction* (Väänänen-Vainio-Mattila et al., 2014)
Automotive	*Deriving User Requirements for Haptic Enhanced Automotive Touch Screen Interaction* (Beruscha et al., 2016)
Passive Haptics	*Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces* (Mlakar & Haller, 2020)
Piezo-Haptic	*Guidelines of Haptic UX Design* (Boreas Technologies, 2020a)
Friction Haptics	*A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces* (Basdogan et al., 2020)
Friction Haptics	*Enhancing physicality in touch interaction with programmable friction* (Levesque et al., 2011)
Friction Haptics	*Exploring the design space of programmable friction for scrolling interactions* (Levesque et al., 2012)

4.3 Future Perspectives

Can we conclude what good search haptics means based on this résumé? The answer is: Yes ... and No! This thesis sheds light on some of the fundamental questions concerning automotive search haptics. However, there are still a lot of unanswered questions and open territories that future studies, concepts, and products might explore.

Haptic design is highly technical — but also application-specific. This thesis explored rather general and generic guidelines for search haptic design. One conclusion is that there is no "best" technology for search haptics (or haptic feedback in general), but practitioners may choose the most appropriate technology for their specific application. In a recent study, Farooq et al. (2023) compared vibrotactile and electroadhesion feedback regarding their suitability for particular screen interactions. What is still missing are technology-specific or system-specific guidelines for appropriate search and confirmation haptic impulses. This might entail the design of vibration or friction patterns with high tactile saliency or relatively high distinguishability.

The field of haptics is constantly evolving. In the last few years, it developed at a rapid pace. For example, the *Haptic Fidelity Framework* only provides a snapshot of currently available haptic technologies. It was already somewhat outdated upon publication. Also, all electrostatic studies were using a state-of-the-art device at the beginning of 2020 — a device still constantly under development. The constant technological advancements and democratization of haptic feedback will have a massive impact on user expectations and habits towards haptics and interaction. People will become more accustomed to active haptic sensations, which probably reflect their expectations of interaction. More capable devices might also lead to more degrees of freedom in haptic design. This means that all of the publications mentioned above should be revisited in the near future. The outcome may probably change for some studies with more capable devices.

The active haptics part of this thesis mainly included an electrostatic friction device. From the range of other available active haptic technologies, ultrasonic friction devices are especially interesting for search haptics due to their exploration-driven approach. There are initial studies exploring the design space of ultrasonic friction stimuli (Levesque et al., 2011, 2012). Similar to studies employing electrostatic friction devices, ultrasonic friction modulation studies have primarily implemented a single-task design (Basdogan et al., 2020). Future studies may explore the application of ultrasonic friction devices in automotive-relevant settings. As both technologies have a similar perceptual approach (i.e., varying friction), it might be interesting for practitioners to see how both friction approaches compare to each other from a user perspective. Is one of the approaches more pleasant, more precise, etc.?

The strong focus on variable friction devices in this thesis does not mean that vibration-based systems are unsuitable for search haptics. Future experiments and proof-of-concept studies should focus on overcoming the hurdles of vibration-based approaches for search haptic interactions (e.g., latency, system integration, etc.).

Most current-gen interfaces are tap-centric, i.e., confirmation is performed via pushing and pressing. Surface haptics technologies have a strong feel-and-navigation-focused haptic quality and are mainly geared towards exploration but lack a button-click impression. It might be interesting to explore technological and perceptual possibilities to integrate button press haptics with surface haptics devices. Furthermore, it might be interesting to leverage opportunities from novel interface technologies and examine different UI metaphors to replace push-focused confirmation interactions. A prevailing question is: Does confirmation always need to be associated with pushing and tapping?

The résumé at the beginning of part indicates that passive haptics is more suitable for search haptics. This verdict is based on observations and conclusions from this thesis' research activities and has not been explicitly tested in an experimental setup. It would be interesting to test this hypothesis in an applied experiment and precisely examine the differences that set passive haptics apart from active haptics concerning different haptic interactions based on the *Framework of Haptic Processing in Automotive User Interfaces* (Breitschaft et al., 2019a): Are passive haptic cues more suitable for search haptics than active haptics? What do users miss with active search haptics? Can this be generalized, or does the implementation always depend on the system integration? Furthermore, this research undertaking might also pinpoint the initial research question: Is there a way to faithfully recreate passive search haptic impressions using active haptic devices?

Until now, most interfaces only employ either active or passive haptic technologies (each coming with a specific set of technological pros and cons) to create the haptic impression. On the one hand, passive haptic interfaces have a very strong haptic impression as search and confirmation sensations are highly distinct. On the other hand, active haptic interfaces allow for the creation of flush and decluttered surfaces. An interesting idea might be the combination of active and passive haptics to fuse the best of both worlds. For example, passive haptics could be used for search and active haptics for confirmation while retaining a closed, seamless, monolithic surface for design purposes. Continental (2018) showed a haptic-enabled touchscreen with 3D-surface shapes to support search haptics. An even more interesting approach would be to examine whether active haptic impulses can amplify the passive haptic impression of edges. This might allow the implementation of shallower surface features while retaining a strong tactile impression. This combination might also qualify for much more degrees of freedom concerning design.

I am confident haptics will play a massive role in future interaction design and consumer electronic devices. I hope that following this work, a stronger psychological perspective will be brought into the highly engineering-focused haptic feedback discussions.

4.4 Conclusion

The trend towards surface-integration of control elements in automotive interior surfaces might make interfaces aesthetically more pleasing but inevitably introduces the risk of additional visual demand due to the lack of search haptic cues known from traditional analog interfaces. This is accompanied by a clear transition from conventional, analog button interfaces to digitalized forms of interactions. Applying different types of haptic feedback potentially restores the tangibility known from analog interfaces. However, haptics is no omnipotent remedy to make interfaces more efficient to operate eyes-free as it can augment search and confirmation during automotive interaction.

The effectiveness of search haptics depends on the fit of context requirements, user expectations, perceptual prerequisites, use cases, haptic design, and technical implementation. There is no general answer to "good" search haptic design. However, this thesis tries to draw general design guidelines for search haptic feedback based on different theoretically- and empirically-driven studies. Passive haptics allows for a strong and appropriate feel-focused tactile impression. Passive haptic features are highly salient, which makes them great for detection. Passive haptic forms trigger deeply rooted functional associations and can thus be implemented for orientation and identification purposes beyond mere detection. That doesn't mean active haptics is not suitable for featureless interfaces. Surface haptic technologies, especially friction-based systems, are geared towards a high-quality feel-focused haptic impression — as opposed to vibration-based systems, which are often geared towards push-based confirmation haptics. Active haptic feedback makes flat, non-moving surfaces come to life, conveys a "wow"-factor, and inhabit the potential to create a novel haptic vocabulary. Nevertheless, there are still some perceptual and technical challenges with active haptic solutions that practitioners need to consider upon integration, e.g., the generally weak haptic impression due to technical limitations of some current state systems. Especially for active haptic technologies matching the haptic system to the haptic experiences practitioners want to convey is essential.

One of the main messages of this thesis is that implementing a stronger psychological approach might bridge the gap between multidisciplinary practitioners in the field of haptics and thus facilitate haptic design. A more profound psychological turn also facilitates haptic design by focusing on context, basic modes of interaction, user requirements, and perceptual capabilities before choosing a specific technology for haptic feedback. It is clear that haptics greatly impacts user experience and product appreciation. In the context of increasing digitalization of experiences, it becomes a decisive and discriminating factor for brand perception, user experience, and product appreciation. All in all, search haptics is the perfect answer to the overarching question: "Where's my button?"

References

Ackerman, D. (1991). *A natural history of the senses* (1st ed.). Vintage Books. http://www.loc.gov/catdir/description/random047/91050048.html

Anguelov, N. (2009). *Haptische und akustische Kenngrößen zur Objektivierung und Optimierung der Wertanmutung von Schaltern und Bedienfeldern für den Kfz-Innenraum*. Retrieved April 30, 2023, from https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa-24037

Barfield, W. (2009). The Use of Haptic Display Technology in Education. *Themes in Science and Technology Education*, *2*, 11–30. https://eric.ed.gov/?id=EJ1131321

Basdogan, C., Giraud, F., Levesque, V., & Choi, S. (2020). A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces. *IEEE Transactions on Haptics*, *13*(3), 450–470. https://doi.org/10.1109/TOH.2020.2990712

Bau, O., Poupyrev, I., Israr, A., & Harrison, C. (2010). TeslaTouch: electrovibration for touch surfaces. *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, 283–292. https://doi.org/10.1145/1866029.1866074

Bergmann Tiest, W. M. (2010). Tactual perception of material properties. *Vision research*, *50*(24), 2775–2782. https://doi.org/10.1016/j.visres.2010.10.005

Bernstein, A., Bader, B., Bengler, K., & Künzner, H. (2008). Visual-haptic interfaces in car design at BMW. In M. Grunwald (Ed.), *Human Haptic Perception: Basics and Applications* (pp. 445–451). Birkhäuser. https://doi.org/10.1007/978-3-7643-7612-3_36

Beruscha, F., Brosi, C., Krautter, W., & Altmüller, T. (2016). Deriving User Requirements for Haptic Enhanced Automotive Touch Screen Interaction. *SID Symposium Digest of Technical Papers*, *47*(1), 271–273. https://doi.org/10.1002/sdtp.10663

Beruscha, F., Krautter, W., Lahmer, A., & Pauly, M. (2017). An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens. *2017 IEEE World Haptics Conference (WHC)*, 201–206. https://doi.org/10.1109/WHC.2017.7989901

Biet, M., Giraud, F., & Lemaire-Semail, B. (2007). Squeeze film effect for the design of an ultrasonic tactile plate. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, *54*(12), 2678–2688. https://doi.org/10.1109/TUFFC.2007.596

Birbaumer, N.-P., & Schmidt, R. F. (Eds.). (2018a). *Biologische Psychologie* (7. Auflage). Springer. https://doi.org/10.1007/978-3-540-95938-0

Birbaumer, N.-P., & Schmidt, R. F. (2018b). Somatosensorik. In N.-P. Birbaumer & R. F. Schmidt (Eds.), *Biologische Psychologie* (7. Auflage, pp. 321–340). Springer. https://doi.org/10.1007/978-3-540-95938-0_15

Breitschaft, S. J., & Carbon, C.-C. (2020a). An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.14518.32327

Breitschaft, S. J., & Carbon, C.-C. (2020b). Semantic Differentiation of Haptic Edges rendered on an Electrostatic Friction Modulation Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.34650.98245

Breitschaft, S. J., & Carbon, C.-C. (2021). Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design. *Frontiers in psychology*, *12*, 2619. https://doi.org/10.3389/fpsyg.2021.646986

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019a). A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. *Frontiers in psychology*, *10*(1470). https://doi.org/10.3389/fpsyg.2019.01470

Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019b). Using haptic shapes for orientation and identification in automotive user interfaces [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE.

Breitschaft, S. J., Heijboer, S., Shor, D., Carbon, C.-C., & Tempelman, E. (2020a). Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.32973.26086

Breitschaft, S. J., Heijboer, S., Shor, D., Tempelman, E., Vink, P., & Carbon, C.-C. (2022a). The Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-Based Haptic Technologies Through Fidelity. *IEEE Transactions on Haptics*, *15*(2), 232–245. https://doi.org/10.1109/TOH.2022.3152378

Breitschaft, S. J., Pasthukov, A., & Carbon, C.-C. (2020b). Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Display [Poster Presentation]. In *EuroHaptics Conference 2020, Leiden, The Netherlands*. https://doi.org/10.13140/RG.2.2.35489.84320

Breitschaft, S. J., Pastukhov, A., & Carbon, C.-C. (2022b). Where's My Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces. *IEEE Transactions on Haptics*, *15*(2), 292–303. https://doi.org/10.1109/TOH.2021.3131058

Bubb, H. (Ed.). (2015). *Automobilergonomie* (Aufl. 2015). Springer Vieweg. https://doi.org/10.1007/978-3-8348-2297-0

Bubb, H., Bengler, K., Breuninger, J., Gold, C., & Helmbrecht, M. (2015). Systemergonomie des Fahrzeugs. In H. Bubb (Ed.), *Automobilergonomie* (Aufl. 2015, pp. 259–344). Springer Vieweg. https://doi.org/10.1007/978-3-8348-2297-0_6

Carbon, C.-C. (2016). Integration of User-Centric Psychological and Neuroscience Perspectives in Experimental Design Research. In P. Cash, T. Stanković, & M. Štorga (Eds.), *Experimental Design Research: Approaches, Perspectives, Applications* (pp. 113–126). Springer International Publishing. https://doi.org/10.1007/978-3-319-33781-4_7

Carbon, C.-C. (2019). Psychology of Design. *Design Science*, *5*, 339. https://doi.org/10.1017/dsj.2019.25

Carbon, C.-C., & Jakesch, M. (2013). A model for haptic aesthetic processing and its implications for design. *Proceedings of the IEEE*, *101*(9), 2123–2133. https://doi.org/10.1109/JPROC.2012.2219831

Carbon, C.-C., & Leder, H. (2005). The Repeated Evaluation Technique (RET). A method to capture dynamic effects of innovativeness and attractiveness. *Applied Cognitive Psychology*, *19*(5), 587–601. https://doi.org/10.1002/acp.1098

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *The Behavioral and brain sciences*, *36*(3), 181–204. https://doi.org/10.1017/S0140525X12000477

Cuijpers, R. H., Smeets, J. B. J., & Brenner, E. (2004). On the relation between object shape and grasping kinematics. *Journal of neurophysiology*, *91*(6), 2598–2606. https://doi.org/10.1152/jn.00644.2003

Culbertson, H., Schorr, S. B., & Okamura, A. M. (2018). Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, *1*(1), 385–409. https://doi.org/10.1146/annurev-control-060117-105043

Diderot, D. (1749). *Lettre sur les aveugles à l'usage de ceux qui voient*.

El Rassi, I., & El Rassi, J.-M. (2020). A review of haptic feedback in tele-operated robotic surgery. *Journal of medical engineering & technology*, *44*(5), 247–254. https://doi.org/10.1080/03091902.2020.1772391

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(2), 97–120. https://doi.org/10.1016/j.trf.2005.04.012

Eren, A. L., Burnett, G., & Large, D. R. (2015). Can in-vehicle touchscreens be operated with zero visual demand? An exploratory driving simulator study. [Paper Presentation]. *The 4th International Conference on Driver Distraction and Inattention*.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*(6870), 429–433. https://doi.org/10.1038/415429a

Farooq, A., Raisamo, R., Lylykangas, J., Spakov, O., & Surakka, V. (2023). Comparing Electrostatic and Vibrotactile Feedback for In-Car Touchscreen Interaction using common User Interface Controls. *Proceedings of the 6th International Conference on Intelligent Human Systems Integration (IHSI 2023) Integrating People and Intelligent Systems, February 22–24, 2023, Venice, Italy*. https://doi.org/10.54941/ahfe1002822

Federal Aviation Administration (Ed.). (2011). AC 20-175 - Controls for Flight Deck Systems.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, *47*(6), 381–391. https://doi.org/10.1037/h0055392

Gaffary, Y., & Lécuyer, A. (2018). The use of haptic and tactile information in the car to improve driving safety: A Review of Current Technologies. *Frontiers in ICT*, *5*(5). https://doi.org/10.3389/fict.2018.00005

Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, *69*, 477–491. https://doi.org/10.1037/h0046962

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Greenwood.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin Harcourt.

Goldstein, E. B., & Brockmole, J. R. (2017). *Sensation and Perception* (10th edition). Cengage Learning.

González, I. E., Wobbrock, J. O., Chau, D. H., Faulring, A., & Myers, B. A. (2007). Eyes on the road, hands on the wheel. In C. G. Healey & E. Lank (Eds.), *Proceedings of Graphics Interface 2007 on - GI '07* (p. 95). ACM Press. https://doi.org/10.1145/1268517.1268535

Götz, M. (2007). *Die Gestaltung von Bedienelementen unter dem Aspekt ihrer kommunikativen Funktion* [Dissertation]. Technische Universität München [Fakultät für Maschinenwesen]. Retrieved March 13, 2018, from https://mediatum.ub.tum.de/632979

Grane, C., & Bengtsson, P. (2012). Haptic addition to a visual menu selection interface controlled by an in-vehicle rotary device. *Advances in Human-Computer Interaction*, *2012*(2), 1–12. https://doi.org/10.1155/2012/787469

Grane, C., & Bengtsson, P. (2013). Driving performance during visual and haptic menu selection with in-vehicle rotary device. *Transportation Research Part F: Traffic Psychology and Behaviour*, *18*, 123–135. https://doi.org/10.1016/j.trf.2012.12.011

Gregory, R. L. (1980). Perceptions as Hypotheses. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *290*(1038), 181–197. http://www.jstor.org/stable/2395424

Grunwald, M. (2008). *Human Haptic Perception: Basics and Applications*. Birkhäuser Basel. https://doi.org/10.1007/978-3-7643-7612-3

Grunwald, M. (2017). *Homo hapticus: Warum wir ohne Tastsinn nicht leben können*. Droemer.

Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education*, *57*(4), 2281–2290. https://doi.org/10.1016/j.compedu.2011.06.012

Harrison, C., & Hudson, S. E. (2009). Providing dynamically changeable physical buttons on a visual display. In D. R. Olsen, R. B. Arthur, K. Hinckley, M. R. Morris, S. Hudson, & S. Greenberg (Eds.), *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09* (p. 299). ACM Press. https://doi.org/10.1145/1518701.1518749

Hayward, V., & MacLean, K. E. (2007). Do it yourself haptics: part I. *IEEE Robotics & Automation Magazine*, *14*(4), 88–104. https://doi.org/10.1109/M-RA.2007.907921

Heijboer, S., Breitschaft, S. J., & Carbon, C.-C. (2019a). Characterization of Active Haptic Feedback for User Interface Design and Development [Work in Progress Paper & Poster Presentation]. In *IEEE World Haptics Conference 2019, Tokyo, Japan*. IEEE.

Heijboer, S., Schumann, J., Tempelman, E., & Groen, P. (2019b). Physical fights back. In C. P. Janssen, S. F. Donker, L. L. Chuang, & W. Ju (Eds.), *Automotive UI '19: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct Proceedings - AutomotiveUI '19* (pp. 93–98). ACM Press. https://doi.org/10.1145/3349263.3351510

Hekkert, P., & van Dijk, M. (2017). *Vision In Design: A Guidebook for Innovators*. BIS Publishers.

Hoggan, E., Brewster, S. A., & Johnston, J. (2008). Investigating the effectiveness of tactile feedback for mobile touchscreens. In M. Czerwinski, A. Lund, & D. Tan (Eds.), *Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems - CHI '08* (p. 1573). ACM Press. https://doi.org/10.1145/1357054.1357300

Ishii, H. (2008). Tangible bits: Beyond pixels. In A. Schmidt, H. Gellersen, E. van den Hoven, A. Mazalek, P. Holleis, & N. Villar (Eds.), *Proceedings of the 2nd international conference on Tangible and embedded interaction - TEI '08* (pp. xv–xxv). ACM Press. https://doi.org/10.1145/1347390.1347392

Itti, L. (2007). Visual salience [Scholarpedia, 2(9), 3327]. *Scholarpedia*, *2*(9), 3327. https://doi.org/10.4249/scholarpedia.3327

Jakesch, M., & Carbon, C.-C. (2011). Humans prefer curved objects on basis of haptic evaluation. *Perception*, *40*(1_suppl), 1–239. https://doi.org/10.1177/03010066110400S102

Jakesch, M., Zachhuber, M., Leder, H., Spingler, M., & Carbon, C.-C. (2011). Scenario-based touching: On the influence of top-down processes on tactile and visual appreciation. *Research in Engineering Design*, *22*(3), 143–152. https://doi.org/10.1007/s00163-010-0102-5

Jones, L. A. (2018). *Haptics*. MIT Press. https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5493344

Jones, L. A., Lederman, S. J., & jones. (2006). *Human hand function*. Oxford University Press. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=215666

Kaaresoja, T. (2015). *Latency guidelines for touchscreen virtual button feedback* [Dissertation]. University of Glasgow [College of Science and Engineering]. Retrieved May 15, 2022, from https://theses.gla.ac.uk/7075/

Kahrimanovic, M., Bergmann Tiest, W. M., & Kappers, A. M. L. (2009). Context effects in haptic perception of roughness. *Experimental Brain Research*, *194*(2), 287–297. https://doi.org/10.1007/s00221-008-1697-x

Kappers, A. M. L., & Bergmann Tiest, W. M. (2015a). Aftereffects in touch. *Scholarpedia*, *10*(3), 32730. https://doi.org/10.4249/scholarpedia.32730

Kappers, A. M. L., & Bergmann Tiest, W. M. (2015b). Haptic saliency. *Scholarpedia*, *10*(4), 32734. https://doi.org/10.4249/scholarpedia.32734

Kim, E., & Schneider, O. (2020). Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX. *CHI '20: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–13. https://doi.org/10.1145/3313831.3376280

Kim, H., Kwon, S., Heo, J., Lee, H., & Chung, M. K. (2014). The effect of touch-key size on the usability of In-Vehicle Information Systems and driving safety during simulated driving. *Applied Ergonomics*, *45*(3), 379–388. https://doi.org/10.1016/j.apergo.2013.05.006

Klatzky, R. L., & Lederman, S. J. (1993). Toward a computational model of constraint-driven exploration and haptic object identification. *Perception*, *22*(5), 597–621. https://doi.org/10.1068/p220597

Klatzky, R. L., & Lederman, S. J. (1995). Identifying objects from a haptic glance. *Perception & psychophysics*, *57*(8), 1111–1123.

Klatzky, R. L., Pawluk, D., & Peer, A. (2013). Haptic perception of material properties and implications for applications. *Proceedings of the IEEE*, *101*(99), 2081–2092. https://doi.org/10.1109/JPROC.2013.2248691

Klatzky, R. L., & Peck, J. (2012). Please touch: Object properties that invite touch. *IEEE Transactions on Haptics*, *5*(2), 139–147. https://doi.org/10.1109/TOH.2011.54

Klatzky, R. L., & Reed, C. (2009). Haptic exploration. *Scholarpedia*, *4*(8), 7941. https://doi.org/10.4249/scholarpedia.7941

Klein, K. (2022). Rethinking Touch HMI Controls for Automotive Displays and Smart Surfaces. *Information Display*, *38*(1), 24–29. https://doi.org/10.1002/msid.1274

Koffka, K. (1935). *Principles of Gestalt Psychology*. Harcourt, Brace and Company.

Kühner, M. (2014). *Haptische Unterscheidbarkeit mechanischer Parameter bei rotatorischen Bedienelementen* [Dissertation]. Technische Universität München [Fakultät für Maschinenwesen]. Retrieved April 26, 2018, from https://mediatum.ub.tum.de/?id=1145031

Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: a tutorial. *Attention, Perception & Psychophysics*, *71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9

Lederman, S. J., & Klatzky, R. L. (1997). Relative availability of surface and object properties during early haptic processing. *Journal of Experimental Psychology: Human perception and performance*, *23*(6), 1680.

Levesque, V., Oram, L., & MacLean, K. E. (2012). Exploring the design space of programmable friction for scrolling interactions. *2012 IEEE Haptics Symposium (HAPTICS)*, 23–30. https://doi.org/10.1109/HAPTIC.2012.6183765

Levesque, V., Oram, L., MacLean, K. E., Cockburn, A., Marchuk, N. D., Johnson, D., Colgate, J. E., & Peshkin, M. A. (2011). Enhancing physicality in touch interaction with programmable friction. In D. Tan, G. Fitzpatrick, C. Gutwin, B. Begole, & W. A. Kellogg (Eds.), *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11* (p. 2481). ACM Press. https://doi.org/10.1145/1978942.1979306

Linjama, J. T., & Mäkinen, V. (2009). E-Sense screen: Novel haptic display with Capacitive Electrosensory Interface [Demo Presentation]. In M. E. Altinsoy, U. Jekosch, & S. Brewster (Eds.), *Haptic and Audio Interaction Design: 4th International Conference, HAID 2009 Dresden, Germany, September 10-11, 2009 Proceedings*. Springer Berlin Heidelberg.

Lust, M., & Schaare, R. (2016). Bedienoberflächen mit aktivem haptischem Feedback. *ATZ - Automobiltechnische Zeitschrift*, *118*(6), 48–53. https://doi.org/10.1007/s35148-016-0043-z

Maciej, J., & Vollrath, M. (2009). Comparison of manual vs. speech-based interaction with in-vehicle information systems. *Accident; analysis and prevention*, *41*(5), 924–930. https://doi.org/10.1016/j.aap.2009.05.007

MacLean, K. E. (2008). Haptic interaction design for everyday interfaces. *Reviews of Human Factors and Ergonomics*, *4*(1), 149–194. https://doi.org/10.1518/155723408X342826

MacLean, K. E., & Hayward, V. (2008). Do It Yourself Haptics: Part II [Tutorial]. *IEEE Robotics & Automation Magazine*, *15*(1), 104–119. https://doi.org/10.1109/M-RA.2007.914919

Minogue, J., & Jones, M. G. (2006). Haptics in Education: Exploring an Untapped Sensory Modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317

Mlakar, S., & Haller, M. (2020). Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces. *Proceedings of CHI '20: CHI Conference on Human Factors in Computing Systems (CHI '20)*, 1–10.

Moussette, C. (2012). *Simple haptics: Sketching perspectives for the design of haptic interactions* (Vol. 1). Umeå Institute of Design, Umeå University.

Mueller, S. (2016). *Das optimale Bedienelement und der optimale Bedienort für eine Nutzerfunktion* [Dissertation]. Technische Universität München [Fakultät für Maschinenwesen]. Retrieved March 13, 2018, from https://mediatum.ub.tum.de/node?id=1227514

Mullenbach, J., Shultz, C., Piper, A. M., Peshkin, M., & Colgate, J. E. (2013a). Surface haptic interactions with a TPad tablet. In S. Izadi, A. Quigley, I. Poupyrev, & T. Igarashi (Eds.), *Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology - UIST '13 Adjunct* (pp. 7–8). ACM Press. https://doi.org/10.1145/2508468.2514929

Mullenbach, J., Blommer, M., Colgate, J. E., & Peshkin, M. A. (2013b). *Reducing Driver Distraction with Touchpad Physics* [Master Thesis]. Northwestern University. Retrieved April 30, 2023, from https://robotics.northwestern.edu/documents/publications/Mullenbach_Masters_Thesis_Final.pdf

National Highway Traffic Safety Administration (Ed.). (2016). Human factors design guidance for driver-vehicle interfaces. Retrieved March 25, 2022, from https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/812360_humanfactorsdesignguidance.pdf

Norman, D. A. (2007). *The Design of Future Things*. Basic Books. http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10533389

Norman, D. A. (2008). Signifiers, not Affordances. *Interactions*, *15*(6), 18. https://doi.org/10.1145/1409040.1409044

Norman, D. A. (2013). *The Design of Everyday Things: Revised and expanded edition*. Basic Books.

O'Halloran, A., O'Malley, F., & McHugh, P. (2008). A review on dielectric elastomer actuators, technology, applications, and challenges. *Journal of Applied Physics*, *104*(7), 071101. https://doi.org/10.1063/1.2981642

Ortlieb, S. A., Kügel, W. A., & Carbon, C.-C. (2020). Fechner (1866): The Aesthetic Association Principle—A Commented Translation. *i-Perception*, *11*(3), 204166952092030. https://doi.org/10.1177/2041669520920309

Osgouei, R. H. (2020). Electrostatic Friction Displays to Enhance Touchscreen Experience. In *Modern Applications of Electrostatics and Dielectrics* (Vol. 4). IntechOpen. https://doi.org/10.5772/intechopen.91056

Palani, H. P., Fink, P. D. S., & Giudice, N. A. (2020). Design Guidelines for Schematizing and Rendering Haptically Perceivable Graphical Elements on Touchscreen Devices. *International Journal of Human–Computer Interaction*, *36*(15), 1393–1414. https://doi.org/10.1080/10447318.2020.1752464

Palani, H. P., & Giudice, N. A. (2016). Usability parameters for touchscreen-based haptic perception [Work In Progress Paper Presentation]. *2016 IEEE Haptics Symposium (HAPTICS)*. Retrieved June 20, 2019, from https://umaine.edu/vemi/publication/usability-parameters-touchscreen-based-haptic-perception/

Pallasmaa, J. (2012). *The eyes of the skin: Architecture and the senses* (3. ed.). Wiley.

Parisi, D. H. (2018). *Archaeologies of touch: Interfacing with haptics from electricity to computing*. University of Minnesota Press. https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1614001

Peck, J., & Childers, T. (2003). Individual Differences in Haptic Information Processing: The "Need for Touch" Scale. *Journal of Consumer Research*, *30*(3), 420–442.

Petermeijer, S. M., Abbink, D. A., Mulder, M., & de Winter, J. C. F. (2015). The effect of haptic support systems on driver performance: A Literature Survey. *IEEE Transactions on Haptics*, *8*(4), 467–479. https://doi.org/10.1109/TOH.2015.2437871

Pielot, M., Kazakova, A., Hesselmann, T., Heuten, W., & Boll, S. (2012). PocketMenu. In E. Churchill, S. Subramanian, P. Baudisch, & K. O'Hara (Eds.), *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services - MobileHCI '12* (p. 327). ACM Press. https://doi.org/10.1145/2371574.2371624

Pitts, M. J., Burnett, G., Skrypchuk, L., Wellings, T., Attridge, A., & Williams, M. A. (2012a). Visual–haptic feedback interaction in automotive touchscreens. *Displays*, *33*(1), 7–16. https://doi.org/10.1016/j.displa.2011.09.002

Pitts, M. J., Burnett, G., Williams, M. A., & Wellings, T. (2010). Does haptic feedback change the way we view touchscreens in cars? *ICMI-MLMI '10: International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction*, *38*, 1–4. https://doi.org/10.1145/1891903.1891952

Pitts, M. J., Skrypchuk, L., Wellings, T., Attridge, A., & Williams, M. A. (2012b). Evaluating user response to in-car haptic feedback touchscreens using the lane change test. *Advances in Human-Computer Interaction*, *2012*(1), 1–13. https://doi.org/10.1155/2012/598739

Pitts, M. J., Williams, M. A., Wellings, T., & Attridge, A. (2009). Assessing subjective response to haptic feedback in automotive touchscreens. *Automotive UI '09: Proceedings of the 1st international Conference on Automotive User interfaces and interactive Vehicular Applications*, 11–18. https://doi.org/10.1145/1620509.1620512

Ranaweera, A. T., Martin, B. A. S., & Jin, H. S. (2021). What you touch, touches you: The influence of haptic attributes on consumer product impressions. *Psychology & Marketing*, *38*(1), 183–195. https://doi.org/10.1002/mar.21433

Reed, C. L., & Ziat, M. (2018). Haptic Perception: From the Skin to the Brain. In *Reference Module in Neuroscience and Biobehavioral Psychology*. Elsevier. https://doi.org/10.1016/B978-0-12-809324-5.03182-5

Reisinger, J. (2009). *Parametrisierung der Haptik von handbetätigten Stellteilen* [Dissertation]. Technische Universität München [Fakultät für Maschinenwesen]. Retrieved March 26, 2018, from https://mediatum.ub.tum.de/654165

Richter, H., Ecker, R., Deisler, C., & Butz, A. (2010). HapTouch and the 2+1 state model. *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 72–79. https://doi.org/10.1145/1969773.1969787

Rösler, F., Battenberg, G., & Schüttler, F. (2009). Subjektive Empfindungen und objektive Charakteristika von Bedienelementen. *ATZ - Automobiltechnische Zeitschrift*, *111*(4), 292–297. https://doi.org/10.1007/BF03222068

Rümelin, S. (2014). *The cockpit for the 21st century: exploring large and shaped interactive surfaces for direct interaction.* [Dissertation]. Ludwig-Maximilians-Universität München. https://edoc.ub.uni-muenchen.de/17428/1/Ruemelin_Sonja.pdf

Rümelin, S., & Butz, A. (2013). How to make large touch screens usable while driving. In J. Terken (Ed.), *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '13* (pp. 48–55). ACM Press. https://doi.org/10.1145/2516540.2516557

Rydström, A., Grane, C., & Bengtsson, P. (2009). Driver behaviour during haptic and visual secondary tasks. *Automotive UI '09: Proceedings of the 1st international Conference on Automotive User interfaces and interactive Vehicular Applications*, 121–127. https://doi.org/10.1145/1620509.1620533

Schandry, R. (2016). *Biologische Psychologie: Mit Online-Material* (4., überarbeitete Auflage). Beltz. http://sub-hh.ciando.com/book/?bok_id=2121934

Schneider, O., MacLean, K. E., Swindells, C., & Booth, K. (2017). Haptic experience design: What hapticians do and where they need help. *International Journal of Human-Computer Studies*, *107*, 5–21. https://doi.org/10.1016/j.ijhcs.2017.04.004

Shultz, C., Peshkin, M. A., & Colgate, J. E. (2015). Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek. *2015 IEEE World Haptics Conference (WHC)*, 57–62. https://doi.org/10.1109/WHC.2015.7177691

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic bulletin & review*, *20*(1), 21–53. https://doi.org/10.3758/s13423-012-0333-8

Skedung, L., Arvidsson, M., Chung, J. Y., Stafford, C. M., Berglund, B., & Rutland, M. W. (2013). Feeling small: Exploring the tactile perception limits. *Scientific reports*, *3*, 2617. https://doi.org/10.1038/srep02617

Sreelakshmi, M., & Subash, T. D. (2017). Haptic Technology: A comprehensive review on its applications and future prospects. *Materials Today: Proceedings*, *4*(2), 4182–4187. https://doi.org/10.1016/j.matpr.2017.02.120

Thornbury, J. M., & Mistretta, C. M. (1981). Tactile sensitivity as a function of age. *Journal of gerontology*, *36*(1), 34–39. https://doi.org/10.1093/geronj/36.1.34.

Tikka, V., & Laitinen, P. (2006). Designing Haptic Feedback for Touch Display: Experimental Study of Perceived Intensity and Integration of Haptic and Audio. In D. McGookin & S. Brewster (Eds.), *Haptic and Audio Interaction Design: First International Workshop, HAID 2006* (pp. 36–44). Springer.

Tivadar, R. I., Arnold, R. C., Turoman, N., Knebel, J.-F., & Murray, M. M. (2022). Digital haptics improve speed of visual search performance in a dual-task setting. *Scientific reports*, *12*(1), 9728. https://doi.org/10.1038/s41598-022-13827-5

Tokatli, O., Tracey, M., Hwang, F., Barrett, N., Jones, C., Johnson, R., Webb, M., & Harwin, W. (2018). A Classroom Deployment of a Haptic System for Learning Cell Biology. In D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, & A. Frisoli (Eds.), *Haptics: Science, Technology, and Applications* (pp. 379–389, Vol. 10894). Springer International Publishing. https://doi.org/10.1007/978-3-319-93399-3_33

Tremblay, F., & Master, S. (2015). Touch in aging. *Scholarpedia*, *10*(2), 9935. https://doi.org/10.4249/scholarpedia.9935

Tsetserukou, D. (2010). HaptiHug: A Novel Haptic Display for Communication of Hug over a Distance. In A. M. L. Kappers, J. B. F. van Erp, W. M. Bergmann Tiest, & F. C. T. van der Helm (Eds.), *Haptics: Generating and Perceiving Tangible Sensations* (pp. 340–347). Springer Berlin Heidelberg.

Tsetserukou, D., Neviarouskaya, A., Prendinger, H., Kawakami, N., Ishizuka, M., & Tachi, S. (2009). iFeel_IM! Emotion Enhancing Garment for Communication in Affect Sensitive Instant Messenger. In M. J. Smith & G. Salvendy (Eds.), *Human Interface and the Management of Information. Designing Information Environments* (pp. 628–637, Vol. 5617). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-02556-3_71

Tunca, E., Fleischer, R., Schmidt, L., & Tille, T. (2016). Advantages of active haptics on touch surfaces. *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 137–144. https://doi.org/10.1145/3003715.3005406

Tunca, E., Zoller, I., & Lotz, P. (2018). An Investigation into Glance-free Operation of a Touchscreen With and Without Haptic Support in the Driving Simulator. *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 332–340. https://doi.org/10.1145/3239060.3239077

Väänänen-Vainio-Mattila, K., Heikkinen, J., Farooq, A., Evreinov, G., Mäkinen, E., & Raisamo, R. (2014). User experience and expectations of haptic feedback in in-car interaction. In S. Loke, A. Zaslavsky, L. Kulik, & E. Pitoura (Eds.), *Proceedings of the 13th International Conference on Mobile and Ubiquitous Multimedia (MUM 2014): 25-27 November, Melbourne, Australia* (pp. 248–251). ACM. https://doi.org/10.1145/2677972.2677996

van Erp, J. B. F., & Toet, A. (2015). Social Touch in Human-Computer Interaction. *Frontiers in Digital Humanities*, *2*(3), 603. https://doi.org/10.3389/fdigh.2015.00002

van Erp, J. B., & van Veen, H. (2001). Vibro-tactile information presentation in automobiles. *Proceedings of Eurohaptics*, *2001*, 99–104.

Vardar, Y. (2020). *Tactile Perception by Electrovibration*. Springer Nature. https://link.springer.com/book/10.1007/978-3-030-52252-0

Vardar, Y., Guclu, B., & Basdogan, C. (2018). Tactile Masking by Electrovibration. *IEEE Transactions on Haptics*, *11*(4), 623–635. https://doi.org/10.1109/TOH.2018.2855124

Vezzoli, E., Ullrich, C., den Butter, G., & Pijewski, R. (2022). *XR Haptics: Implementation & Design Guidelines ; with Enterprise VR application areas, use cases, and implementation examples*. Bowker identifier services.

Vollrath, M., & Krems, J. F. (2011). *Verkehrspsychologie: Ein Lehrbuch für Psychologen, Ingenieure und Informatiker* (1. Aufl.). Kohlhammer.

Weber, B., & Eichberger, C. (2015). The Benefits of Haptic Feedback in Telesurgery and Other Teleoperation Systems: A Meta-Analysis. In M. Antona & C. Stephanidis (Eds.), *Universal Access in Human-Computer Interaction. Access to Learning, Health and Well-Being* (pp. 394–405, Vol. 9177). Springer International Publishing. https://doi.org/10.1007/978-3-319-20684-4_39

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. *The skin senses*, 195–222.

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, *88*(3), 638–667. https://doi.org/10.1037/0033-2909.88.3.638

Wellings, T., Williams, M., & Tennant, C. (2010). Understanding customers' holistic perception of switches in automotive human-machine interfaces. *Applied Ergonomics*, *41*(1), 8–17. https://doi.org/10.1016/j.apergo.2009.03.004

Wellings, T., Williams, M. A., & Pitts, M. J. (2008). Customer perception of switch-feel in luxury sports utility vehicles. *Food Quality and Preference*, *19*(8), 737–746. https://doi.org/10.1016/j.foodqual.2008.03.004

Wigdor, D., & Wixon, D. (2011). *Brave NUI world: Designing natural user interfaces for touch and gesture*. Elsevier; Morgan Kaufmann.

Winfield, L., Glassmire, J., Colgate, J. E., & Peshkin, M. (2007). T-PaD: Tactile Pattern Display through Variable Friction Reduction. *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, 421–426. https://doi.org/10.1109/WHC.2007.105

Zhang, Y., & Harrison, C. (2015). Quantifying the Targeting Performance Benefit of Electrostatic Haptic Feedback on Touchscreens. In N. Nunes, E. Costanza, P. Olivier, & J. Schöning (Eds.), *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces - ITS '15* (pp. 43–46). ACM Press. https://doi.org/10.1145/2817721.2817730

Online References

ADAC. (2022). *Ablenkung im Auto: Wenn die Bedienung zur Gefahr wird*. ADAC e.V. Retrieved July 26, 2022, from https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/ausstattung/ablenkung-durch-bedienelemente/#das-ziel-bedienung-muss-intuitiv-sein

Aito. (2016). *Faurecia and Aito showcase 'Cockpit of the Future' at Paris Motor Show*. Retrieved April 16, 2020, from https://aito-touch.com/faurecia-and-aito-showcase-cockpit-future-paris-motor-show

Alps Alpine. (2021). *HAPTIC COMMANDER™*. Retrieved March 19, 2022, from https://tech.alpsalpine.com/e/info/technology/tec_haptic/hapticcommander/

Apple. (2020a). *Human Interface Guidelines: Haptics*. Retrieved January 27, 2021, from https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/haptics/

Apple. (2020b). *iPod-Modell bestimmen*. Retrieved April 7, 2020, from https://support.apple.com/de-de/HT204217

Arcadeo Gaming. (2021). *The world's First Connected Gaming Chair*. Retrieved March 8, 2021, from https://www.arcadeo.com/

Audi AG. (2020). *Haptisches und akustisches Feedback einstellen*. Retrieved November 10, 2020, from https://www.audi.de/de/brand/de/erklaervideos/layer/a8-feedback.html

Baker, J. (2019). *Haptic UX — The Design Guide for Building Touch Experiences*. Retrieved September 3, 2022, from https://medium.muz.li/haptic-ux-the-design-guide-for-building-touch-experiences-84639aa4a1b8

bHaptics. (2021). *TactSuit X40*. Retrieved January 20, 2021, from https://www.bhaptics.com/

BMW Group. (2013). *Functional Bookmarks | BMW Genius How-To*. Retrieved March 14, 2022, from https://www.youtube.com/watch?v=b_CZaR9uvgA

BMW Group. (2021). *The all-new BMW iDrive.* Retrieved March 15, 2021, from https://www.press.bmwgroup.com/global/article/detail/T0327315EN/the-all-new-bmw-idrive?language=en

BMW Group. (2023). *BMW i Vision Dee - The Ultimate Companion*. Retrieved January 20, 2023, from https://www.bmw.de/de/topics/faszination-bmw/bmw-concept-cars/bmw-vision-ivisiondee-2023.html

Boreas Technologies. (2020a). *Guidelines of Haptic UX Design*. Retrieved September 3, 2022, from https://www.boreas.ca/blogs/piezo-haptics/guidelines-of-haptic-ux-design?lang=en

Boreas Technologies. (2020b). *Improve Your Product User Experience With Better Haptics*. Retrieved February 23, 2020, from https://sub.boreas-technologies.ca/ebooks

Bosch. (2015). *Bosch NeoSense Display with haptic feedback*. Retrieved March 20, 2020, from https://www.youtube.com/watch?v=tuRr1cST74Q

Budiu, R. (2019). *Tesla's Touchscreen UI: A Case Study of Car-Dashboard User Interface*. Nielsen Norman Group. Retrieved May 24, 2019, from https://www.nngroup.com/articles/tesla-big-touchscreen/

Budiu, R. (2022). *Fitts's Law and Its Applications in UX*. https://www.nngroup.com/articles/fitts-law/

Consumer Electronics Show. (2020). *Haptic Mobile Phone*. Retrieved March 25, 2022, from https://www.ces.tech/Innovation-Awards/Honorees/2020/Honorees/H/Haptic-Mobile-Phone.aspx

Consumer Electronics Show. (2022). *Piezo Haptic Trackpad Module*. Retrieved March 25, 2022, from https://ces.tech/Innovation-Awards/Honorees/2022/Honorees/P/Piezo-Haptic-Trackpad-Module.aspx

Continental. (2014). *Daimler zeichnet Continental für Touchpad der neuen Mercedes-Benz C-Klasse aus*. Retrieved April 30, 2021, from https://www.continental.com/de/presse/pressemitteilungen/2014-02-28-daimler/

Continental. (2015). *Mehr Sicherheit und Komfort im Auto: Continental präsentiert Touch-Display mit aktiver haptischer Rückmeldung*. Continental. Retrieved March 26, 2022, from https://www.continental.com/de/presse/pressemitteilungen/2015-05-28-innovative-search-haptics-103508

Continental. (2018). *Touch-Display mit 3D-Oberfläche von Continental erhält höchste Auszeichnung des CES Innovation Awards*. Continental. Retrieved March 26, 2022, from https://www.continental.com/de/presse/pressemitteilungen/2018-01-04-3d-touch-display/

Daimler AG. (2018). *Revolution im Cockpit. Mercedes-Benz User Experience*. Retrieved April 30, 2021, from https://www.daimler.com/innovation/case/connectivity/mbux.html

Daimler AG. (2021a). *Der MBUX Hyperscreen erfindet neu, wie wir mit dem Auto interagieren*. Retrieved March 14, 2022, from https://www.youtube.com/watch?v=oTe-rCUJQDs

Daimler AG. (2021b). *The new EQS: MBUX Hyperscreen*. Retrieved March 28, 2021, from https://media.daimler.com/marsMediaSite/en/instance/ko/The-new-EQS-MBUX-Hyperscreen.xhtml?oid=49404868

Daimler AG. (2021c). *Vorgeschmack auf die neue S-Klasse: Das neue MBUX*. Retrieved January 27, 2020, from https://www.mercedes-benz.com/de/innovation/connected/vorgeschmack-auf-die-neue-s-klasse-das-neue-mbux/

Day, L. (2023). *Hyundai Promises To Keep Buttons in Cars Because Touchscreen Controls Are Dangerous*. Retrieved April 23, 2023, from https://www.thedrive.com/news/hyundai-promises-to-keep-buttons-in-cars-because-touchscreen-controls-are-dangerous

DS Automobiles. (2022). *DS 4 | DS SMART TOUCH*. Retrieved March 14, 2022, from https://www.youtube.com/watch?v=6aBsZ4Wa5Uk

Engadget. (2022). *Dell's XPS 13 Plus is simply gorgeous | CES 2022*. Retrieved March 24, 2022, from https://www.youtube.com/watch?v=cvxsgl7X5dA

Google Inc. (2020). *Android Haptics*. Retrieved October 28, 2020, from https://material.io/design/platform-guidance/android-haptics.html#usage

Gruener, W. (2013). *Cadillac CUE: Why a Touch Screen is Not Always a Good Idea*. Retrieved April 30, 2021, from https://www.tomshardware.com/news/cadillac-cue-entertainment-ix-ux,20143.html

Halvorson, B. (2019). *Why Mazda ist purging touchscreens from its vehicles*. Retrieved April 3, 2022, from https://www.motorauthority.com/news/1121372_why-mazda-is-purging-touchscreens-from-its-vehicles

Hap2U. (2020). *Haptic Technology*. Retrieved February 14, 2021, from https://www.hap2u.net/haptic-technology/

Haptics Industry Forum. (2020). *New specification for HD haptics released*. Retrieved February 12, 2022, from https://hapticsif.org/

Haptics Industry Forum. (2021a). *Recommended Practices for Automotive Haptics*. Retrieved March 19, 2022, from https://secureservercdn.net/104.238.71.109/dpf.3ab.myftpupload.com/wp-content/uploads/2021/10/Recommended-Practices-for-Automotive-Haptics.pdf

Haptics Industry Forum. (2021b). *Recommended Practices for Automotive Haptics*. Retrieved January 28, 2022, from https://secureservercdn.net/104.238.71.109/dpf.3ab.myftpupload.com/wp-content/uploads/2021/10/Recommended-Practices-for-Automotive-Haptics.pdf

Hayden, S. (2022). *Meta Acquires Berlin-based Haptic Tech Startup Lofelt*. Retrieved December 27, 2022, from https://www.roadtovr.com/meta-acquires-lofelt-deal-haptics/

Immersion Corporation. (2020). *Active Sensing Technology Automotive TouchScreen Demo*. Retrieved April 30, 2021, from https://www.immersion.com/resource_video/active-sensing-technology-automotive-touchscreen-demo/

Immersion Corporation. (2021). *Creating Digital Touch Devices with Haptic Technology*. Retrieved April 30, 2021, from https://www.youtube.com/watch?v=lw-A7PnQ_fk

Interaction Design Foundation. (2022). *Affordances*. Retrieved August 7, 2022, from https://www.interaction-design.org/literature/topics/affordances

Kessels, C. (2019). *An in-depth look at the UX of the Porsche Taycan*. Retrieved November 2, 2020, from https://uxdesign.cc/an-in-depth-look-at-the-ux-design-of-the-porsche-taycan-540254d6d996

Kolesárová, L. (2018). *Designing For The Tactile Experience*. Retrieved September 3, 2022, from https://www.smashingmagazine.com/2018/04/designing-tactile-experience/

Kyocera Corporation. (2018). *Haptivity: Virtual reality for mechanical button feeling*. KYOCERA Fineceramics GmbH. Retrieved January 27, 2021, from http://www.kyocera.eu/index/products/lcds_glass_glass_touch_panels/haptivity.html

Lofelt. (2020). *Introducing Lofelt Studio*. Retrieved January 15, 2022, from https://www.youtube.com/watch?v=HfB2YM1-ouE&ab_channel=Lofelt

LoPresti, P. (2020). *Surface Haptics: A Safer Way for Drivers to Operate Smooth-Surface Controls*. Electronic Design. Retrieved January 27, 2021, from https://www.electronicdesign.com/markets/automotive/article/21145025/surface-haptics-a-safer-way-for-drivers-to-operate-smoothsurface-controls

Mimo Monitors. (2022). *TanvasTouch*. Retrieved March 19, 2022, from https://www.mimomonitors.com/collections/tanvastouch-products

mobile.de. (2020). *Bedienkonzepte im Auto: Mehr als die Hälfte möchte weiterhin Knöpfe und Regler*. Retrieved November 24, 2020, from https://newsroom.mobile.de/bedienkonzepte-im-auto-mehr-als-die-haelfte-moechte-weiterhin-knoepfe-und-regler/

Moreno, M., & Weddle, A. B. (2013). *The Value of Multimodal Feedback in Automotive User Interfaces* (Immersion Corporation, Ed.). Retrieved April 14, 2022, from https://www.immersion.com/wp-content/uploads/2015/10/multimodal-value_auto-UI_aug13v1.pdf

Motor1. (2011). *Cadillac unveils new CUE infotainment system*. Retrieved December 1, 2020, from https://www.youtube.com/watch?v=CB_FmEfedA0

Nissan Motor Co. (2021). *The power of touch*. Retrieved March 19, 2022, from https://global.nissanstories.com/en/releases/ariya-haptic

Porsche AG. (2017). *Digital evolution: Porsche Advanced Cockpit and new PCM*. Retrieved April 30, 2021, from https://newsroom.porsche.com/en/products/porsche-cayenne-2017-interior-advanced-cockpit-pcm-connectivity-third-generation-suv-14079.html

Punchcut. (2020). *The Tactile Era: 10 Principles for Haptic Design*. Retrieved September 3, 2020, from https://medium.com/punchcut/the-tactile-era-10-principles-for-haptic-design-49bb70b2f569

Rao, S. (2012). *High-definition haptics: Feel the difference!* Texas Instruments Incorporated. http://www.ti.com/lit/an/slyt483/slyt483.pdf

Razer. (2021). *Razer Hypersense*. Retrieved March 15, 2021, from https://www.razer.com/de-de/technology/razer-hypersense

SenseGlove. (2021). *SenseGlove Nova*. Retrieved March 15, 2021, from https://www.senseglove.com/

Shultz, C. (2020). *Surface haptics technology enriches touchscreen interactions*. EDN. Retrieved October 29, 2020, from https://www.edn.com/surface-haptics-technology-enriches-touchscreen-interactions/

Stein, S. (2021). *Meta wants you to feel the metaverse with high-tech haptic gloves*. Retrieved March 25, 2022, from https://www.cnet.com/tech/computing/meta-wants-you-to-feel-the-metaverse-with-high-tech-haptic-gloves/

Stockburger, C. (2013). "*Touchscreens sind unmännlich*". Der Spiegel. Retrieved April 1, 2020, from https://www.spiegel.de/auto/fahrkultur/interview-mit-martin-grunwald-ueber-haptik-design-im-auto-a-895416.html

Tanvas. (2020a). *Tanvas: Touch the next level*. Retrieved January 27, 2021, from https://tanvas.co/

Tanvas. (2020b). *TanvasTouch for Automotive Video Demo*. Retrieved April 27, 2021, from https://tanvas.co/blog/tanvastouch-for-automotive-video-demo

Tanvas. (2022a). *Tanvas innovates with surface haptic solutions for flexible AMOLED displays*. Retrieved March 19, 2022, from https://tanvas.co/press-releases/tanvas-innovates-with-surface-haptic-solutions-for-flexible-amoled-displays

Tanvas. (2022b). *TanvasTouch Dev Kit: Create a Sensation!* Retrieved March 19, 2022, from https://tanvas.co/products/tanvastouch-dev-kit

Teslasuit. (2021). *TeslaSuit - The Suit*. Retrieved March 15, 2021, from https://teslasuit.io/the-suit/

Tsui, C. (2020). *Long Live Buttons: Honda's Not Sold On Touchscreens*. Retrieved April 3, 2022, from https://www.thedrive.com/tech/32797/long-live-buttons-hondas-not-sold-on-touchscreens

van de Bruggen, H. (2022). *Is Tesla's v11 update... bad design?* Medium. Retrieved December 30, 2022, from https://medium.com/geekculture/is-teslas-v11-update-bad-design-1af36b13228b

Warren, T. (2020). *The PS5's new controller is amazing — here's how it works*. Retrieved March 24, 2022, from https://www.theverge.com/2020/11/3/21547303/sony-ps5-dualsense-adaptive-triggers-haptics-teardown-features

Weddle, A. B., & Yu, H. (2013). *Confirmation haptics for automotive interfaces: Cadillac CUE User Study*. Immersion Corporation. Retrieved January 9, 2019, from https://www.immersion.com/wp-content/uploads/2015/10/CUE-whitepaper_jun13v1.pdf

Weddle, A. B., Yu, H., & Moreno, M. (2013). *UX impacts of haptic latency in automotive interfaces: Literature Review and User Study*. Immersion Corporation. Retrieved January 15, 2019, from https://pdfs.semanticscholar.org/de7c/0c19188642cc925c256608f048163ea5973d.pdf

Zipper, D. (2023). *The Glorious Return of a Humble Car Feature*. Retrieved April 30, 2023, from https://slate.com/business/2023/04/cars-buttons-touch-screens-vw-porsche-nissan-hyundai.html

Appendix A

The contributions are listed in the order reported in the thesis.

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PHYSICAL FIGHTS BACK: PERCEPTION FRAMEWORK FOR HAPTIC PRACTITIONERS IN USER INTERACTION DESIGN

HAPTIC PRACTITIONERS.

Haptic feedback is an inherent part of future, seamless user interfaces. From the ever-growing list of companies and startups to the thriving and diverse community of engineers, psychologists, and designers, the moment for haptics and touch-based feedback has arrived. Yet, the abundance of review papers on haptic feedback fail to give an application-based overview of haptic technologies for practitioners. Mostly, they offer either a very broad approach to haptic feedback [1] or focus on specific domains, such as technical details [2] or specific application areas (e.g. automotive), lacking contextual, emotional and application-focused details [3].

HAPTIC FIDELITY FRAMEWORK.

As shown below in figure 1, we propose three categories (low, medium and high fidelity) of haptic technologies based on capabilities that haptic actuators have in order to vibrate, simulate, or augment information from a perceptual point of view. While a morphing surface (MS) can act as a magnified texture (HF), it can create also create surface vibrations (LF) when used dynamically.

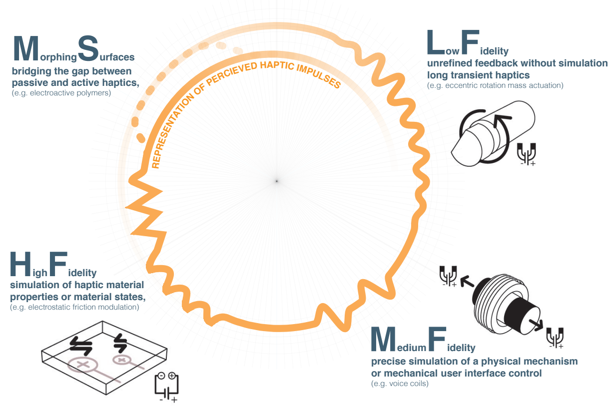

Fig. 1: Graphical representation of perceived haptic impulses (orange line) within the haptic fidelity framework.

OVERARCHING EXPERIENTAL-PERCEPTION BASED MODEL.

To create a practical review of current commercially available technologies we seek to provide a perception-based technology selection method for practitioners that considers engineering, psychophysical, and design perspectives. This method will enable practitioners to label their interaction requirements to a haptic perception – improving the selection of appropriate haptic effect and technology. A preliminary setup for a hierarchy tree will give ground for further discussion on how to incorporate emotional, engineering, and interaction requirements of a product into a common set of selection criteria, creating a practical haptic design guide that links product emotions and psychophysical effects to technologies and their hardware integration and settings.

REFERENCES.

[1] Sreelakshmi, M., & Subash, T. D. (2017). Haptic Technology: A comprehensive review on its applications and future prospects. *Materials Today*: Proceedings, 4(2), 4182–4187. doi: 10.1016/j.matpr.2017.02.120

[2] Biswas, S., & Visell, Y. (2019). Emerging Material Technologies for Haptics. Advanced Materials Technologies, 4(4), 1900042. doi: 10.1002/admt.201900042

[3] Carbon, C.-C. (2019). Psychology of Design. Design Science, 5, 339. doi: 10.1017/dsj.2019.25

BUT WE NEED YOUR INPUT!!

CONSIDER CONTRIBUTING TO OUR CONTINUED RESEARCH BY, SCANNING THE QR-CODE, FILLING IN THE FOLLOWING SHORT SURVEY (5 QUESTIONS) AND AFTERWARDS JOIN AN ONLINE DISCUSSION

Fig. 2: Hypothetical order of influence in the haptic desicion making

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A.2 Haptic Fidelity Framework: A Qualitative Overview and Categorization of Cutaneous-based Haptic Technologies Through Fidelity

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The Haptic Fidelity Framework:
A Qualitative Overview and Categorization of Cutaneous-based Haptic Technologies Through Fidelity

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Abstract — **After decades of research and development, haptic feedback is increasingly appearing in consumer products. While the prevalence of haptic feedback is increasing, the integration rarely offers increased fidelity to previous generations. We argue this is because of the tremendous complexity of successful haptic design engineering, but critically, also because of information saturation. With novel cutaneous feedback technologies and companies emerging almost daily, the multi-disciplinary nature of haptics and the marketing-driven terminology used to stand out in a crowded market makes it challenging to select and integrate actuators correctly.**

To manage this complexity and facilitate the interdisciplinary exchange of user requirements and material affordances, we introduce a novel classification criterion for haptic actuators focused on the bandwidth and fidelity of potential effects. We introduce vocabulary for describing the precise experience the actuators and corresponding systems should deliver. This same criterion and language can also prove valuable for steering near-future technology development of new and improved actuators and enabling novice and experienced practitioners to understand and integrate cutaneous feedback in their products.

Index Terms — **Haptic Feedback, Haptic Technology, Interaction Design, Vibrotactile Feedback, Surface Haptics, Haptic Experience**

I. Introduction

The field of haptics is experiencing growth unlike ever before. The average haptic practitioner's background is shifting towards user interaction (UI) and user experience (UX) rather than the psychophysics or roboticist academic community. While haptics is a small part of modern product UI and UX, they are increasingly relied upon to "close the loop" and confirm an action or add tactile information to an action. Haptic startups are increasingly winning prizes and admiration at trade shows, like the Consumer Electronics Show (CES), indicating a growing interest in haptic feedback in both the business and consumer markets [1], [2]. With the current combined market valued between $7B to $19B and with predicted growth of 7-16% expected year to year through 2026, demand shows little sign of abating [3].

Part of this growth is from technological advances in actuator technology and part of this growth is driven by a paradigm shift in interface design– with flat, glass touchscreens increasingly being the default. One of the great contradictions in modern interface design is that we are in the age of flat, formless, featureless displays, yet touch perception has never been more critical. Designers have traded physical knobs and buttons for virtual, two-dimensional interface elements. This surface featurelessness has led to a fusion of interactive and non-interactive surfaces in products, with haptic features playing a pivotal role in distinguishing interactive and non-interactive surfaces. The challenge of converting virtual/digital objects into feel-able items with active haptic technologies is an increasingly diversified pool of hapticians. Thus, many practitioners find themselves overwhelmed with literature that primarily focuses on the "what and how" - or the usability and the technical aspect. Additionally, little guidance is available on the "why," leading to the question of "How can we create compelling touch interactions?"

The haptics industry has only recently begun to come together and discuss a standard set of technical metrics and requirements to standardize high-definition haptic feedback [4]. Herein lies the problem we aim to solve in this paper: providing a new starting point for those entering the discipline, starting not at the actuator [5] or around perception science [6], [7] but instead on experience, fidelity, and interaction design [8], [9], [10].

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II. Towards a User Experience-Centric Categorization of Haptic Technology

There are plenty of recent review papers on haptic technology in the literature. Yet, they do not fully address an up-to-date overview of commercially available haptic technologies that practitioners can implement.

In contrast to previous papers that have classified haptics by physical principles, technical operating principles, or even technical parameters, we propose a framework based on a psychological/perceptual-driven approach. We categorize technologies based on their fidelity and bandwidth for displaying a haptic feedback signal or set of signals [11].

The focus of currently available reviews is either a) overly broad, with a focus on terminology and application areas of haptics in general [12], b) tailored to a particular field of application, such as robotics or automotive [13], c) focused on specific types of haptic actuator technologies, such as dielectric elastomers [14] or novel haptic actuation materials [15], d) focused on particular perceptual phenomena – e.g., haptic technologies that can be used to create artificial touch sensations [16] or e) an overview/review from a haptic company in the form of self-published white papers [17], [18], [19]. Besides missing links towards application and integration, most reviews also focus on research devices rather than technologies with a mature status [20].

Banter's review on haptic enriched touchscreens and touch surfaces is one of the most recent overview papers on commercially available technologies [21]. However, overviews on haptic technologies are outdated very quickly due to the pace of innovation. Since the launch of the iPhone in 2007, haptic technology has been reinvigorated, leading to the birth of several haptic startups, acquisitions of small firms, penetration, and implementation of haptic technologies by suppliers.

Additionally, the sheer extent of detail in many review papers can be overwhelming for practitioners who are not familiar with the world of haptics and simply want to acquire an overview of which technology suits their application. For practitioners, it is crucial to understand both the working principles of different technologies and the users' experience.

Haptic experience can hardly be expressed by a comparison of mere technical parameters. In a recent paper, *Psychology of Design*, Carbon [22] plays the advocate for a deeper psychological turn in design. A techno-centric perspective ignores human-centered design by neglecting the constructive and association-based nature of perception. Touch has memory -- context and prior experiences influence the user's perception of haptic stimuli [23], [24].

III. The Haptic Fidelity Framework

With this paper, we target the progressively expanding multi-disciplinary field of haptic practitioners. Hence, we need a systematization that can address various backgrounds and levels of expertise. A fidelity- and experience-based categorization supports haptic practitioners in selecting the appropriate technological approach for their interaction purpose.

A. Technical Prerequisites

Haptic feedback is a broad term that encompasses several sub-modalities of touch [6]. Haptic technologies in consumer electronic and screen-based devices mainly convey feedback via cutaneous information. While technologies that convey haptic information via kinesthetic [25], mid-air interaction [26], electrotactile [27] or thermal cues [28] can be valuable to interfaces, this review paper is tailored haptic technologies most relevant to consumer devices: cutaneous technologies that sense information based on mechanoreceptors.

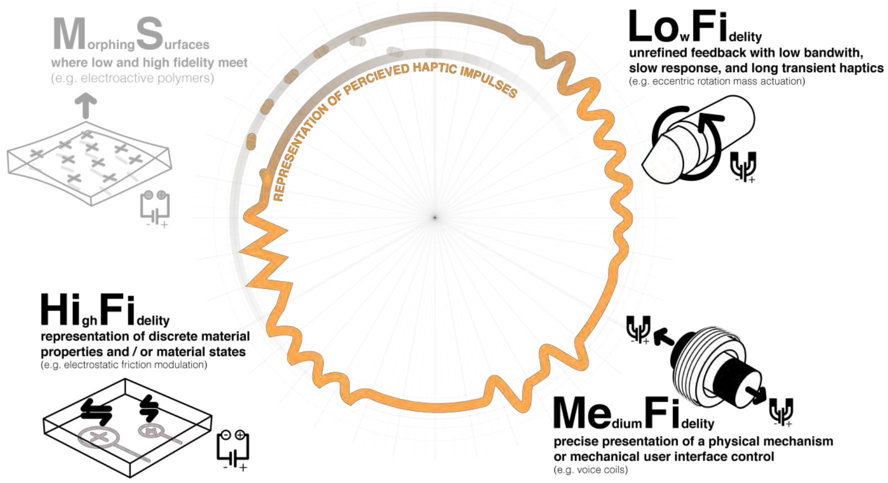

Fig. 1. Within the Haptic Fidelity Framework technologies are categorized according to their fidelity level (low, medium and high). The orange line schematically illustrates the prototypical haptic event (in the form of an acceleration curve) that becomes increasingly distinct with higher fidelity.

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This framework will only review technologies requiring direct physical skin contact between finger and surface and technologies that convey haptic feedback mainly via tactile information, such as skin deformation, pressure, and vibrotactile perception.

B. Different Stages of Fidelity

Uniquely, we aim to categorize haptic technologies by their haptic fidelity. Fidelity does not refer to the quality or mechanical perfection of the isolated haptic result, but to a technology's ability to convey a user's broad range of perceivable scenarios and experiences. Although some higher fidelity technologies can generate similar feelings as their lower fidelity counterparts while providing additional data within the same signal, fidelity rankings are not perse hierarchical. Tradeoffs also exist as fidelity increases. The relatively blunt nature of low fidelity haptics can shake heavy masses, something most delicate and precise high-fidelity haptics cannot achieve. The orange waveform in Fig. 1 illustrates the progressively increasing fidelity that accompanies the increased responsiveness and bandwidth as you move through the framework.

We begin with Low Fidelity (LoFi) haptics in the top right corner of the Haptic Fidelity Framework. LoFi haptics, as depicted by the orange line, have vague reverberating vibrations with no clearly defined start and termination. The only haptic experience possible is a perceived vibration – an example here would be simple rumbles or on/off buzzes.

Moving further clockwise, we encounter *Medium Fidelity (MeFi)* haptics. These technologies communicate a crisp demarcated haptic event in a clear direction or axis, and some even convey various intensities in exercised forces. Typically, MeFi haptic solutions can simulate the mechanical workings of buttons and switches.

As we continue to expand our bandwidth and fidelity, we find *High Fidelity* (HiFi) haptics. HiFi haptics can present complex waveforms and patterns that simulate localized textures with debossed elements, different friction coefficients, or various compliance levels by a simulation of mechanical compression of materials.

The fourth and final category exemplifies the circular nature of our fidelity framework, with technologies that sit at the intersection between the low- and high-fidelity level. These technologies enable surfaces to morph or emulate material hardness changes and thus can also vibrate and simulate texture. From a technological perspective, the vibrations caused by those technologies are the same as you would experience in LoFi technology. Crispness is limited by the actuators' soft and slow movements. However, the LoFi haptic experience is augmented with morphing surface features which contribute to a beyond-HiFi experience. Thus, we believe there to be a connection to morphing surfaces between low- and high fidelity. As Morphing Surface actuators are not categorized as haptic feedback technologies, they will not be described further in this review.

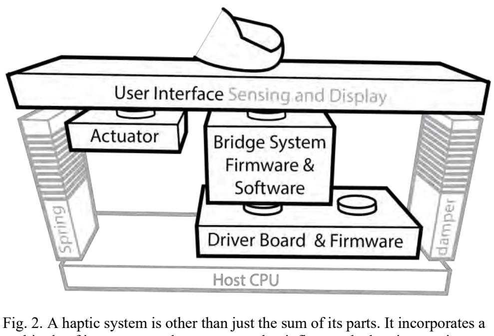

Fig. 2. A haptic system is other than just the sum of its parts. It incorporates a multitude of interconnected components that influence the haptic experience.

C. Actuation Method

The mechanism with which a cutaneous feedback device develops the impulse to stimulate the skin can vary. Below we offer a quick summary of primary actuation methodologies.

Rotating (R) feedback devices convert angular momentum into a vibrotactile impulse. Rotational devices rely on imbalanced rotor shafts to create vibration – usually an approximation to a sine wave. Typically, a stator produces an electric field that causes a rotor to turn generating the angular momentum

Oscillating (Os) feedback devices produce a linear movement by converting electromagnetic energy into kinetic energy. Most oscillating systems can be modeled as mass-spring-damper systems and achieve sharp, precise movements. Some can be over-damped to produce either deceleration or acceleration of components to approximate square waves.

Material deformation (M) actuation relies on the expansion/contraction (M-Ex) or twisting/flexing (M-Fx) of material or chamber due to the application of an external force. Standard methods use shape-memory materials, pneumatics, or piezoelectric materials.

Electrostatic (Es) actuation is also non-contact, but only across extremely short (µm) distances. Electrostatic feedback applies an electrical charge potential between display and user. By varying the charge intensity and charge polarity, an electrostatic display can repel or attract parts of the skin, creating linear and shear movement. Due to the highly localized nature of electrostatic displays, large impulses are difficult to be generated.

D. Building Blocks of Haptic Systems

Haptic systems bridge electronics, driver boards, actuators, software, firmware, and lastly, a mechanically affected surface, enclosure or housing (see Fig. 2). These electronics may include analog components or booster circuits to increase the actuator's voltage or a dedicated haptic microcontroller (µC). The µC converts haptic parameters and timing to a signal that drives the actuator, converting electrical signals into haptic sensations. Sometimes, control electronics and actuators will be integrated into mechanical stacks that cannot be separated for space or latency concerns.

The last ingredients for a haptic system are firmware and software that allow the system to communicate and operate. Firmware is a low-level layer of software stored on µCs. Since many haptic technologies and companies are still developing, the firmware may vary over the lifespan of an implementation.

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With firmware that can minimize the limitations of their actuators, systems can move up the fidelity framework, and thus haptic implementations can exceed the fidelity provided by actuators alone. Haptic software permits the user to configure haptic patterns by code or by offering platforms that substitute code with numerical or graphical representations of haptics, such as sine waves, bitmaps, or sliders (HapticLabs.io [29]) or translate waves from audio-files into haptic patterns (e.g., Lofelt Studio [30]).

Haptics APIs and other specific programming information can be IP sensitive and only obtained after NDAs are in place. LoFi and MeFi haptics are becoming standard practice in HMI systems, and corresponding brand-related secrecy, hardware, and software has begun to play a role in platform election. (e.g., the inclusion in the Arduino platform actually means clear democratization of products).

IV. Haptic Technologies

Here we classify haptic systems or individual components via the Haptic Fidelity Framework. First we describe the general haptic feeling and experience at every fidelity level based on timeliness, intensity, density, timbre, design principles, and technical complexity [10]. Second, we describe currently available haptic systems and technologies. An overview of the different stages of fidelity with corresponding types of working principles and technologies is given in Table I. Table I also describes approximate technical parameters for each actuation principle. Haptic drivers are also included in this overview as they are an integral part of haptic systems. They will only be reported briefly in our text as they are based on different key drivers features than actuators, such as gain, frequency range and communications protocols. A detailed description would exceed the scope of this paper.

A. Low Fidelity Haptics

LoFi haptics was the first to be widely implemented in consumer electronics products, such as mobile phones and gaming controllers. To this day, they are still the most used haptic actuators in prototyping haptic interactions because of their relatively low cost and complexity level. In general, LoFi haptics provides the feeling of buzzing, rumbling -- mere vibration. Their diffused vibrational feel limits LoFi use-cases to notification of an incoming call or a rumble to augment specific situations in gaming. Temporal aspects of LoFi haptics can be generalized as delayed, diffused, imprecise, blunt, and transient. This is most applicable to technologies using a rotating principle with relatively low damping values and a long spin-up time due to the inertia (see Table I). Because of the latency, short and precise "click" effects are hard to achieve, leading to potential unsatisfactory interplay with other sensory modalities. Driver ICs can be used to enhance responsiveness.

Although the intensity can vary, LoFi haptics typically couple amplitude and frequency behavior, meaning that one cannot be modulated independently. Some systems allow for variation in frequency by adjusting parameters such as voltage or current. The perceived intensity of the vibration can be quite considerable but easily pose the risk of being annoying and unpleasant when overused [31], [32], [33]. Additionally, a

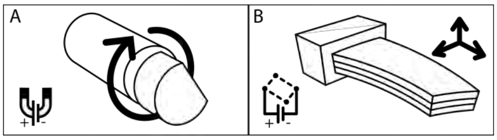

Fig. 3. (A) ERMs are based on electromotor principle where vibration is caused by an eccentric mass attached to a DC motor. (B) Piezo benders are composed out of bimorph piezo materials, meaning once current is applied the bender produces movement in a certain direction.

considerable, mostly unwanted soundscape often accompanies the haptic signal.

Feedback cannot be localized at specific positions on a screen or product without using complex suspension systems as the rotating mass is shaking the whole device, making these systems most suitable for handheld or wearable devices. Moreover, LoFi haptic feedback will typically not be uniform due to the form factor and position of the actuator inside the product. On the upside, available actuators are low-cost, highly accessible in different form factors, and can easily be integrated to create haptic systems. This makes them popular for prototyping and hardware sketching [9]. Due to the wide variety of available actuators and LoFi haptics' relatively monotonous haptic possibilities, this category will not be considered as extensively as other haptic systems.

1) Eccentric Rotating Mass (LoFi - R)

Eccentric Rotating Mass actuators (ERM) work much like an improperly loaded washing machine. When a mass is unevenly distributed around a point of rotation, oscillation occurs (Fig. 3A). Larger masses and faster rotation increase the magnitude of the vibration. ERMs are available in many different form factors that are cheap and easy to integrate and control with voltage or pulse width modulation (PWM) signals. Hobbyist-focused suppliers such as Adafruit [34] and Sparkfun [35] provide systems that include pancake-style ERM actuators with Arduino-based breakout boards, making ERMs popular for rapid prototyping or early product mockups containing haptic feedback. Precision Microdrives [36] and Grewus [37] provide different styles of ERM-based actuators, including pancake-style, encapsulated or PCB-mounted variations.

While not needed, fidelity can be improved with easily accessible driver circuits and firmware improve system responsiveness via breaking and back driving. (e.g. DRV260X series from Texas Instruments [38], Dialog Semiconductor's DA728X series [39]) Some suppliers already package their standard capacitive controllers with output libraries/features, e.g. pulse width modulation, specifically for haptic actuators [40].

2) Material Deformation – Piezo Bender (LoFi – M-Fx)

Piezo actuators exist in different form- and size-factors with single- and multi-layered piezoceramic elements. In contrast to single-layer, multi-layer piezoceramic elements contain several electrode layers resulting in a higher displacement and force, but also thicker actuators. There are also bimorph piezo elements, which consist of metal or silicon substrates that have piezoelectric layers glued to each side (one side is contracting

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while the other is expanding), leading to bending movement. Hence, they are often referred to as piezo benders.

While many piezo bender actuators are used for very specific MEMS (Micro-Electro-Mechanical Systems) purposes, such as opening valves, the Piezo Vibe by Murata Manufacturing [41] is an example of a piezo bender actuator that can be used to create a rumbling feeling. It uses the piezoelectric effect to deform its ceramic layers in order to produce a vibrating feeling (Fig. 3B). Due to its low power consumption and very small size, it is primarily targeting wearable devices.

B. *Medium Fidelity Haptics*

Consumer electronic devices have recently shifted to haptic systems that can simulate a button press or mechanical click feedback on solid and featureless surfaces. Hence, one of the main driving aspects of MeFi haptic feedback is to substitute mechanical, visually moving, tactile switches with electromechanical actuators to retain a monolithic appearance of haptic systems.

In terms of temporal aspects, the fundamental difference to LoFi feedback is increased responsiveness and controllability of the actuator, avoiding long transient vibrations. This allows for haptic effects that convey the feeling of "haptic clicks". Actuators can be programmed to convey longer-lasting vibrations but are limited by their frequency bandwidth. Latency and response time are considerably lower than those of LoFi actuators but generally higher than those of HiFi systems (see Table I).

The intensity of the haptic impulse correlates to the form factor of the actuator and the amount of mass actuated. In automotive contexts, larger MeFi haptic actuators generate a strong impulse even though actuated mass is often more than a kilogram. The more typical implementation of MeFi haptics in handheld and mobile devices demonstrates the size adaptability in MeFi haptics. Audible noise can still accompany intense MeFi haptics in poorly isolated enclosures. The conciseness of the haptic event is influenced by the dampening of the vibrational impulses. The actuator's integration in the haptic device's mechanical stack becomes increasingly complex as actuated mass (linked to haptic display size) increases.

Although there are exceptions, most MeFi actuators do not rotate or swivel but move a single axis by using the electromagnetic working principle (1-DoF instead of 2-DoF, see Fig. 5). This linear movement can change the perceived character of the device depending on the orientation relative to the user. It can be a design factor to consider during integration.

Due to the wide variety of form factors and output forces, it is difficult to summarize the haptic timbre of MeFi haptics. A key trend to note is that complexity of haptic systems increases as the fidelity of the feedback increases. From a mechanical perspective, MeFi systems are not more complicated to integrate or tinker with than LoFi actuators, making them a valuable resource for hardware sketching [9]. Some MeFi components are easily accessible via electronics distributors. Yet, companies often use custom-specific and proprietary actuators, such as Apple's Taptic Engine and CoreHaptics API.

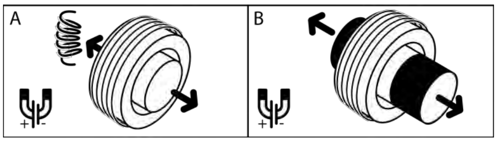

Fig. 4. (A) Solenoid and (B) Voice-Coil actuators are both based on the electromagnetic working principle. Displacement is created by the interaction of a coil, which acts as an electromagnet once voltage is applied to and a moving mass which is either a ferromagnet (A) or a permanent magnet (B).

1) *Medium Fidelity – Oscillating (MeFi – Os)*

MeFi actuators based on an oscillating electromagnetic working principle can be describes as Solenoid or Linear Resonant Actuators (LRA). Both yield a similar haptic impression. They differ in their technical setup (see Fig. 4 & Fig. 5).

a) Solenoids

In general, solenoid actuators are based on an electromagnetic working principle and consist of a coil, which generates an electromagnetic field, a steel slug suspended within the coil, and a spring system or endplates that limit the movement of the slug (see Fig. 4A & Fig. 5A). Current applied to the coil excites an electromagnetic field which moves the steel slug unidirectionally to its end position. Subsequently, a suspension system will push the steel slug back to its starting position. The force the solenoid can convey is directly connected to the force of the magnetic field [42].

Off-the-shelf and standard solenoid components for haptic actuation from suppliers like Johnson Electric [43] or Adafruit [44] can be found at nearly all major electronics distributors (e.g. Conrad, Mouser, Digikey). Even though they are often used for controlling valves, they can also be used to create a haptic experience (e.g. [9], p.146 "The Knocker"). Probably one of the "most felt" medium-fidelity haptic actuators is Apple's Taptic Engine found in MacBooks. The laptop version of the Taptic Engine seems to differ regarding to actuation technology for handheld and computing devices, with the magic trackpad known from MacBooks resembling a solenoid. Four electromagnetic coils pull a ferromagnetic rod connected to the trackpad surface in a lateral direction [45].

Niceclick is a patented haptic system by Trama Engineering [46] that tries to mimic the feeling of a conventional button with a haptic dome made out of spring metal, rubber, or a combination of them. They speak of "Touch 4-D" which integrates sensing in a lateral (x-, y-axis) and normal direction (z-axis). Feedback is given in a vertical direction by an electromagnet that attracts a ferromagnetic element. Soft supports within the actuator act as a spring-damper system [47]. Together with Grewus, Trama focuses on the automotive industry to provide a fully integrated interface solution to reduce cost and make interfaces safer to use.

For a couple of years, there is increasing use of active haptic systems in the context of seamless automotive control panels [48], [23] and enabling touchscreen with haptic feedback [49], [50], [51], [52]. As there are specific requirements for integration, haptic systems are mostly custom-built and covered

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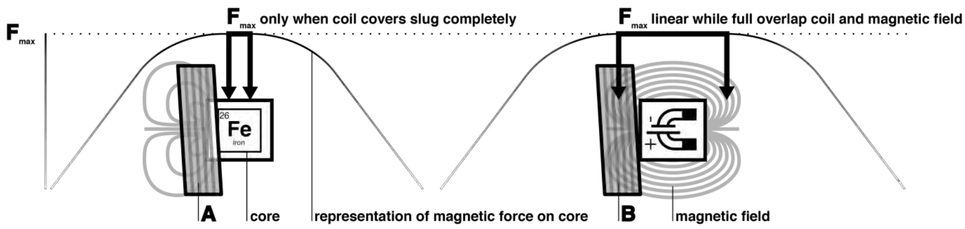

Fig. 5. A graphical representation on the magnetic force in- and a cross section of (A) Solenoids, and (B) LRAs. As visible in (A), the ferromagnetic core will only start to create its magnetic field when the coil starts to overlap, reaching a maximum in the magnetic field when coil and core fully overlap. In (B), the coil will already fully interact with the magnetic field even before overlapping the core. Since the core's magnetic field will not be affected by the electromagnetic field of the coil, the resulting force will remain constant – assuming the current remains constant as well.

by non-disclosure-agreements. Thus, it is often unclear whether voice coil or solenoid-based technologies are used. Additionally, the driving measures regarding dampening are also opaque. High actuation forces typically suggest solenoid-based systems. Another proprietary haptic solution for the automotive industry is the Bosch NeoSense [53], [54]. Uniquely, it contains confirmation haptics – button press and clicks – as well as search haptics which enables the user to feel buttons through different textures [23].

b) Linear Resonant Actuators (LRA)

LRAs and solenoids differ in whether, respectively, a permanent magnet or only a ferromagnetic material is used (Fig. 5). LRAs are based on an electromagnetic working principle and consist of a permanent magnet, a spring, and a coil. By applying current to the coil, an electromagnetic field is produced, creating a magnetic interaction between the permanent magnet and the electrically induced coil. Polarity can be reversed, meaning push and pull forces on the magnet can be created. In such systems, either the coil or the magnet is stationary while the other will move. As a result, the magnet can move bi-directionally on a single axis perpendicular to the coil. As a rule of thumb, the maximum force the actuator can produce depends on the magnetic field's strength. Constant forces are also possible with this kind of actuator [42].

Typical LRAs are produced by Precision Microdrives [55], and Jinlong Machinery [56]. They offer a range of different linear resonant actuators for actuation in either y- or z-axis, depending on the final application or the shape and placement of the spring actuation. Variations to the typical cylindrical form factor, such as flat actuators used in mobile phones, are offered by Actronika [57]. As with any mass-damper system, there is a resonant frequency to the oscillations. An LRA's efficiency increases the closer it actuates at its resonant frequency. As such, LRAs produce noticeable vibrations in a very narrow frequency band. Thus, in their most simple configuration, LRAs have variable amplitude and a fixed frequency. LRAs are driven by the alternating current polarity at the resonant frequency. Isolating the actuator itself, the resonant frequency is typically between 150-300 Hz, coinciding with the peak frequency response rate of the skin [5], [6]. However, resonance values change when the product and actuator are combined. Coinciding with the developments in other actuators, Cirrus Logic [58] offers microchips that are both capable of driving an actuator and sensing the actuation by measuring current and voltage. The limited range of products and the use of dedicated actuators versions allow for maximum actuator efficiency and thus a high-quality haptic experience [59].

Voice-coil actuators (VCA), an improvement on the LRA principle of operation, are just starting to rise in popularity. Common examples include Apple's handheld version of the Taptic Engine, which seems to be based on an LRA-principle [60], the LoFelt L5 actuator [61], Tactile Labs' range of Haptuators [62], and the Exciter by Grewus [63]. However, rather than oscillating a cone and compressing air, a voice coil actuator moves a mass and excites the skin. The voice coil can run over a large frequency range solving the traditional limitation of an LRA. The voice coil design is difficult to drive, typically requiring filtration of the signal, and has a non-linear response curve across frequency and amplitude ranges.

Interestingly, voice coils can be directly driven by audio amplifiers and due to the similar structure of a loudspeaker the actuator can also be used for audio feedback, such as Sparkfun's Surface Transducer [64] and Grewus' Exciter. The most well-known VCA these days is the mobile form of the Taptic Engine, found in Apple's iPhone, iPad, and AppleWatch product lines. With Core Haptics in iOS 13 Apple gave developers much more freedom in using the Taptic Engine to create haptic impulses [32]. Third-party integrations like the LoFelt Studio provide a haptic design toolkit to ease the creation of immersive haptic experiences [30]. The VCA has also recently entered the gaming market, with Foster's VCA technology being integrated into the Sony Playstation 5 [65].

Another modification of the LRA basic design, a multidimensional (MD) LRA, offers additional DoF, with each axis using a unique resonant frequency. By biasing movement across multiple axes, MD LRAs can present wider spectrum actuation than traditional LRAs. Alps offers actuators that can control haptic effects in multiple directions by suspending the coil in housing between two magnetic endplates. The Alps Haptic Reactor [66] has two resonance points for vibration. The Alps Quadra even has four resonance points for greater bandwidth. This novel approach has helped drive the adoption of Alps technology in many current game controllers and TV remotes [67].

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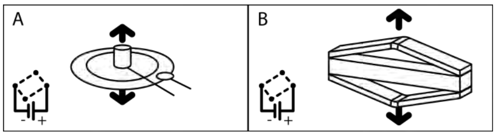

Fig. 6. (A) Piezoceramic material expands when voltage is applied, leading to the bending of the bonded ridged substrate. (B) The PowerHap consists of a multilayer piezoceramic element with two conic metal domes, that produce displacement as a result of the voltage-induced expansion of the piezoceramic material.

The TacHammer, which Nanoport [68] classifies as a Linear Magnetic Ram, seems to combine the basic principles of a voice-coil and a solenoid actuator. The TacHammer series offers a broad range of changeable impact disks and spacers to influence the actuated mass. One significant difference with regular LRAs is the suspended magnet that provides different modes of operation: (1) impact, where the magnet hits the endplate on one side and (2) traditional, which drives the ram into a magnetic brake on the other side of the actuator resulting in a vibrating effect by working as a traditional LRA [69].

Besides the actuator, drivers are essential for a haptic system with solenoids to function (see Fig. 2). The type of driver is becoming more and more of a differentiating factor for haptic quality as fidelity increases. Major haptic driver suppliers for MeFi actuators are, for example, the Cypress' CY8C20xx6H product family, Microchip's MTCH810 drivers, and Texas Instruments' DRV25XX/DRV26XX drivers [40], [70], [71]. Dongwoon is a driver supplier that includes Immersion-certified haptic libraries [72]. Texas Instruments also has versions of their drivers that come supplied with Immersion's libraries. Adafruit uses a TI DRV2605-chip [73] on their Arduino-compatible breakout-boards.

2) Medium Fidelity – Material Deformation (MeFi-M)

There are also MeFi actuators that create haptics via material deformation. They include piezoceramic-based or shape memory alloys that actuate by expanding/contracting or foil-based actuators that actuate by twisting/flexing.

a) Piezoceramic Based Actuators (MeFi - Ex)

Piezo-related haptic feedback is based on the piezoelectric effect. Piezoelectric materials consist of piezo crystals that convert voltage to mechanical displacement and vice-versa. In addition to being able to sense user input such as a press, this smart material can move or deform surfaces with relatively small displacements but high accelerations and precision. In general, piezo elements are relatively thin and energy-efficient in comparison to most LoFi and MeFi actuators (Fig. 6).

Disk-like piezo actuators with single-layer piezoceramic elements are probably the most known and cheapest piezo actuators (Fig. 6A). Murata [74] offers a range of what they call piezoelectric diaphragms, while Kyocera Corporation [75] also offers ring and rectangular-shaped single plate piezo elements. Multilayer piezo elements can be bought from Murata, Kyocera Corporation [76], and TDK.

TDK sells a distinctive line of more expensive and powerful multi-layer piezo actuators [77] for a variety of automotive as well as information and communication use-cases [78]. Similar to a piezo disk, the Piezohapt is a flat actuator with a multi-layer piezo glued to a thin metal surface. This way it delivers vibrations over the whole metal surface, which can be used beneath display components [79]. The Powerhap (Fig. 6B) can be described as two oppositely cone-shaped metal domes ("Cymbals") with multiple piezo layers in between [80]. There is also an additional version that consists of just the cross-section of the Powerhap. When voltage is applied, the piezo layer's length or size decreases and makes the domes contract in height, creating the haptic effect. TDK offers a proprietary driver that allows the Power- and Piezohapt to be driven up to 60V or 120V depending on their size and force for simple clicks [80].

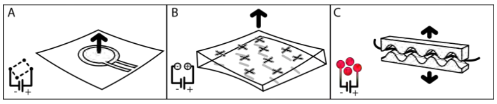

Fig. 7. (A) Piezoelectric polymers have been used to produce transparent film-type vibrotactile actuators. (B) EAP-actuators are based on an electrostatic principle. Two mutually charged layers attract each other while a conductive in between is stretched or flexed. (C) Shape memory alloy wires will shrink when joule-heated once current is applied.

Texas Instruments has various dedicated piezo drivers with an integrated voltage boost circuit in their product lineup (e.g., DRV2700, DR8662). They claim that startup time of 1.5ms is lower than those of competitors [71].

b) Foil based Actuators – (MeFi - Fx)

Electroactive polymers (EAP) are smart materials that change size and shape when exposed to an electric potential. Dielectric elastomer actuators (DEA) are a class of EAPs. The basic principle of DEAs is based on two conductive layers of electrodes with a non-conductive flexible or stretchable polymer in between. The two conductive layers will be charged oppositely and attract each other (governed by the Coulomb force), thereby squeezing or stretching the material in the middle. The conductive material and the substrates and isolation can be varied (Fig. 7B). Stretched and relaxed states can be evoked by alternating the polarity of current. This physical movement can lead to a tactile experience. Tactile experience is described chiefly by a vibration that can be adjusted by varying frequency and amplitude.

Despite much research on using electroactive polymers as haptic actuators, only a few companies offer industrialized products, most of the research results in one-off prototypes. Following the general working principle in Fig. 7A, piezoelectric polymers (PVDF) have been used to produce transparent film-type vibrotactile actuators [81], [82]. The EU-funded HAPPINESS project (Haptic Printed Patterned Interfaces for Sensitive Surfaces) aims to replace mechanical components within car interfaces by using more "soft" and flexible printed actuators that combine touch sensors with localized haptic feedback [83], [84], [85]. Piezotech [86] provides different kinds of printed piezopolymer actuators that are also suited for haptics.

Following an electrostatic working principle explained in Fig. 7B, other companies have produced actuators on squeezable and stretchable substrates. Senseg released a novel kind of actuator in 2019 – the Elastomeric Film Actuator, or in short, the ELFIAC[1]. The elastomer films make it a flexible and highly adaptable actuator in terms of size and shape. The actuator structure is composed of stacked printed electrodes on foil layers, with micropillars between the electrodes. Wacker [87] is releasing a range of EAP laminates acting as an actuator. A silicone film separates opposingly charged electrodes. Applied voltages lead the electrodes to attract and cause the silicone film to be squeezed and expand in shape. Multiple Nexipal layers are stacked to enable larger strokes. As a last example, Novasentis [88] is selling EMP (Electro-Mechanical Polymer) actuators especially for the mobile, wearable, and gaming market. A thin electroactive polymer film is bonded to a rigid substrate, and when a voltage is applied, vibrations can be created. Novasentis' actuators enable localized and programmable feedback, even at relatively low operating voltages. When driven with high frequencies, these actuators can produce sound. For the driver, Novasentis has teamed up with Microchip [89] to provide a driver that can deliver up to 250V for haptic actuators.

c) Shape Memory Alloy Actuators (MeFi - Ex)

Shape memory alloy (SMA) based actuators switch between two different form states when heated or cooled by driving current through the metal for joule heating. While displacements are relatively large, most applications use SMA actuators to create displacement for purposes other than tactile feedback, e.g., as opening mechanisms in valves. SMA actuators are relatively slow in actuation and recovery time, and the risk of mechanical fatigue is high [90]. Additionally, some of the SMA's characteristics, such as operating temperature, mismatch with functional requirements for specific markets. Seidensha [91], [92] and Cambridge Mechatronics [93] have shown actuators that can provide non-visible haptic feedback using SMA-actuators. Two dented inter-fitting elements with an SMA wire in between are pushed apart when the wire contracts (Fig. 7C). Compared to other similar haptic technologies, the resulting feedback is relatively silent while the haptic remains quite clear and precise.

C. High Fidelity Haptics

Within the category of HiFi haptics, haptic feedback is tunable to a level that exceeds pure vibrations and enables extensive haptic languages [94]. While previous technologies rely on vibrations to provide haptics, some HiFi technologies are based on friction stimuli. The common denominator of these HiFi haptic technologies can be explained as the possibility to provide haptic sensations that simulate material properties, textures, or shapes without it being a physical characteristic of the surface. Bandwidth in terms of sensations reaches from precise button click simulations and complex surface textures to compliant material.

Describing the temporal characteristics of HiFi haptics involve an almost immediate response, i.e., a lower latency than MeFi haptics and "crispness" of the haptic sensation (see Table I). Systems are, in general, more geared towards providing localized actuation at the fingertip rather than actuating larger surfaces. Also, a few HiFi technologies will require the user to explore the surface by pressing or sliding the surface actively. Some haptic technologies are more suitable for rendering textures and providing feedback with more complex impulse characteristics. Others are primarily intended and more suitable for a little higher quality MeFi haptics sensation, such as mimicking "clicks". HiFi experiences are rarely defined by the actuator's properties. Often the driver, system, and rendering algorithms behind the actuator enable more complex haptic effects.

Levesque et al. [95] and Levesque, Oram, and MacLean [96] conducted an initial exploration of friction stimuli in the context of UI use-cases, such as target acquisition, slider, selection, and drag-and-drop tasks. Friction stimuli have been used to augment virtual textures and interfaces elements, such as buttons [20]. Nevertheless, user-centered haptic evaluations of such stimuli in applied user settings are still scarce [97], [98].

HiFi haptics also involves new means of providing haptic feedback, which go beyond vibration-based systems. By controlling the friction coefficient between finger and surface (friction modulation), haptic systems can render textures that feel like embossed ridges or slippery surfaces. Though providing an extensive set of possibilities to restore haptics on otherwise featureless surfaces, it is also challenging to design for these approaches [97]. Basdogan, Giraud, Levesque, and Choi [20] review the current state of friction modulation regarding perceptual mechanisms, rendering algorithms, and applications purposes. HiFi systems are in most cases provided by specialized haptics companies as part of research programs, or OEM-specific disclosed development programs. Though development kits may be available for tinkering and selling purposes, most proof-of-concept projects with OEMs or suppliers require specific knowledge and customized hardware. This also applies to the even more exclusive, proof-of-concept haptic prototypes provided by various research groups or material suppliers.

1) Software-Enhanced Piezoceramic Haptic Feedback

It is essential to distinguish between actuators, drivers, and corresponding software as most companies begin to specialize. Because haptic fidelity increases signal complexity, there is a greater demand to control actuators via a graphical user interface or a simple to use software package. The complexity enabled by these software solutions makes the software/firmware the primary technology of piezo-based HiFi haptic systems. Software-enhanced refers to the influence of control electronics on driving piezo actuators. There are a few companies that specialize in driving piezo actuators. Most drivers are claimed to be very energy efficient and include piezo pressure sensing.

[1] Senseg's website is out of service upon the submission of this paper in February 2021. Information on the ELFIAC (https://www.senseg.com/wp-content/uploads/2019/08/Senseg_ELFIAC_whitepaper_launch_edition_AUG 2019.pdf) can be accessed via archive.org

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The Dutch-Finnish company Aito [99] mainly focuses on sensing and driving off-the-shelf single-layer piezo disks, as shown in Fig. 6A. The Aito system employs conventional single-layer piezo disks from regular manufacturers like TDK, Murata, or Kyocera. Next to actuating a complete surface (similar to a trackpad actuation), Aito's proprietary system can provide localized haptic feedback by tightly integrating piezo disks into a mechanical stack of the interface (the actuation layer only adds 0.3 mm thickness to the entire UI stack). Local actuation in z-direction, which means only providing haptic feedback where the finger is touching the surface, is possible with a wide array of material overlays, such as wood and even steel– also in the context of automotive prototypes [98], [99], [100]. Important for haptic practitioners is the possibility to fine-tune haptic effects with the AITO UX Design Studio, which comes with different evaluation kits (Haptile Trackpad or HapticTouch). Next to having flat single layer piezo disks in different form factors, Kyocera provides multi-layer actuators that show larger displacement [76]. Kyocera's haptic system Haptivity is currently available as an evaluation kit [100]. It is able to recreate the feeling of real buttons in-car interfaces and entails both their multi-layer piezo actuators and discrete driver.

The CapDrive IC by Boreas [101], a Canadian startup, also uses multi-layer piezos to sense and provide haptic feedback for mobile, wearables, and automotive purposes. In contrast to Aito, Boreas mainly uses the TDK Piezohapt and Powerhap actuators to actuate entire surfaces instead of providing localized feedback under the fingertip, with the exception of the side buttons on their mobile phone demo [102]. With the biggest type of Powerhap there is a maximum displacement of 230 µm possible. Boreas also provides a development kit (Boreas BOS1901 PCB) for driving 60V with a dedicated haptics software studio to test and design haptic effects. There is close cooperation between TDK, Boreas and Immersion to provide haptic solutions for a wide array of different markets, such as smartphones, gaming and automotive [103].

2) *High Fidelity – Friction Modulation*

Variable Friction displays are a relatively new type of surface haptics that create haptic feedback by changing friction on the bare finger during a lateral movement across a surface instead of using vibration impulses. Previously mentioned technologies are mostly vibration-based haptics, while the following types are friction-based. Two types of mechanisms can be described: (1) increasing or (2) decreasing friction (see Fig. 8).

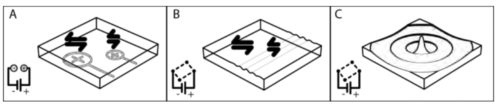

Fig. 8. (A) Electrostatic friction modulation increases the friction force between a sliding finger and surface by varying the attraction force of a voltage-induced conductive layer while (B) ultrasonic friction devices decrease friction force by creating ultrasonic waves via piezoelectrics. (C) Bending waves produced by an algorithm-controlled actuation of piezoelectrics leads to a highly localized surface deflection.

a) *Electrostatic Friction Modulation*

Increasing friction on haptic displays is based on the principle of electrostatics [104]. A recent in-depth description of the current affairs of electrostatic devices is given by Osgouei [105]. Electrostatic friction modulation refers to attraction between charge in the screen and charge in the skin. Most modern electrostatic friction modulation devices refer to the effect of electroadhesion, meaning any change in adhesion due to an increased electrostatic force, without referring to the type of charge or frequency. A smaller subset of electroadhesion refers to electrovibration, which deals with only AC signals and a limited vibration range that humans can feel [104]. Initial psychophysical studies employing electrovibration devices were carried out by Bau, Poupyrev, Israr, and Harrison [106] using the Tesla Touch device. Breitschaft, Pastukhov and Carbon examined the effectiveness of electrostatic friction modulation in an automotive dual-task context [107]. In the following years (early 2010's) Nokia [108] and Microsoft also worked on devices using electrovibration [109].

Advantages over vibration-based technologies are that devices are solid-state, noise-optimized, low-energy, and low latency. Haptic effects are fully software-defined [110]. Tanvas [111], a US-based startup, offer commercially available development kits including their proprietary TanvasTouch electrostatic friction modulation technology [110]. Together with the automotive supplier Innolux they provide an automotive solution for the TanvasTouch technology [112]. Senseg, which have been the first company to offer electrostatic friction modulation in the early 2010s now offer the Tixel[2] (formerly E-Sense) in conjunction with their proprietary high-voltage driver as a technical solution for electrostatic friction modulation [113]. Earlier iterations of their technology have been integrated into prototypes by Toshiba [114].

b) *Ultrasonic Friction Modulation*

Ultrasonic actuation decreases friction on haptic surfaces. Vibration of the surface at an ultrasonic level by piezoceramics creates an "air-cushion" and reduces the contact area of the fingertip and surface. This results in a lower friction sensation on the bare finger while it is sliding across the surface. Biet, Giraud, and Lemaire-Semail [115] refer to this as the "squeeze film effect". For an in-depth review see [20]. Pioneering work on the design of ultrasonic devices, such as the TPad, has been done by a research group from Northwestern University [116], [117]. In 2014 Fujitsu released a haptic sensory tablet prototype using ultrasonic vibrations [118]. Microsoft presented a Lumia prototype with ultrasonic haptics [119]. In recent years Hap2U, a french-based startup, worked towards the commercialization of ultrasonic friction modulation devices. They built several prototypes using friction haptics on different materials and form factors [120], [2]. Haptics can be tested and evaluated using their Xplore Touch demo kit. Like electrostatic devices, ultrasonic actuation has a very high bandwidth of haptic effects, from rendering simple "clicks" to complex textures.

[2] Senseg's website is out of service upon the submission of this paper in February 2021. Information on Tixel (https://www.senseg.com/tixel/) can be accessed via archive.org.

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3) *High Fidelity - Bending Waves*

Bending waves, or time-reversal wave focusing, have also been described as an effective way to render precise, highly localized, and multitouch-capable haptic clicks. Waves produced by piezo-electrics attached to the sides of the surface propagate through the surface and concentrate at specific locations at the surface leading to a very small deflection [121], [122]. CEA's concept involves not only hardware components but also a complex algorithm to control the output of the device and propagation of waves through the surface. LOTUS (Localized Feedback Tactile Feedback on Smart Surfaces) has so far only been shown as part of a CES demonstration [123]. To date, Redux Labs, a formerly UK-based company, has been the only company to distribute demonstrators using bending waves. They were acquired by Google [124].

TABLE I
SUMMARY OF HAPTIC TECHNOLOGIES DESCRIBED WITHIN THE HAPTIC FIDELITY FRAMEWORK (APPROXIMATED VALUES)

Fidelity	Actuation Principle	Product	Force (G-p.p.)	Frequency Range (Hz)	Operating Voltage (V)	Rising Time (ms)	Recovery time (ms)	Power Consumption (mA)
LoFi	Eccentric Rotating Mass	e.g., Adafruit, Sparkfun, Precision Microdrives, Grewus	C: 0.15-2.5 B: 0-20	0 - 200	C: 1.5-5 B: 1.5-12	80-100	50-100	100-500+
	Piezo Bender	Murata Piezo Vibe	0-1.2	200 - 300	1.8 - 3.5	< 10	n/a	5-10
MeFi	Piezo-electric Polymer	Piezotech, HAPPINESS-Project	displacement up to 8 µm	1500-7000	6-35	< 1	n/a	20
	Electroactive Polymer (EAP)	ELFIAC (Senseg), Nexipal (Wacker), Electro-Mechanical Polymers (Novasentis)	3.5	1 Hz – few kHz	100 - 500	< 5 (EMP)	n/a	~30
	Solenoid	Standard Actuators (e.g., Johnson Electric), Niceclick (TRAMA), Custom-purpose Solenoids (e.g., Automotive industry)	varies	varies	varies	varies	varies	varies
	Linear Resonant Actuator	Voice-Coil-Acuator: LoFelt L5, Grewus Exciter, Sparkfun Surface Transducer, Actronika Hapcoil, Taptic Engine (Apple)	0-15	0 - 15000	0-3.3	5-15	5-15	200 – 500+
		Multdimensional LRA: Alps Haptic Reactor	2-4	X: 120 - 180 Y: 300 - 360	2.7-3.3	5-15	5-15	depends on haptic driver
		Linear Ram Actuator: Nanoport Tachammer	Imp: 0-27 Trad: 0-11	0.5 - 200	3.6 - 10	Imp: 0.2 Trad 5.1	Imp 6.3 Trad 7.5	800*
	Shape Memory Alloy	Seidensha, Cambridge Mechatronics	up to 20	XXX	0-5V (AC) 0-12V (DC)	depends on voltage	n/a	n/a
	Singlelayer Piezo	Piezoelectric Diaphragm (e.g., Murata), Kyocera (ring & rectangular shaped)	0.5-5	0-1000	0-120	5-15	5-15	5-15
	Multilayer Piezo	TDK PowerHap & PiezoHapt, Murata, Kyocera	2.5-20	0-1000	0-120	5-15	100	5-15
HiFi	Software-Enhanced Piezo	Aito HapticTouch, Boreas CapDrive IC, Kyocera Haptivity	3.5-8 (technically up to 50G)	150-400	60-400	2-15	5-15	5-15
	Bending Wave	Lotus (CEA), Redux Labs	N/A	n/a	n/a	N/A	N/A	n/a
	Electrostatic Friction Modulation	TanvasTouch, Senseg Tixel	N/A	N/A	>100	N/A	N/A	n/a
	Ultrasonic Friction Modulation	Hap2U	N/A	>20 kHz	>40	N/A	N/A	200-1000

Note: The provided values are an approximation based on reference designs and vary upon system integration. For detailed values see the respective technical specification sheets. This table does not include haptic drivers. N/A = not applicable, n/a = information was not available at the time of writing the manuscript or cannot be shared due to confidentiality, C = Coin, B = Barrel; *800mA required to power haptic driver

V. DISCUSSION

While we believe in our approach's advantages, we acknowledge it has some limitations worth discussing. We hope this classification methodology and review can help novice practitioners design haptics beyond a mere technological perspective through a deeper understanding of the user behavior and user experience evoked by these devices.

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The first shortfall is our prioritization of a psychologically and qualitative driven view of sensation over a physiological or quantitative focus on perception. Our proposed clustering prioritizes what users believe they feel rather than exploring neuroscience or technical features. While a technical and physical understanding of a technologies' perceptual impact is essential for integrating an actuator into a device, it is even more important to convey compelling haptic experiences to users [10] Psychological factors, such as experience, context, and task demand [22], [23], [24], [10], [125] need to be considered in how a user perceives haptic feedback. Our fidelity-based categorization aids practitioners with different backgrounds and levels of expertise and supports the matching of haptic requirements to actuator effects.

A second limitation is that we only address a single sub-modality of haptic feedback, namely cutaneous feedback ignoring that the immersion and realism of haptic feedback are driven by the user's multimodal and cross-sensory engagement or stimulation [126]. Indeed, the combination of feedback demonstrated by morphing surfaces shows how augmentation or combination of multiple LoFi feedback can increase a haptic actuator's true fidelity. However, the focus on cutaneous technologies, which are most relevant for UI and UX practitioners due to their frequent implementation in consumer electronics – and automotive devices, allows for an accessible and comprehensible overview.

A third limitation is that we simplify haptic systems by mostly reviewing the actuator itself, and if applicable, the actuator-driver combination in a reference design. The individual implementation of an actuator can have a drastic result on the fidelity of the haptic feedback. Although we mention multiple examples of features in the haptic equation that lead to higher fidelity, e.g., closed-loop systems, this review does lack contextual information on features such as mechanical integration, haptic surface properties and spring-damper systems. We argue that devices using the same actuator technology but implementing different electronics or mass-damper systems will have a similar level of fidelity due to the basic actuator's haptic characteristics. We chose to apply a simplified view of haptic devices, looking primarily at the actuators to provide a comprehensible overview of current technologies.

Finally, we acknowledge that this overview on currently available technologies may already be outdated at the time of publication, with companies discontinuing or introducing new products. Some references that were part of initial literature research (April 2020) were no longer available upon submitting this paper as companies have potentially been restructured or discontinued. The proposed overview of technologies is a snapshot of the current industry (January 2021).

VI. Conclusion

With innovations in haptic feedback occurring almost daily, and an ever-growing appetite for haptic feedback in devices, we expect the challenge of intuitively and quickly understanding the capability of an actuator to remain. We have arrived at a point where haptic technology offers multiple tiers of fidelity and multiple methods to create it. Thus, there is a growing need for standards and classification methods to help isolate the technical signal from the marketing noise.

This paper presents a method tailored to those new to the discipline, allowing them to select actuators and their respective hardware stacks quickly and intuitively. Additionally, through this review methodology, we offer the ability to evolve feedback upward, encouraging practitioners utilizing lower fidelity actuators to consider what might be possible if they utilize a higher fidelity technology.

Standard libraries or signal generation toolkits should be considered for the community to explore haptics easier and faster and, in this way, spread HiFi haptic use more throughout daily interactions. Only now, the haptic industry comes together to work on a common set of industry-wide standards for "HD-Haptics". While the HW complexity of HiFi haptic systems limits their integration and adoption, and the patent strategies limit iteration and innovation, there remains much to be optimistic about in haptics.

VII. References

[1] F. Guerrini, *Bosch And The 'Connected Car': Touch Screen With Haptic Feedback And Other Stuff On Show At CES 2016.* [Online]. Available: https://www.forbes.com/sites/federicoguerrini/2015/12/07/bosch-and-the-connected-car-touch-screen-with-haptic-feedback-and-other-stuff-on-show-at-ces-2016/?sh=264e40d71d2d (accessed: Jan. 27 2021).

[2] Hap2U, *Touch-Display Mobile Technology wins CES Innovation Award.* 2020, [Online]. Available: https://www.hap2u.net/touch-display-mobile-technology-wins-ces-innovation-award/ (accessed: Feb. 14 2021).

[3] Markets and Markets, *Haptic Technology Market by Component (Actuators, Drivers & Controllers), Feedback (Tactile, Force), Application (Automotive & Transportation, Consumer Electronics, Healthcare, Gaming, Engineering, Education & Research), and Region - Global Forecast to 2022.* 2021 [Online]. Available: https:// www.marketsandmarkets.com/Market-Reports/haptic-technology-market-443.html (accessed: Feb. 14 2021)

[4] Haptics Industry Forum, *New specification for HD haptics released.* 2020 [Online]. Available: https://hapticsif.org/ (accessed: Feb. 14 2021)

[5] V. Hayward and K. E. MacLean, "Do it yourself haptics: part I," *IEEE Robot. Automat. Mag.*, vol. 14, no. 4, pp. 88–104, 2007, doi: 10.1109/M-RA.2007.907921.

[6] L. Jones, *Haptics*. Cambridge: MIT Press, 2018.

[7] S. J. Lederman and R. L. Klatzky, "Haptic perception: a tutorial," *Attention, Perception & Psychophysics*, vol. 71, no. 7, pp. 1439–1459, 2009, doi: 10.3758/APP.71.7.1439.

[8] K. E. MacLean and V. Hayward, "Do It Yourself Haptics: Part II [Tutorial]," *IEEE Robot. Automat. Mag.*, vol. 15, no. 1, pp. 104–119, 2008, doi: 10.1109/M-RA.2007.914919.

[9] C. Moussette, *Simple haptics: Sketching perspectives for the design of haptic interactions*. Umeå: Umeå Institute of Design, Umeå University, 2012.

[10] E. Kim and O. Schneider, "Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Honolulu HI USA, 2020, pp. 1–13.

[11] S. J. Breitschaft, S. Heijboer, D. Shor, C.-C. Carbon, and E. Tempelman, "Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.

[12] M. Sreelakshmi and T. D. Subash, "Haptic Technology: A comprehensive review on its applications and future prospects," *Materials Today: Proceedings*, vol. 4, no. 2, pp. 4182–4187, 2017, doi: 10.1016/j.matpr.2017.02.120.

[13] Y. Gaffary and A. Lécuyer, "The use of haptic and tactile information in the car to improve driving safety: A Review of Current Technologies," *Front. ICT*, vol. 5, p. 445, 2018, doi: 10.3389/fict.2018.00005.

[14] A. O'Halloran, F. O'Malley, and P. McHugh, "A review on dielectric elastomer actuators, technology, applications, and challenges," *J. Appl. Phys.*, vol. 104, no. 7, p. 71101, 2008, doi: 10.1063/1.2981642.

[15] S. Biswas and Y. Visell, "Emerging Material Technologies for Haptics," *Adv. Mater. Technol.*, vol. 4, no. 4, p. 1900042, 2019, doi: 10.1002/admt.201900042.
[16] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, no. 1, pp. 385–409, 2018, doi: 10.1146/annurev-control-060117-105043.
[17] Boreas Technologies, *Haptic Learning Center.* 2020 [Online]. Available: https://www.boreas.ca/pages/piezo-haptics-learning-center (accessed: Apr. 9 2020).
[18] Immersion Corporation, *Haptics in Touch Screen HandHeld Devices.* 2017 [Online]. Available: https://www.immersion.com/wp-content/uploads/2017/08/haptics-in-touch-screen-hand-held-devices.pdf (accessed: Feb. 21 2020).
[19] S. Rao, *High-definition haptics: Feel the difference!* 2012 [Online]. Available: http://www.ti.com/lit/an/slyt483/slyt483.pdf (accessed: Feb. 21 2020).
[20] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces," *IEEE Transactions on Haptics*, 2020, doi: 10.1109/TOH.2020.2990712.
[21] B. Banter, "Touch screens and touch surfaces are enriched by haptic force-feedback," *Information Display*, vol. 26, no. 3, pp. 26–29, 2010.
[22] C.-C. Carbon, "Psychology of Design," *Des. Sci.*, vol. 5, p. 339, 2019, doi: 10.1017/dsj.2019.25.
[23] S. J. Breitschaft, S. Clarke, and C.-C. Carbon, "A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering," *Frontiers in psychology*, vol. 10, no. 1470, 2019, doi: 10.3389/fpsyg.2019.01470.
[24] C.-C. Carbon and M. Jakesch, "A model for haptic aesthetic processing and its implications for design," *Proc. IEEE*, vol. 101, no. 9, pp. 2123–2133, 2013, doi: 10.1109/JPROC.2012.2219831.
[25] V. Z. Perez Ariza and M. Santís-Chaves, "Interfaces Hapticas: Sistemas Cinestesicos vs. Sistemas Tactiles," *Revista EIA*, vol. 13, no. 26, 2017, doi: 10.24050/reia.v13i26.1065.
[26] M. Giordano *et al.,* "Mid-Air Haptics for Control Interfaces," in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, Montreal QC, Canada, 2018, pp. 1–8.
[27] P. Kourtesis, F. Argelaguet, S. Vizcay, M. Marchal, and C. Pacchierotti, *Electrotactile feedback for hand interactions: A systematic review, meta-analysis, and future directions*, 2021, arXiv preprint arXiv:2105.05343.
[28] L. A. Jones, "Perspectives on the evolution of tactile, haptic, and thermal displays," *Presence: Teleoperators and Virtual Environments*, vol. 25, no. 3, pp. 247–252, 2016, doi: 10.1162/PRES_a_00266.
[29] HapticLabs.io, *A knowledge-base to get you started designing with haptic feedback.* 2021 [Online]. Available: https://www.hapticlabs.io/ (accessed: Oct. 15 2021).
[30] Lofelt GmbH, *Get Creative with Haptic Design.* 2020 [Online]. Available: https://lofelt.com/design (accessed: Dec. 3 2020).
[31] S. M. Petermeijer, D. A. Abbink, M. Mulder, and J. C. F. de Winter, "The effect of haptic support systems on driver performance: A Literature Survey," *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 467–479, 2015, doi: 10.1109/TOH.2015.2437871.
[32] Apple, *Human Interface Guidelines: Haptics.* 2021 [Online]. Available: https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/haptics/ (accessed: Jan. 27 2021).
[33] Google Inc., *Android Haptics.* 2020 [Online]. Available: https://material.io/design/platform-guidance/android-haptics.html (accessed: Oct. 28 2020).
[34] Adafruit, *Vibrating Mini Motor Disc.* 2020 [Online]. Available: https://www.adafruit.com/product/1201 (accessed: Mar. 18 2020).
[35] Sparkfun, *Vibration Motor.* 2020 [Online]. Available: https://www.sparkfun.com/products/8449 (accessed: Dec. 3 2020).
[36] Precision Microdrives, *Eccentric Rotating Mass Vibration Motors - ERMs.* 2020 [Online]. Available: https://www.precisionmicrodrives.com/vibration-motors/eccentric-rotating-mass-vibration-motors-erms/ (accessed: Dec 3 2020).
[37] Grewus, *ERM 1003C A.* 2021 [Online]. Available: https://www.grewus.de/produkte/erm-1003c-a/ (accessed: Jan. 27 2021).
[38] Texas Instruments, *Haptic motor drivers – Produkte.* 2021 [Online]. Available: https://www.ti.com/de-de/motor-drivers/actuator-drivers/haptic-motor-drivers/products.html (accessed: Aug. 10 2021).
[39] Dialog Semiconductor, *DA7280: Ultra-Low-Power Wideband Haptic Driver for ERM and LRA Actuators.* 2021 [Online]. Available: https://www.mouser.com/datasheet/2/713/da7280-product-brief-v0p01_sw_dhr-1623677.pdf (accessed: Jan. 27 2021).
[40] Cypress, *CapSense®Plus™ Controller with Integrated Haptics and SmartSense™ Auto-Tuning Technology.* 2020 [Online]. Available: https://www.cypress.com/file/108611/download (accessed: Mar. 23 2020).
[41] Murata Manufacturing, *Murata introduces Piezo Vibe for wearable device.* 2020 [Online]. Available: https://www.murata.com/en-eu/products/info/mechatronics/actuator/2017/0321 (accessed: Mar. 19 2020).
[42] H2W Tech, *Voice Coil Actuators vs. Solenoids: What is the difference?* 2021 [Online]. Available: https://www.h2wtech.com/blog/voice-coil-actuators-vs-solenoids (accessed: Jan. 27 2021).
[43] Johnson Electric, *Haptic Actuators.* 2021 [Online]. Available: https://www.johnsonelectric.com/en/product-technology/motion/haptic-motion-products/haptic-actuators (accessed: Jan. 27 2021).
[44] Adafruit, *Solenoids.* 2020 [Online]. Available: https://www.adafruit.com/category/231 (accessed: Dec. 3 2020).
[45] iFixit, *Inside Apple's Force Touch Trackpad. 2015* [Online]. Available: https://www.youtube.com/watch?v=x3B3bHt8ya8 (accessed: Mar. 20 2020).
[46] Trama Engineering, *Niceclick.* 2020 [Online]. Available: http://www.niceclick.eu/ (accessed: Mar. 23 2020).
[47] F. Cerruti, "Haptic actuator and haptic interface comprising at least one of such actuators," WO2019003254A2, Italien PCT/IT2018/000089, Jan 13, 2019.
[48] E. Tunca, R. Fleischer, L. Schmidt, and T. Tille, "Advantages of active haptics on touch surfaces," in *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2016, pp. 137–144.
[49] E. Tunca, I. Zoller, and P. Lotz, "An Investigation into Glance-free Operation of a Touchscreen With and Without Haptic Support in the Driving Simulator," in *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Toronto ON Canada, 2018, pp. 332–340.
[50] F. Beruscha, W. Krautter, A. Lahmer, and M. Pauly, "An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens," in *2017 IEEE World Haptics Conference (WHC)*, Munich, Germany, 2017, pp. 201–206.
[51] Audi AG, *Haptisches und akustisches Feedback einstellen.* 2020 [Online]. Available: https://www.audi.de/de/brand/de/erklaervideos/layer/a8-feedback.html (accessed: Mar. 20 2020).
[52] C. Kessels, *An in-depth look at the UX of the Porsche Taycan.* 2019 [Online]. Available: https://uxdesign.cc/an-in-depth-look-at-the-ux-design-of-the-porsche-taycan-540254d6d996 (accessed: Mar. 20 2020).
[53] Bosch, *Bosch NeoSense Display with haptic feedback.* [Online]. Available: https://www.youtube.com/watch?v=tuRr1cST74Q (accessed: Mar. 20 2020).
[54] Bosch, *CES 2016 Innovation Award für neuartigen Touchscreen von Bosch*, 2015. Accessed: Mar. 20 2020. [Online]. Available: https://www.bosch-presse.de/pressportal/de/de/ces-2016-innovation-award-fuer-neuartigen-touchscreen-von-bosch-35981.html
[55] Precision Microdrives, *Linear Resonant Actuators - LRAs.* 2020 [Online]. Available: https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/ (accessed: Feb. 23 2020).
[56] Jinlong Machinery, *Coin Linear Vibration Motors (LRA's).* 2021 [Online]. Available: https://vibration-motor.com/products/coin-vibration-motors/coin-linear-resonant-actuators-lra (accessed: Feb. 23 2021).
[57] Actronika, *Haptic Technology.* 2020 [Online]. Available: https://www.actronika.com/haptic-technology (accessed: Nov. 30 2020).
[58] Cirrus Logic, *Enhancing the Haptics Feedback Experience.* 2020 [Online]. Available: https://www.cirrus.com/our-technology/haptics/ (accessed: Nov. 30 2020).
[59] Dixon and Taylor, *Good Vibrations: How Apple Dominates the Touch Feedback Game.* 2019 [Online]. Available: https://de.ifixit.com/News/16768/apple-taptic-engine-haptic-feedback (accessed: Dec. 7 2020).
[60] Wit Rigs, *iPhone XR Teardown | I Broke Open the Taptic Engine.* 2018 [Online]. Available: https://www.youtube.com/watch?v=G-xnVAoeTbE&feature=youtu.be&t=409&app=desktop (accessed: Dec. 7 2020).
[61] Lofelt GmbH, *Lofelt L5 Acutator.* 2020 [Online]. Available: https://e2e.ti.com/cfs-file/__key/communityserver-discussions-components-files/6/Lofelt-L5-Actuator-Datasheet.pdf (accessed: Mar. 23 2020)

[62] TactileLabs, *Products.* 2020 [Online]. Available: http://tactilelabs.com/products/ (accessed: Nov. 30 2020).
[63] Grewus, *Exciter und Voice-Coil-Aktuatoren für allgemeine haptische Rückmeldungen.* 2021 [Online]. Available: https://www.grewus.de/exciter-und-voice-coil-aktuatoren-fuer-allgemeine-haptische-rueckmeldungen/ (accessed: Jan. 27 2021).
[64] Sparkfun, *Surface Transducer - Large.* 2020 [Online]. Available: https://www.sparkfun.com/products/10975] (accessed: Dec. 3 2020).
[65] iFixit, *PlayStation 5 Teardown.* 2021 [Online]. Available: https://www.ifixit.com/Teardown/PlayStation+5+Teardown/138280 (accessed: Oct. 12 2021).
[66] Alps Alpine, *HAPTIC™ Reactor.* 2020 [Online]. Available: https://tech.alpsalpine.com/prod/e/html/haptic/ (accessed: Mar. 18 2020).
[67] H. Ngyuen, *ALPS Haptic Reactor Quadra Will Probably Power Your Next-Gen Gaming Controller.* 2020 [Online]. Available: https://www.ubergizmo.com/2018/10/alps-haptic-reactor-quadra/ (accessed: Apr. 14 2020).
[68] Nanoport, *TacHammer.* 2021 [Online]. Available: https://nanoport.io/haptics/ (accessed: Jan. 27 2021).
[69] Nanoport, *TacHammer Development Kit.* 2021 [Online]. Available: https://nanoport.io/wp-content/uploads/2019.02.11-Dev-Kit-User-Guide.pdf (accessed: Jan. 27 2021).
[70] Microchip, *MTCH810.* 2020 [Online]. Available: https://www.microchip.com/wwwproducts/en/MTCH810 (accessed: Mar. 23 2020).
[71] Texas Instruments, *Piezo drivers – Products.* 2020 [Online]. Available: http://www.ti.com/motor-drivers/actuator-drivers/piezo-drivers/products.html (accessed: Mar. 23 2020).
[72] Dongwoon Anatech, *HD Haptic driver IC.* 2020 [Online]. Available: http://www.dwanatech.com/eng/sub/sub02_0105.php?cat_no=16 (accessed: Apr. 21 2020).
[73] Adafruit, *Adafruit DRV2605L Haptic Controller Breakout.* 2020 [Online]. Available: https://learn.adafruit.com/adafruit-drv2605-haptic-controller-breakout (accessed: Mar. 23 2020).
[74] Murata, *Piezoelectric Diaphragms.* 2020 [Online]. Available: https://www.murata.com/en-eu/products/sound/diaphragm (accessed: Mar. 23 2020).
[75] Kyocera Corporation, *Single Plate Piezo Elements.* 2020 [Online]. Available: https://global.kyocera.com/prdct/fc/product/category/piezoelectric/piezo001.html (accessed: Mar. 23 2020).
[76] Kyocera Corporation, *Piezoelectric Ceramics.* 2020 [Online]. Available: https://global.kyocera.com/prdct/fc/list/category/piezoelectric/ (accessed: Mar. 23 2020).
[77] TDK, *Piezo Haptic Solutions: Touch me – feel me!* 2021 [Online]. Available: https://www.tdk-electronics.tdk.com/de/190976/tech-library/artikel/applications---cases/applications---cases/touch-me---feel-me-/2530404 (accessed: Jan. 27 2021).
[78] TDK, *Haptic Devices in the ICT sector.* 2021 [Online]. Available: https://product.tdk.com/info/en/products/sw_piezo/haptic/piezohapt/technote/apn_ict-haptics.html (accessed: Jan. 27 2021).
[79] TDK, *PiezoHapt™ Actuators: Selection Guide, Piezoelectric actuators for haptic feedback.* 2021 [Online]. Available: https://product.tdk.com/info/en/products/sw_piezo/haptic/piezohapt/index.html (accessed: Jan. 27 2021).
[80] TDK, *PowerHap™ Actuators.* 2021 [Online]. Available: https://product.tdk.com/info/de/products/sw_piezo/haptic/powerhap/index.html (accessed: Jan. 27 2021).
[81] D.-S. Choi and S.-Y. Kim, "Transparent Film-Type Vibrotactile Actuator Array and Its Haptic Rendering Using Beat Phenomenon," *Sensors (Basel, Switzerland)*, vol. 19, no. 16, 2019, doi: 10.3390/s19163490.
[82] Q. van Duong, V. P. Nguyen, A. T. Luu, and S. T. Choi, "Audio-Tactile Skinny Buttons for Touch User Interfaces," *Scientific reports*, vol. 9, no. 1, p. 13290, 2019, doi: 10.1038/s41598-019-49640-w.
[83] C. Frisson *et al.,* "Designing Vibrotactile Widgets with Printed Actuators and Sensors," in *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology - UIST '17*, Québec City, QC, Canada, 2017, pp. 11–13.
[84] P. Poncet *et al.,* "Design and realization of electroactive polymer actuators for transparent and flexible haptic feedback interfaces," in *2016 17th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, Montpellier, France, 2016, pp. 1–5.
[85] P. Poncet *et al.,* "Static and dynamic studies of Electro-Active Polymer Actuators and integration in a demonstrator," *Actuators*, vol. 6, no. 2, p. 18, 2017, doi: 10.3390/act6020018.
[86] Piezotech, *Piezotech® FC and Piezotech® RT: actuators.* 2020 [Online]. Available: https://www.piezotech.eu/en/Applications/Actuators/ (accessed: Mar. 24 2020).
[87] Wacker, *NEXIPAL®.* 2020 [Online]. Available: https://www.wacker.com/cms/en-us/products/brands/nexipal/nexipal.html (accessed: Mar. 24 2020).
[88] Novasentis, *Novasentis.* 2020 [Online]. Available: https://www.novasentis.com/ (accessed: Mar. 24 2020).
[89] Microchip, *HV56020: Dual 250V Haptic Drive Amp Array w/Boost.* [Online]. Available: https://www.microchip.com/wwwproducts/en/HV56020
[90] J. Mohd Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities," *Materials & Design (1980-2015)*, vol. 56, pp. 1078–1113, 2014, doi: 10.1016/j.matdes.2013.11.084.
[91] M. Gondo, "Impact drive type actuator," US20130145760A1, Japan JP2010185151.
[92] M. Gondo, "Tactile feedback device," WO2012023606A1 WO2012023606A1.
[93] Cambridge Mechatronics, *CML Technology: Patented SMA Platform Technology.* 2021 [Online]. Available: https://www.cambridgemechatronics.com/en/cml-technology/ (accessed: Jan. 25 2021).
[94] S. Heijboer, S. J. Breitschaft, and C.-C. Carbon, "Characterization of Active Haptic Feedback for User Interface Design and Development," in *IEEE World Haptics Conference 2019*, Tokyo, 2019.
[95] V. Levesque *et al.,* "Enhancing physicality in touch interaction with programmable friction," in *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, Vancouver, BC, Canada, 2011, p. 2481.
[96] V. Levesque, L. Oram, and K. E. MacLean, "Exploring the design space of programmable friction for scrolling interactions," in *2012 IEEE Haptics Symposium* , Vancouver, BC, Canada, 2012, pp. 23–30.
[97] S. J. Breitschaft and C.-C. Carbon, "An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.
[98] S. J. Breitschaft, A. Pasthukov, and C.-C. Carbon, "Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Display," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.
[99] Aito, *Digital Solution for a Physical Experience.* 2021 [Online]. Available: https://aito-touch.com/aitochip (accessed: Jan. 27 2021).
[100] Kyocera Corporation, *Haptivity: Virtual reality for mechanical button feeling.* 2021 [Online]. Available: http://www.kyocera.eu/index/products/lcds_glass_glass_touch_panels/haptivity.html (accessed: Jan. 27 2021).
[101] Boreas Technologies, *We Enable Piezo Haptics.* 2021 [Online]. Available: https://www.boreas.ca/ (accessed: Jan. 27 2021).
[102] Boreas Technologies, *SmartClick 2.1: Buttonless Smartphone Prototype.* 2021 [Online]. Available: https://www.boreas.ca/pages/smartclik-2-1-buttonless-smartphone-prototype (accessed: Jan. 27 2021).
[103] Boreas Technologies, *TDK cooperates with Boréas on smart haptic solutions*, 2019. Accessed: https://www.boreas.ca/blogs/press-center/tdk-cooperates-with-boreas-on-smart-haptic-solutions?_pos=2&_sid=342b66225&_ss=r. (accessed: Jan. 27 2021).
[104] C. D. Shultz, M. A. Peshkin, and J. E. Colgate, "Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek," in *2015 IEEE World Haptics Conference (WHC)*, Evanston, IL, 2015, pp. 57–62.
[105] R. H. Osgouei, "Electrostatic Friction Displays to Enhance Touchscreen Experience," in *Modern Applications of Dielectrics and Electrostatics in Engineering, Physics, Chemistry, Biology and Medicine [Working Title]*: IntechOpen, 2019.
[106] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "TeslaTouch: electrovibration for touch surfaces," in *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, New York, New York, USA, 2010, pp. 283–292.
[107] S. J. Breitschaft, A. Pastukhov, and C.-C. Carbon, "Where's My Button: Evaluating the User Experience of Surface Haptics in Featureless

Automotive User Interfaces," *IEEE Transactions on Haptics*, PP, 2021, doi: 10.1109/TOH.2021.3131058.
[108] Z. Radivojevic, C. Marinelli, T. Ryhanen, P. Beecher, and P. Andrew, "Apparatus for providing nerve stimulation and related methods," US8805517B2.
[109] Microsoft, *Beyond Tapping and Sliding.* 2014 [Online]. Available: https://www.microsoft.com/en-us/research/blog/beyond-tapping-sliding/?from=http%3A%2F%2Fresearch.microsoft.com%2Fen-us%2Fnews%2Ffeatures%2Fhaptics-080514.aspx (accessed: Jan. 27 2021).
[110] P. LoPresti, *Surface Haptics: A Safer Way for Drivers to Operate Smooth-Surface Controls.* 2020 [Online]. Available: https://www.electronicdesign.com/markets/automotive/article/21145025/surface-haptics-a-safer-way-for-drivers-to-operate-smoothsurface-controls (accessed: Jan. 27 2021).
[111] Tanvas, *TanvasTouch.* 2021 [Online]. Available: https://tanvas.co/products/mimovue-with-tanvastouch/ (accessed: Jan. 27 2021).
[112] Tanvas, *TanvasTouch for Automotive: Feel More than the Road.* 2021 [Online]. Available: https://tanvas.co/sample-applications/automotive/ (accessed: Feb. 14 2021).
[113] J. T. Linjama and V. Mäkinen, "E-Sense screen: Novel haptic display with Capacitive Electrosensory Interface," in *Haptic and Audio Interaction Design: 4th International Conference, HAID 2009 Dresden, Germany, September 10-11, 2009 Proceedings*, 2009.
[114] Engadget, *Toshiba brings texture to touch.* 2010 [Online]. Available: https://www.engadget.com/2010-05-21-toshiba-brings-texture-to-touch-video.html (accessed: Jan. 27 2021).
[115] M. Biet, F. Giraud, and B. Lemaire-Semail, "Squeeze film effect for the design of an ultrasonic tactile plate," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 54, no. 12, pp. 2678–2688, 2007, doi: 10.1109/TUFFC.2007.596.
[116] J. Mullenbach, C. Shultz, A. M. Piper, M. Peshkin, and J. E. Colgate, "Surface haptic interactions with a TPad tablet," in *Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology - UIST '13 Adjunct*, St. Andrews, Scotland, United Kingdom, 2013, pp. 7–8.
[117] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin, "T-PaD: Tactile Pattern Display through Variable Friction Reduction," in *World Haptics 2007: Proceedings : Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems : 22-24 March, 2007, Tsukuba, Japan*, Tsukuba, Japan, 2007, pp. 421–426.
[118] Fujitsu, *Fujitsu Develops Prototype Haptic Sensory Tablet*, 2014. Accessed: Jan. 27 2021. [Online]. Available: https://www.fujitsu.com/global/about/resources/news/press-releases/2014/0224-01.html
[119] J. V. Chamary, *The iPhone 7 Killer Feature Should Be Haptic Feedback.* 2015 [Online]. Available: https://www.forbes.com/sites/jvchamary/2015/09/25/haptic-feedback/ (accessed: Apr. 16 2020).
[120] Hap2U, *Haptic Technology.* 2021 [Online]. Available: https://www.hap2u.net/haptic-technology/ (accessed: Feb. 14 2021).
[121] CEA Tech, *Haptic Activities @ CEA Tech.* 2018 [Online]. Available: http://www.cea.fr/cea-tech/leti/english/Documents/pres-WS-LID-2018/MEMS/HAPTICS%20CEA%20TECH.pdf (accessed: Jan. 27 2021).
[122] C. Hudin, J. Lozada, and V. Hayward, "Localized Tactile Feedback on a Transparent Surface through Time-Reversal Wave Focusing," *IEEE Transactions on Haptics*, vol. 8, no. 2, pp. 188–198, 2015, doi: 10.1109/TOH.2015.2411267.
[123] CEA Tech, *CES 2019 : CEA Tech to exhibit at CES Las Vegas on January 8-11.* 2019 [Online]. Available: http://www.cea-tech.fr/cea-tech/english/Pages/agenda/CES-2019.aspx?Type=Chapitre&numero=7 (accessed: Jan. 27 2021).
[124] Jordan Crook, *Google acquired Redux, a U.K. startup focused on audio and haptics.* 2018 [Online]. Available: https://techcrunch.com/2018/01/11/google-acquired-redux-a-u-k-startup-focused-on-audio-and-haptics/ (accessed: Mar. 16 2020).
[125] S. J. Breitschaft and C.-C. Carbon, "Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design," *Front. Psychol.*, vol. 12, p. 2619, 2021, doi: 10.3389/fpsyg.2021.646986.
[126] D. Shor *et al.,* "Designing Haptics: Improving a Virtual Reality Glove with Respect to Realism, Performance, and Comfort," *IJAT*, vol. 13, no. 4, pp. 453–463, 2019, doi: 10.20965/ijat.2019.p0453.

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A.3 A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering

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A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering

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Driving a car is a highly visual task. Despite the trend towards increased driver assistance and autonomous vehicles, drivers still need to interact with the car for both driving and non-driving relevant tasks, at times simultaneously. The often-resulting high cognitive load is a safety issue, which can be addressed by providing the driver with alternative feedback modalities, such as haptics. Recent trends in the automotive industry are moving towards the seamless integration of control elements through touch-sensitive surfaces. Psychological knowledge on optimally utilizing haptic technologies remains limited. The literature on automotive haptic feedback consists mainly of singular findings without putting them into a broader user context with respect to haptic design of interfaces. Moreover, haptic feedback has primarily been limited to the confirmation of control actions rather than the searching or finding of control elements, the latter of which becomes particularly important considering the current trends. This paper presents an integrated framework on haptic processing in automotive user interfaces and provides guidelines for haptic design of user interfaces in car interiors.

Keywords: haptics, automotive, user experience, framework of haptic processing, interaction design, haptic design, haptic interface

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INTRODUCTION

Studies on haptic feedback in automotive use cases usually start with several remarks about the staggering increase in control options in car interiors and how they are overwhelming for users in terms of cognitive load and distraction in driving situations. Deploying haptic perception reduces reaction time and alleviates cognitive load in the visually demanding task of driving; ultimately, it increases safety (Petermeijer et al., 2015). However, most studies concentrate on technology-based haptic innovations, incorporating aspects such as proof of concept, usability tests, and a strong focus on technical solutions (Banter, 2010; Gaffary and Lécuyer, 2018). This one-eyed landscape of research literature makes it difficult for most stakeholders (such as designers, engineers, and usability researchers) to understand and predict why certain types of haptic feedback in user interfaces succeed while others fail. This is especially true for the automotive industry in which user interfaces need to be intuitive and usable. Practitioners in the automotive industry are currently facing disruptive changes. Through changing perspectives on mobility concepts, functionality in car interiors is dramatically increasing, positively influencing the demand for more flexible, adaptive and intelligent interface solutions. Design studies by different car manufacturers and automotive suppliers depict a clear vision of future car interiors and user interfaces. Concept studies, such as the BMW Vision iNEXT (BMW Group, 2018), are dominated by clean and harmonic interior surfaces that incorporate not only multiple layers of functionality (e.g., sensing, lighting, and haptics) but also a wide variety of new materials (metal, wood, and textiles) in user interfaces (Aito, 2018; Preh, 2018; QUAD Industries, 2018). These so-called "smart surfaces" facilitate the development of dynamically responding and context-sensitive surfaces in interaction situations. The appearance of user interfaces in the car has changed quite drastically in recent years. The amount of visible buttons in car interiors decreases through the seamless integration of interaction panels into design surfaces (see **Figure 1**) and the use of touchscreens. Active haptic technologies support the trend toward surface integration by enabling tactile feedback on seamless surfaces (Lust and Schaare, 2016; Aito, 2018). Most touchscreens and touch-sensitive surfaces, though being potentially aesthetically pleasing, nowadays lack specific haptic feedback. As a consequence, drivers wishing to find elements on a control panel may need to take their eyes off the street, creating potential safety concerns. This is especially true for the use of large touchscreen interfaces, such as in the current Tesla Model S. Budiu (2019) concludes that virtual buttons require a lot of visual attention without the use of haptic feedback. Using haptic feedback as a technological enabler for surface or optimized search haptics is not yet widespread. Although novel and technically promising solutions exist, many of these lack psychological data and knowledge of human perception.

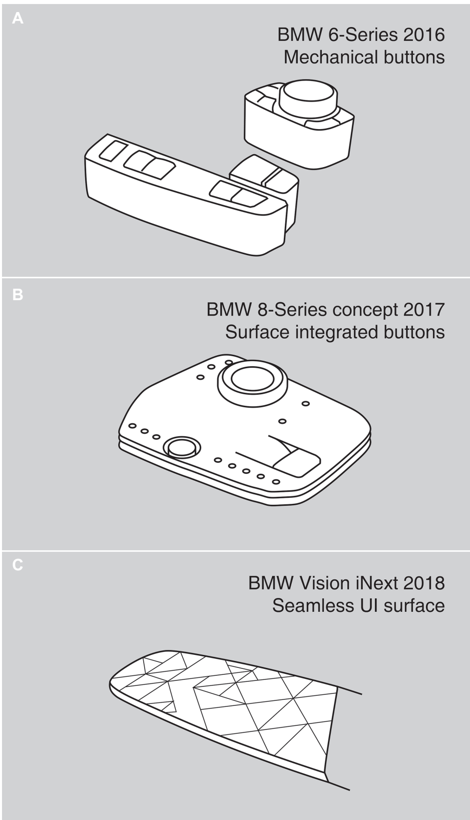

FIGURE 1 | Exemplified depiction of the shift from **(A)** mechanical buttons (BMW Group, 2015) through **(B)** surface-integrated buttons (BMW Group, 2017) to **(C)** seamlessly integrated UI-surfaces (BMW Group, 2018).

With new trends, such as autonomous driving, a drastic increase in touch-sensitive surfaces and the use of new materials in interfaces, psychology-based knowledge on haptic perception and user experience is becoming more important. However, literature on the use of haptic feedback in automotive user interfaces is somewhat fragmented and therefore hard to overlook for practitioners. What is essentially missing is a comprehensive theoretical framework on how users perceive haptic feedback in user interfaces while controlling certain functions.

Motivation and Aim of the Present Paper

The major goal of the this paper is to establish a theoretical framework that outlines and explains haptic processing in automotive user interfaces based on findings from usability studies, perception science, and cognitive psychology. A well-designed haptic interface can help keep the user's eye on the road while controlling, and thus increases driving safety and performance (Kern and Pfleging, 2013).

Current user-centered research on automotive haptic feedback struggles to provide sufficient answers for the challenges posed by the abovementioned trends. Also case studies on currently used interfaces, such as done by Budiu (2019), claim the necessity of haptic feedback in automotive interfaces. Usability studies focus on comparing different interface concepts and technologies by using objective usability measures such as task completion time and error rates. User experience[1] (UX)-factors giving insights on how users interpret certain aspects of the haptic feedback are often neglected. A multitude of studies resembles pure feasibility tests of novel haptic technologies. Generalizability of findings is somewhat limited due to the characteristics of certain haptic technologies. Studies on haptic feedback mostly focus on confirmation and pressing haptics, which overlooks other important steps in the interaction process. A majority of studies reports the effectiveness of haptic feedback on driving safety, but does not provide guidelines as to how haptic feedback can be optimized (for review, see Gaffary and Lécuyer, 2018

[1]The expression User Experience (UX) was first broadly used by Norman (2013). UX comprises all of a user's experiences with a product. This not only entails the user's affective and cognitive associations but also expectations. The focus of user experience design is to meet user's requirements in interacting with a product.

and Petermeijer et al., 2015). Findings are hardly put into a broader user experience context, which leads to a lack of best practices and guidelines on haptic design of automotive user interfaces.

A theoretical framework of literature on haptic feedback (1) enables the detection of gaps in research regarding future automotive haptic technologies, (2) helps stakeholders cope with the challenges and chances posed by human haptic perception, and (3) gives engineers guiding principles in the haptic design of automotive user interfaces.

This paper is structured as follows: (1) a brief overview of the literature on haptic perception and feedback in automotive user interface contexts will be presented, (2) an introduction of a common terminology of haptic feedback in automotive user interfaces will be given, (3) a theoretical framework of haptic processing in automotive interiors will be presented, and (4) practical implications and paradigmatic applications of the framework will be discussed.

HAPTIC PERCEPTION IN AUTOMOTIVE INTERIORS

To understand the complexity of haptic stimuli in automotive interiors, this paper gives a short introduction into haptic perception with respect to its importance in automotive interfaces. For a more general introduction into haptic perception, see Lederman and Klatzky (2009). In the automotive context, the haptic modality is often referred to as a channel capable of alleviating visual and cognitive load (Gaffary and Lécuyer, 2018). This is due to the high amount of visual information that is assumed to be processed during a driving task (Vollrath and Krems, 2011, p. 29). Haptic information in automotive contexts mostly originate from both kinesthetic and tactile (or cutaneous) stimuli. Much of the driving relevant haptic information perceived during driving is not deliberately conveyed *via* user interfaces. These undeliberate information can range from acceleration or lateral forces conveyed by muscles and tendons to vibrations felt due to bumpy road conditions. Nevertheless, focus of user interface designers is to deliberately use haptic feedback for certain use cases. Van Erp and van Veen (2001) describe five different categories of how haptic vibrotactile information can be used in vehicles: warning, spatial, communication, coded, and general information (see **Table 1**). The increasing use of different surface materials also means that haptic surface properties need to be taken into account as a deliberate application of haptic perception. There is an increasing body of research dealing with the aesthetical aspects of material properties (Etzi et al., 2014). Carbon and Jakesch (2013) stress in their "model for haptic aesthetic processing" that with higher cognitive processing of haptic objects, aesthetical and utilization evaluations are integrated into perception of an object. During exploration, associations such as pleasantness and arousal are connected with the explored surfaces and materials. An example is the high quality feel of heavy and sturdy objects. Therefore, the list of haptic information categories proposed in **Table 1** may be extended by aestehtic impressions.

TABLE 1 | Classes of haptic information in automotive interior based on van Erp and van Veen (2001).

Category	Description	Possible application
Spatial	Using haptic information to indicate the location of important objects	Awareness of surrounding,[1] blind spot[2]
Warning	Using haptic information to warn the driver in dangerous situations	Lane departure,[1] collision prevention[1]
Communication	Using haptic information as a subtle communication channel	Navigation[1]
Information	Using haptic information to display current status information regarding the car	Speed control,[1] Maneuver support,[1] eco-friendly[2]
Interaction	Using haptic information in interaction with control units	Controlling the car's functions[1]
Aesthetical[3]	Using haptic information to evoke aesthetical appreciation[4]	Brand image,[3] perceived quality[5]

Possible applications are allocated to a single category for a clear overview. However, a few applications may overlap in their information category, such as lane departure, whose main goal is to warn the driver, but also gives information on the location on the road.
[1]Gaffary and Lécuyer (2018), [2]Petermeijer et al. (2015), [3]Carbon and Jakesch (2013), [4]Swindells et al. (2007), [5]Glohr et al. (2015).

Haptic Feedback in Automotive User Interfaces

This section gives a short overview on the literature of haptic feedback in situations of controlling a car's function. Gaffary and Lécuyer (2018) and Petermeijer et al. (2015) give a broad overview on the use and effectiveness of haptic feedback in the automotive context. They emphasize the impact of haptic feedback on driving safety, reaction time, and driver performance. There are also studies challenging these findings, for instance, Pitts et al. (2012a) found a mixed influence of haptic feedback on driving relevant experimental variables. Performance in a lane change test did not significantly differ across different feedback modalities (visual, visual + haptic, visual + audio, visual + haptics + audio). Haptic feedback was chosen based on preference ratings in a preliminary study. However, in the main study, participants reported that haptic feedback in the visual + haptic, and also in the visual + audio + haptic condition was not strong enough to be perceived robustly. Participants showed a preference for combined visual and auditory feedback in confidence and hedonic ratings. Possibly, the choice of haptic feedback impulse was an influencing factor in this outcome. In fact, in an earlier study, Pitts et al. (2009) pointed out an increase in acceptance and user experience when haptic feedback is involved. Pitts et al. (2010) were able to show an increase in confidence with the haptic feedback modality. Also, Weddle and Yu (2013) found that users felt more confident and pleasant by using an interface with haptic feedback in comparison to a non-haptic tablet. Furthermore, Pitts et al. (2012a) found that the importance of haptic feedback increases when visual feedback is delayed in interactive situations. But also within the haptic modality, high latency from touch to feedback can already decrease task performance and satisfaction (Weddle et al., 2013). Rydström et al. (2009) concluded that the usage of haptic information in control units encourages users to keep their eyes on the road. Since haptic exploration is a serial perception process, subjects tend to take longer for task completion, and hence mainly rely on visual information. Nonetheless, Burnett and Irune (2009) describe haptic perception as a key indicator of perceived quality in car switches. Ng et al. (2017) compared direct touch, pressure-based-touch, and a physical dial as possible input methods and found that pressure-based touch took the longest and produced more but shorter glances than only touch input. They again found shorter task completion times and higher preference ratings for pressure-based buttons and the turning knob with haptic feedback in a previous study (Ng and Brewster, 2016). Richter et al. (2010) conducted a preliminary study with their *HapTouch*-Device, a force-sensitive input device with haptic feedback, which showed reduced error rates and task completion times for a haptic feedback condition. They reported a positive influence of haptic feedback on small and large touchscreen devices—although this finding is based on a small sample size of five participants only. Grane and Bengtsson (2012) found that haptic feedback in rotary control elements can produce fewer turn errors and lower task completion times than pure visual feedback. However, they could not detect a correlation between the amount of haptic information and errors or time. Kern and Pfleging (2013) concluded that haptic feedback can be helpful in many driving situations when the implementation of the feedback is carefully considered.

In summary, automotive user interfaces can benefit from the use of haptic feedback, despite challenging findings in multisensory feedback settings. An explanation for the mixed findings may be that the effectiveness of haptic feedback strongly depends on the specific use and implementation of the haptic feedback technology. Unfortunately, there are only few studies examining best practices on how to seamlessly integrate different haptic technologies into interaction concepts.

Common Terminology on Haptic Feedback

In recent years, there is a growing number of companies, especially in the consumer electronic industry, developing and delivering innovative haptic feedback solutions. Many of these tech companies use their own wording to describe their feedback technology. This makes it hard for OEM-developers and consumers to compare different technologies. Additionally, as the research community mainly refers to haptic feedback, there is also a lack of common terminology in the scientific area. Hence, the following section gives a categorization on different terminologies of haptics that are being used in the automotive context. **Figure 2** shows various meanings of the term "haptics" in the context of car interiors. In general, haptics in control elements can be viewed from a technological (How is haptic feedback generated?) and a perceptual perspective (What can be felt by the user? How are the haptic impulses interpreted?). This separation can also be found in Bubb et al. (2015). We will follow a psychological view, where we differentiate between search and confirmation haptics. In the context of searching and identifying user interfaces, surface haptics can be referred to as search haptics (see **Figure 2**).

Surface and Search Haptics

Surface haptics refers to all haptic surface and material properties that can be used in car interiors. One of the rare examples of haptic processing models is the "model of haptic aesthetic processing" developed by Carbon and Jakesch (2013). They presume that high-level processing of haptic stimuli involves utilization and aesthetic evaluation. This means, interior materials convey hedonic as well as functional aspects. Regarding hedonic aspects, surface haptics refers to the use of haptics to evoke aesthetical evaluations. For example, certain surface materials are used to underline certain associations, such as perceived quality, coziness, or warmth, connected to the car (Bubb et al., 2015, p. 285). However, in automotive user

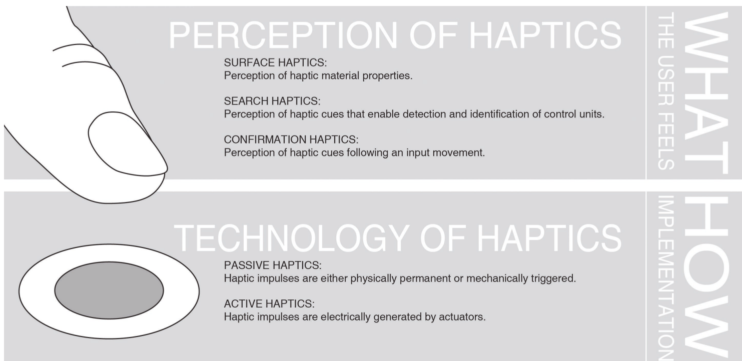

FIGURE 2 | Overview on different terminologies of haptics in the context of automotive interiors. Haptics in automotive user interfaces contains a perception and technological part.

interfaces surface properties such as joints, edges, recesses, other surface geometries, and textures can also have a clear functional reason, for instance, to support drivers in the blind operation of car interfaces to free up visual resources for the primary driving task.

Search haptics refers to the functional use of haptic surface properties, such as joints, ridges, edges, detents, surface geometries and textures as orientation, indication and separation cues to interactive areas in a car interior. Search haptics has so far mainly been a by-product of the mechanical integration of control elements, such as, gaps between buttons. There is little research on how to use haptic cues to optimally support users in finding interactive areas, differentiating between adjacent control elements, and giving users orientation in interior surfaces. The lack of research becomes even more obvious with an increasing use of seamless interactive surfaces in nowadays designs, such as touch and gesture-sensitive surfaces.

Confirmation Haptics

Confirmation haptics refers to clear and specific haptic feedback for changing the operation status of a control element. Confirmation cues can be manifold. The simplest example is the feel of a button click after pressing. The aim of confirmation haptics is to give users a clear and distinctive haptic feedback to increase the guidance for blind operation and ultimately, to increase perceived as well as objective safety.

Still, every interaction concept is based on a technological counterpart – the hardware. In the automotive industry, haptic technologies can be separated into two categories: passive and active haptic feedback technologies – or short *passive* and *active haptics*. Both of these can be applied to search and confirmation haptics.

Passive Haptics

Passive haptics refers to haptic feedback generated by mechanical elements, or physically anchored and permanent stimuli. It involves no external electrical energy input. The energy is generated by pressure from the user, and the haptic feedback is generated by the reaction of the mechanical elements to this energy.

Within surface and search haptics, passive haptics refers to non-changing surface shapes, geometries, and textures. On a computer keyboard, for instance, the hardly noticeable (and in fact widely unnoticed) bumps on the *F* and *J* keys are also a form of passive search haptics[2].

Within confirmation haptics, there is a differentiation between translational and rotational control elements (Bubb et al., 2015). These mainly involve orthogonal movements, such as button presses, or rotary movements (turning knobs). In passive haptic buttons, feedback can be generated by micro-switches, metal domes, and other types of switches in a wide variety of sizes and form factors (e.g., Alps Alpine Co., 2019; C&K Switches, 2019). By applying orthogonal forces to the surface there is an increase in displacement up to a certain force threshold where a jump in force occurs. This “snap” is felt as haptic feedback. Feedback in rotary knobs is mostly generated by mechanical detents. By turning the knob, the mechanics snap into a detent—producing a click feeling (Reisinger, 2009). The haptic feedback is defined by specifically designed force-displacement-curves (Kühner, 2014; Bubb et al., 2015). **Figure 3** depicts characteristic haptic curves of translational and rotational control elements.

Active Haptics

Active haptics refers to haptic feedback that requires external electrical energy input (MacLean, 2008). Typically, a sensor reacts to tangential (e.g., sliding, swiping) or orthogonal (e.g., press) movements of the user which then triggers an actuator. The actuator moves the interaction surface in a manner often characterized by high acceleration and short travel.

A major advantage of active haptic systems is their programmability and flexibility. Haptic impulses can be changed depending on application and situation. The same technology can be used in different automotive use case such as search and confirmation haptics. In order to design an intuitive interface, we need a clear distinction of various haptic signals in a user setting. Palani and Giudice (2016) argue that empirical parameters for specific active haptic technologies may not be applicable to touchscreen-based haptic perception. Some technologies do not employ pressure-sensitive mechanoreceptors. In addition, other technologies and interaction concepts require active finger movements. However, knowledge on how to implement novel active haptic technologies in an automotive user interface including the typical challenges that need to be considered when applying such technologies are still sparse. This is especially true for impulse parameters. Heijboer et al. (2019) collected subjective descriptions and associations of a variety of piezo-actuated signals and made an attempt to structure these descriptions and associations. Understanding how users experience and describe active haptic signals can aid in successfully implementing active haptics in interface design.

In the field of active haptics, there are numerous applicable haptic technologies. These can roughly be categorized into:

- systems that are moving the interactive surface through the use of an actuator, such as low-fidelity vibrotactile feedback (Klatzky et al., 2014) and high-definition feedback (Lust and Schaare, 2016; Aito, 2018),
- systems that employ friction modulation (Meyer et al., 2014) while sliding over a surface, such as ultrasonic friction (Biet et al., 2007) and electrostatic friction (Bau et al., 2010),
- systems that deform the surface, e.g., electroactive polymers (Matysek et al., 2009) and pin arrays (Culbertson et al., 2018).

For an extensive review of haptic technologies we would like to refer to Banter (2010) and Culbertson et al. (2018).

[2]The bumps on the *F* and *J* keys on a keyboard are an easy, but effective way of how haptics can aid in everyday-life. The bumps provide easy finger orientation and reference frame for 10-finger typing—some new notebook keyboard layouts do not provide them anymore, unfortunately, and: users indeed lose control in a quite implicit way.

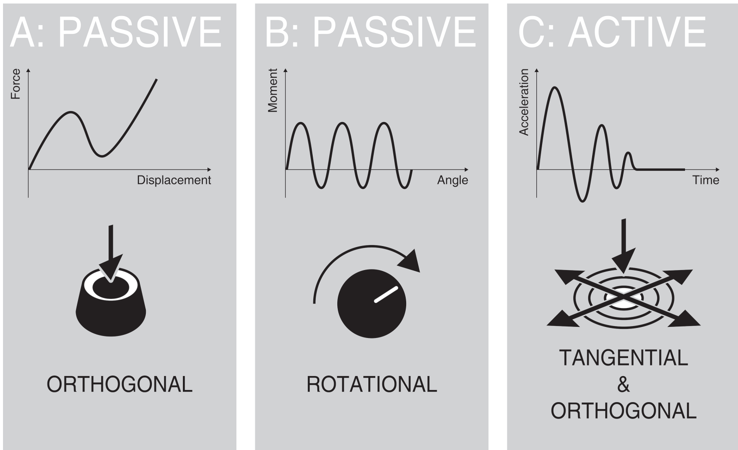

FIGURE 3 | Characteristic haptic curves of a **(A)** passive haptic orthogonal, **(B)** a passive haptic rotational, and **(C)** an active haptic feedback system.

A THEORETICAL FRAMEWORK OF HAPTIC PROCESSING IN AUTOMOTIVE USER INTERFACES

The "theoretical framework of haptic processing in automotive user interfaces" (in short fHAPro-AUTO, see **Figure 4**) focuses on a systematic description of haptic processing in the case of controlling a car's function. More precisely, it aims to explain in a model-based way, how users perceive and integrate different haptic stimuli during an intentional physical interaction. By constructing the model into discrete phases, crucial steps in the perception that allow for the derivation of guidelines in the design process are shown. In a later section of this paper, there is an outline of a possible study design to validate the proposed phases. The framework is based on existing literature in perception sciences, user interface design and user experience as well as observations from everyday practice. Thus, the model does *not* yet provide empirical evidence but systematizes and harmonizes the given literature.

Current Discussions on Automotive User Experience

In recent years, haptics within user experiences and within the automotive context has seen growing interest, leading to interesting discussions relevant to the scope of this framework. This section sums up the most important and relevant models and discussions. The general structure of the fHAPro-AUTO is based on other models in UX. The main difference of the fHAPro-AUTO to other discussions and models in UX is the focus of haptic processing in controlling a car's function including automotive-specific challenges regarding safe and easy-to-use interfaces.

A model in haptic processing not only including perceptual but also cognitive aspects is the "model for haptic aesthetic processing" of Carbon and Jakesch (2013). The general structure of their model and the proposed framework is similar due to the serial nature of haptic processing. Additionally, phase specific top-down processes, such as context of exploration and expectations, and an increasing integration of tactile information and affective evaluations into a holistic mental representation of an interface are aspects that are relevant in both models. A major difference is the focus of the model for haptic aesthetic processing on haptic objects in general, whereas the fHAPro-AUTO is focusing on automotive interfaces.

Gaffary and Lécuyer (2018) provide an extensive review on how haptic feedback can aid various automotive use cases, such as warning and navigation. A classification of how and where haptic information can be conveyed in a car is also given, thus summarizing relevant studies and technologies. In contrast, the proposed framework focuses on how haptic information can be used in the context of controlling a car's function to support the interaction process. This is mentioned only briefly in Gaffary and Lécuyer (2018).

MacLean (2008) carried out another extensive introduction to haptic interface design, providing valuable information on human perception capabilities and constraints, multimodal interaction, haptic feedback systems, and possible uses of haptic feedback in interaction. However, the focus is on everyday objects, such as mobile phones. Although the proposed framework could also be applied to everyday object interaction, the main intention is to give guidelines for automotive interface design.

An interesting discussion on current haptic challenges with regard to structural and technical aspects was led by Schneider et al. (2017). Here, information on the workflow

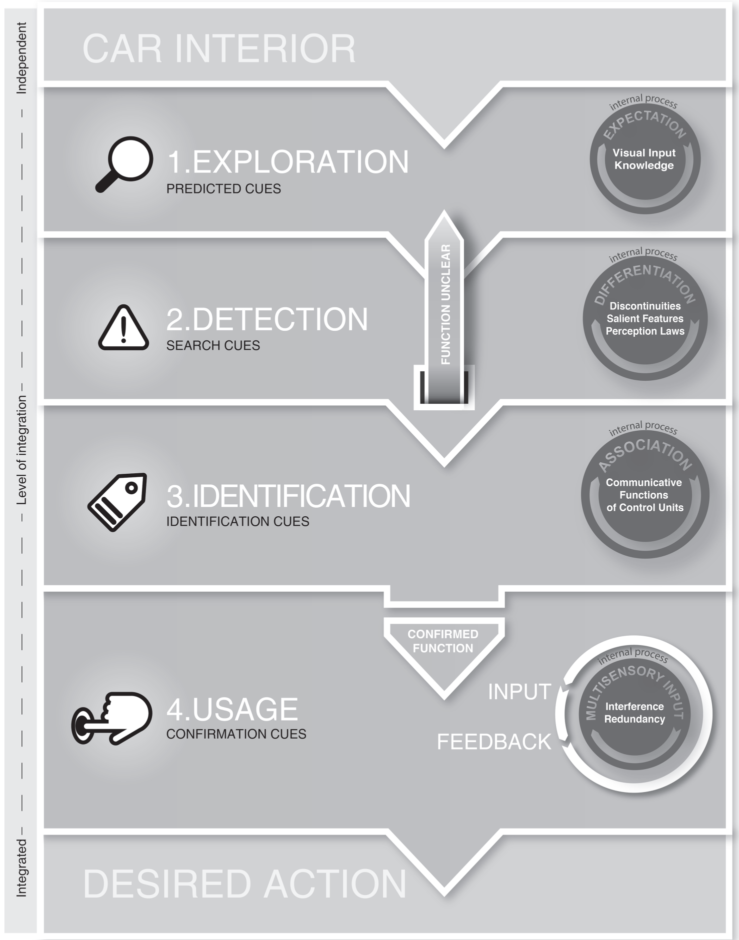

FIGURE 4 | Theoretical framework of haptic processing in automotive user interfaces (fHAPro-AUTO).

in the haptic design process was collected from practitioners in different professional areas. They structured common activities, challenges, and also recommended solutions. A strong point is made for the use of psychological research in haptic design by arguing that haptics *"does not end at the actuator"*. Schneider et al. (2017) give general guidelines on how to design with haptic technologies, which is one of the main differences to the automotive scope of the proposed framework. Some of their sub-themes are also relevant in this case, for example haptic latency to create reliable feedback. They argue that hapticians often deal with user constraints, such as designing *feelable but not seeable* interfaces. The present framework aims to deliver more specific guidelines for this challenge in an automotive context.

General Structure of the Framework

The "fHAPro-AUTO" consists of four discrete and serially proceeding phases with an increasing integration of independent haptic signals into an integrated part of the user interface. The input of the model consists of a car's interior with a multitude of different interactive and non-interactive surfaces. Surface-integrated or hidden-till-light interfaces may not always be visible at first glance. The starting point of haptic processing is a user's intention to control a certain function (such as cruise control, volume or temperature) in a car by manipulating a physical control. The four phases – *Exploration*, *Detection*, *Identification,* and *Confirmation* – are described with respect to relevant findings from haptic perception and cognitive research. As haptic stimuli carry valuable information during the perception process, their design is explicitly discussed. Additionally, phase-specific top-down loops modulating haptic processing are discussed. These top-down loops stand for cognitive processes that influence processing at each phase. They can be seen as reoccurring evaluation cycles that start with the beginning of each phase. These phase-internal processes influence processing by facilitating or hindering evaluation of haptic information.

The framework is based on closed-loop control. Information processing in a specific phase proceeds once required haptic information is adequately assessed by the user. In an interaction situation, it seems reasonable to assume that processing and exploration is proceeding once users categorized haptic as valuable to the interaction process.

The framework focuses on haptic processes in touch interactions that require physical contact with certain surfaces by the use of haptic exploration movements. It does not offer descriptions for interaction processes that are conducted by other sensory modalities to touch, such as gesture or speech. Hence, it is not a holistic explanatory approach to describe multimodal user interactions. However, the model takes into account certain multisensory influences on haptic perception during perception and interaction.

Different Phases of Perception and Top-Down Loops

Context

Context heavily influences perception, already at early phases of perception (Carbon and Jakesch, 2013). Contextual information can be given by a certain situation, task, personal mood, experience, cultural background as well as other information the perceived object is carrying. In a car, the context in somewhat fixed, as the passenger's task is to drive it. Certain relevant driving functions are anchored in a physical user interface, which requires interaction to manipulate. In haptic perception, context cannot only be created by cognitive factors, but also due to material properties and their haptic exploration strategies (Klatzky et al., 1987; Bergmann Tiest, 2010). Haptic materials may feel differently according to which materials were previously touched. For example, the perceived roughness of materials depends on how rough or smooth previously explored surfaces felt (Kahrimanovic et al., 2009). According to research done by Jakesch et al. (2011), functional and aesthetical evaluation of haptic materials rely on contextual information. A car's brand or experience with different user interface concepts modulate the processing of different materials depending on whether they fit into existing interaction concepts or meet expectations set by the brand name.

Processing Phase 1: Exploration

Rationale of the Exploration Phase

Haptic processing and exploration of interior surfaces is initiated by a user's intention to manipulate a physical control in the interior in order to change a certain function. The input of the first stage is a yet unspecified car interior with different interactive areas. In accordance with other models on haptic perception, the initial processing phase is the low-level perceptual analysis of basic surface properties (Klatzky and Lederman, 1993; Carbon and Jakesch, 2013), using various exploration movements (Klatzky et al., 1987). Carbon and Jakesch (2013) presume three different types of exploration during the first encounter with an unknown object: "orthogonal," "tangential," and "measure" exploration. Measure exploration means extraction of haptic object information, such as weight and size, but is less relevant in an automotive use case. In an automotive user interaction context, crucial haptic features are mainly extracted by tangential and orthogonal exploration, e.g., sliding or pressing (Götz, 2007). Using these exploration strategies, users do not only extract basic material properties such as roughness, hardness, slipperiness and thermal cues, but also gain knowledge on additional surface features, such as geometries, shapes and textures (Klatzky et al., 1987; Carbon and Jakesch, 2013). Hence, haptic glances (Klatzky and Lederman, 1995) give a "first impression" of interior surfaces. These are first haptic insights on possibly interesting features that are to be further explored, such as bumps or edges. Processing proceeds to the next stage even if there are no special haptic features that invite the user to further exploration, such as on touchscreens. In this case, user might rely on other modalities for further exploration.

This phase sets the starting points for exploration in further phases. The output of this phase is purely physical perception of possibly interesting haptic cues, without including interpretations of possible functionalities. However, perception of basic haptic features is crucial for the integration of different haptic perceptions into a holistic model of the car interior and constitutes starting point for evaluation in following phases.

Top-Down Loop 1: Expectations

Haptic perception is influenced by expectations at an early phase (Carbon and Jakesch, 2013). A current, intensively discussed theory in cognitive science is the approach of hierarchical predictive coding (see review by Clark, 2013), which emphasizes the importance of expectations and predefined assumptions in perception. To minimize cognitive load, the human makes assumptions about the external world and only uses sensory input to validate previously formed assumptions. Muth et al. (2016) put predictive coding into an aesthetical context by using predictive coding as an explanation for experiencing pleasure in "decoding" ambiguous artwork. This approach may also be applied in a framework of haptic processing. Perception of early material properties may be used to form hypotheses on possible functionalities of interior surfaces and initiate further exploration. Presumptions based on bottom-up perceptions may function as a priming stimulus. Empirical studies have shown that, for instance, priming can be used to facilitate or hinder perception processes (Palmer, 1975; Albrecht and Carbon, 2014).

Expectations include experience and explicit knowledge on tangible user interfaces concepts as well as prior multisensory, particularly visual, input. Experienced users might skip or fast forward the perceptual process due to their knowledge as to where controls are located and how they are activated. Klatzky et al. (1993) propose a strong influence of prior visual information on haptic exploration in a visual preview model. The user builds up an expectation of previsously viewed objects that are evaluated by touch if the visual input is ambiguous. This is especially important for haptic stimuli as there are tactile properties that can hardly be encoded by vision alone, such as hardness, thermal properties, or slipperiness (Baumgartner et al., 2013). Setting and meeting appropriate expectations becomes even more relevant with the use of seamless user interfaces. This is mainly due to the fact that they lack visual information when interfaces are only shown in specific situations. However, visual prior sets the user's expectations about how and what user should explore in a control panel. Contrary to today's daily habits of interaction with touch-sensitive surfaces by tangential swipe and touch gestures, automotive control elements mostly require orthogonal or tangential pressure. If the user's expectations are not meet, for example, a function is not activated by touching, but pressing or interactive surfaces are not coded with haptic feedback, processing is hindered as the user might be confused. Especially using affordances, a term introduced by Gibson (1979), can help to predict possible user expectations.

At an early stage of haptic processing, it is important to meet the user's expectations of a user interface by providing appropriate and easy-to-understand haptic information. This is especially important in designing seamless user interfaces.

Haptic Information: Prediction Cues

Haptic information processed in this phase are prediction cues. These cues mainly attract attention during the exploration process and invite for further exploration, but are not yet connected to a specific functionality. Users connect them to some kind of relevance, such as separators, orientation and reference points. Therefore, stimulus properties can be widespread to raise attention – textures, gratings, edges, joints, or mere unevenness in a surface. In addition, basic haptic properties, such as hardness, roughness, slipperiness and thermal properties need to be taken into account, as they can shape haptic exploration early on (Carbon and Jakesch, 2013).

Processing Phase 2: Detection

Rationale of the Detection Phase

The main goal in the detection phase is to detect interactive surfaces and differentiate them from pure design elements. This detection process can be seen as a goal-driven exploration, which is biased by salient haptic features on surfaces. The input of this phase consists of haptic features that were encoded in the exploration phase. Users exploit discontinuities in surface properties but also various exploration strategies to assess whether there is something that can be pressed, pulled, moved or turned. By scanning the surfaces, the user tries to answer implicit questions like "Where is my button?"

In car interiors, separators of interactive and non-interactive surfaces are mostly joints, edges, and recesses. However, not only boundaries but also haptic sensations within an interactive area may be an intuitive and efficient way to indicate interactivity. For example, Lust and Schaare (2016) proposed using unique haptic feedback to code certain content menus on touchscreen-based haptic devices. Surface features such as edges, raised-dots, and even a certain wobbling due to play, may invite direct interaction due to their functional association. Users detect different haptic sensations, such as different materials and textures, and assess their functional purpose. Processing proceeds to the next phase when relevant discontinuities are perceived. The output of this phase is a representation of where interactive elements are on the surface based on perceived discontinuities. Their functionality is yet unknown. However, it is not yet clear, which perceptual input sets interactive areas clearly apart from non-interactive surfaces and which technologies are appropriate to use. Moreover, it is unclear how transitions between different content areas on touchscreen-based interfaces should be coded in terms of haptic feedback patterns to ensure an eye-free operation. To separate different buttons, differentiation *via* a change in perceptual input has to occur.

Top-Down Loop 2: Differentiation

Processes influencing perception in this phase ease the differentiation of different haptic stimuli. A basic user interface design principle in graphical user interfaces is to make interactive surfaces and important changes visible (Nielsen, 1994; Harley, 2018). The same is true for tangible user interfaces, where interactive areas should be detectable by distinct haptic features. Visually salient stimuli have been shown to capture perceiver's attention (Kerzel and Schönhammer, 2013). For an overview of haptic saliency see Kappers and Bergmann Tiest (2015). Due to their pop-out effect in perception, salient features carry valuable context-sensitive information for the user. Carmakers use changes in haptic geometries, edges and joints to separate different buttons, but also to set them apart from mere design surfaces, which are also indicated in **Figure 1**. This helps the user to blindly find certain controls and keep their eyes on the road. But that is also why a user may effectively be looking for salient stimuli. Users are also guided by prediction cues they perceived in the previous exploration phase. Experimental paradigms, such as haptic search (see also Kappers and Bergmann Tiest, 2015), can help to judge haptic saliency and draw conclusions on the processing of different surface properties. In haptic search paradigms, participants have to decide if certain stimuli properties are amongst the stimulus material they can explore during the experimental procedure. For instance, a high contrast between the target and the distractor stimuli, leads to a fast and easy response action (Lederman and Klatzky, 1997). In user interfaces a high contrast in haptic feedback patterns between control elements and design surfaces facilitates information processing. In contrast, haptic patterns with a low contrast pose confusion and hinder or at least slow down information processing. It seems beneficial to think about specific threshold values that are needed to be reached in order to ensure safe and efficient usage.

Additionally, Gestalt principles (Wagemans et al., 2012a,b) at play when exploring surfaces may influence differentiation. Gallace and Spence (2011b) concluded that most Gestalt laws found for vision are also applicable to haptics. Gestalt psychology shows that humans organize perceptual input in a way that perceived input makes sense. Incorporating different gestalt laws, such as a high figure-ground-contrast, the law of continuation and good Gestalt (Prägnanz) haptic user interface design may be enhanced due to faster processing of different haptic information. For instance, a high figure-ground contrast, meaning using distinct haptic materials for design and interactive surfaces, eases interpretation and processing.

Haptic Information: Search Cues

Important haptic features that are encoded in this phase are search cues. Search cues contain salient properties as they are normally used to mark buttons and other control elements. Therefore, they should mainly consist of discontinuities on surfaces. In general, discontinuity means any kind of haptic feedback on in-car surfaces, which means they are technology-dependent. For passive haptics, it is mainly geometries or shapes elevated or indented on a surface (see **Figure 1**). Examples are edges, raised-lines or raised-dots, detents, joints, recesses or embossments. But also sudden changes of the surface material like a harsh transition from rough to smooth can be interpreted as search haptics. Lederman and Klatzky (1997) found that intensive discrimination features are processed at an early stage, whereas orientation of raised-lines is accessible later on. In active haptics (except for shape-changing technologies), haptic feedback is not physically anchored and constant. Nevertheless, already a perceivable imprecise haptic signal on a flat surface may already feel distinct enough for users. Tunca et al. (2016) tested a seamless button bar with single "click" haptic feedback as separators between buttons. They found slightly higher error rates and distraction compared to a passive haptics counterpart, but see potential with an enhanced haptic design. It is still unclear if different active haptic technologies can be used to generate and simulate classic passive search haptic signals, such as edges or other geometries.

As discussed earlier, such discontinuities may contain relevant information on transitions. In order to design for salient features, perception thresholds (absolute and difference) need to be taken into account. These may vary depending on the technology and hardware setup being used. Palani and Giudice (2016) examined vibrotactile and electro-static parameters for line detection and line tracing. A line with of 1 mm had a 100%-detection rate in both electrostatic and vibrotactile cuing-conditions. Detection rates for thinner lines were better in the vibrotactile condition. Also other usability parameters of touchscreen-based haptic technologies, such as minimum angular magnitude of vibrotactile lines has been researched (Palani et al., 2018). Gershon et al. (2016) compared exploration of an angular stimulus in four different conditions. Angle judgments were good in all conditions; however, exploration was shortest in vision, followed by a tangible (passive haptic) display and a touchscreen device with vibratory and frictional impulses. Properties used for design and interaction surfaces need to be distinctive enough to be perceived as two different materials or impulses. Bergmann Tiest (2010) and Klatzky et al. (2013) give insights on perception thresholds of single passive haptic dimensions, such as roughness and hardness. Bau et al. (2010) examined detection and perception thresholds for electrostatic displays.

In the automotive context, thresholds have to be considered even more conservatively due to physical and cognitive interferences while driving, such as uneven road conditions (Lust and Schaare, 2016). As haptic feedback is often seen as brand-specific, objective values on strength of haptic feedback and activation force are often a matter of disclosure. Therefore, studies are not publicly available.

Beruscha et al. (2017) assume that for easy interaction, users need a reference point on interfaces as already mentioned in Section "Passive Haptics." This coincides with notions made by Budiu (2019) on the use of virtual buttons on automotive touchscreens. Thus, clearly defined search haptic cues can also be used as an anchor point that provides orientation and enables users to build up a reference frame of the interface. These anchors are starting points for further exploration of interactive surfaces, and the basis of an input movement.

Processing Phase 3: Identification

Rationale of the Identification Phase

The goal of the identification phase is to clarify the suitable control element for the intended interaction. The input of this phase is the representation of the interface with regard to transitions from interactive and noninteractive elements. Because of the detection phase, users encoded the location of user interfaces. Moreover, they can specify if the interface contains more than just one adjustable element. Yet, the functionalities of single buttons are not clear. In this phase, the user identifies functionality of an interface element, i.e., how the interface can be controlled, but also the precise control element leading to the desired action. Well-designed haptic cues support users with the identification. During haptic exploration within interface boundaries (search cues) perception is enriched with associations on whether the element can be pressed, scrolled, toggled, etc. Additionally, previously perceived search cues are integrated into a holistic representation of the user interface. Both, the unique form factor of buttons on a control panel and spatial information, such as "Is the desired button on the left side of the interface?," enable the user to differentiate between single elements on a control unit. All this information leads to a confirmed identification, i.e., finding a suitable control element for changing the intended function. Only if the user identifies the suitable control element, haptic processing goes on to the confirmation phase (see **Figure 4** "Confirmed Function"). If control elements have been identified falsely, processing is fed into a reoccurring exploration (see **Figure 4** Loop "Function unclear"). With ongoing haptic processing, local aspects of user interfaces, such as discontinuities and other surface features, are integrated to generate a holistic perception of in-car user interfaces. The user assigns different meanings to specific control elements. At the end of this phase the user's mental model, which so far incorporated transitions and locations of interactive elements, is enriched by functionalities of these interactive areas. Hence, in the following phase an input action in the form of pressing or sliding can be performed.

Top-Down Loop 3: Association

Cognitive aspects influencing haptic perception in the identification phase are mainly processes that ease an association of haptic with semantic information. Carbon and Jakesch (2013) pointed out that haptic exploration of objects is increasingly enriched by associations as well as aesthetical and functional evaluations. Götz (2007) examined communicative functions of control elements. He found an association between certain design features of control elements (e.g., shape, curvature and fluting of the surface) and perceived functionality. Norman (2013) interprets these "signifiers" as an essential part of interaction design for products to be self-explaining. That means shapes, such as those found by Götz (2007), may trigger semantic associations and previous knowledge as they fit and support specific haptic exploration strategies, such as pressing or grabbing. Using shapes rich in affordances might ease memory retrieval on interaction possibilities. Götz (2007) focused solely on the visual appearance of mechatronic control elements as this is the "first encounter" with an interface. Moreover, he focused on manual controls. However, with technological innovations in interface technologies shapes, textures and other interaction movements, such as swiping, can be used in interfaces. Breitschaft et al. (2019) examined how different haptic shapes can be used to indicate interaction possibilites in automotive user interfaces. They found that participants do implicitly assign functional properties, such as confirmation, more-or-less and selection, to certain shapes. For example, participants associated a horizontal raised-lined with a more-or-less and a solid raised circle with a confirmation functionality. Using affordances posed by different shapes can help user to acquire and operate control elements while keeping their eyes on the road.

User interfaces are easier to understand if control elements consist of haptic information yielding clear associations about functionality. Therefore, using material properties that carry implicit associations about their function may enhance perception and increase user experience.

Haptic Information: Identification Cues

Haptic information processing in the identification phase refers to identification cues that goes beyond a mere detection and separation. This means that the user can derive information such as function, differentiation, and movement from how user interfaces are constructed. Götz (2007) focused on design features for an on/off, more-or-less and cursor function. Examples for unique design features are:

- On/off: a convex or concave crown of a surface or elevated circular elements with a revolving chamfer or radius
- More-or-less: circular protruded shape with vertically fluted sides
- Cursor: a spherical segment which is centered to a surface, similar to a trackball on notebook keyboards

These findings are valid for passive haptic manual control elements. Also, the reference surface of a control element contains affordances on interaction. Moving components, such as by pressing or shifting require joints, which in return give feedback which kind of interaction is required. Novel technologies enable new seamless interfaces with new interaction movements, such as swiping. On/off, more-or-less and selection seem to be functional qualities also true for surface-integrated haptic shapes (Breitschaft et al., 2019). It is still a matter of further research, which physical properties are "signifying" design features (shapes and textures) on seamless surfaces. It is also unclear how these findings can be translated to active haptics in order to use them for identification of "virtual" control elements on touch-sensitive surfaces. Surface properties that have previously been used as search cues may also be utilized as identification cues. In the detection phase, stimuli, such as raised-lines, edges and recesses are interpreted as discontinuities, indicating the borders of interactive surfaces. Future studies should focus on the use of active haptic feedback to elicit an interaction movement.

External Loop: Function Unclear

The end of the identification phase is a crucial point for the interaction and perception process. The user uses prediction, search and identification cues to fully identify the control element that can be used to change the initially intended function. If the intended control element is found, the interaction process proceeds to the usage phase. If the respective element is not found or the function is still unclear, the haptic processing in the interaction process starts again with exploration, detection, and identification. Insights that are generated by an ongoing haptic search are integrated into subsequent haptic perception processes (see top-down loop *Expectations*). In poorly designed interfaces, where haptic information fails to distinguish between different phases, the user may increasingly rely on information from other modalities for interaction. For example, if the user cannot figure out how a switch is operated by exploring the shape alone, he may take a quick visual look to ease operation.

The fHAPro-AUTO aims to look at haptic cues from a functional point of view. Nevertheless, Sonneveld and Schifferstein (2009) conclude that it is crucial for the product design process to know why users interact with an object the way they do. Besides functional haptic cues, users might further interact with a surface because they find joy in just playing around and experiencing haptic sensations (Carbon and Jakesch, 2013). Tactile materials, such as textiles, natural wood or aluminum provoke arousal and emotions that may be experienced as pleasing, or comforting by users, leading them to a non-functional haptic interaction. Some surfaces may also just look inviting to touch, even though haptic cues are not relevant in the interaction process (Klatzky and Peck, 2012). Therefore, the act of touching may also only be initiated for hedonic reasons.

Processing Phase 4: Usage

Rationale of the Usage Phase

In the usage phase, the user manipulates the previously identified function using haptic feedback. Input from the previous phase includes a representation of where and how elements within the interface can be manipulated. Haptic cues that are perceived during direct interaction are directly connected to a change of the operation status of the function. These cues are interpreted as a confirmation of input actions, which can be switching a function on/off, adjusting more-or-less or selecting items by using a cursor or scrolling (Götz, 2007). Especially for continuously adjustable control elements, an ongoing evaluation of input and feedback takes place. By turning, sliding or pushing the user tries to collect precise information about the relation of confirmation cues and their representation in the user interface. Ongoing confirmation cues are evaluated with respect to the targeted action. That means the user is further performing the input movement indicated by the control element, until the targeted output is reached. Confirmation cues are used to verify that the user is reaching, or has reached, the intended goal. Once the desired target is reached the interaction is completed.

Top-Down Loop 4: Multisensory Input

Processing of haptic information in the usage phase is modulated by multisensory input. Human perception and judgments in complex situations do not rely on a single modality. In-car user interaction is increasingly enriched by multimodal input and output technologies. According to the "modality-appropriateness" hypothesis by Welch and Warren (1980), the modality that is most suitable for encoding specific features of an object is dominating the perception and evaluation process. As seen in an earlier Section "Top-Down Loop 1: Expectations," multimodal feedback can be very useful in in-car interactions. The user may rely on auditory cues, such as an increase in song volume, as confirmation. In this case, haptic information may be neglected, because auditory information is a more reliable source. Modality-appropriateness is also discussed with regard to theories on multisensory integration (Ernst and Bülthoff, 2004). This is likely to be true if additional visual feedback, for example a graphical user interface on a screen is provided. According to Stein and Rowland (2011), multisensory integration of cross-modal stimuli follows three basic principles: spatial, temporal and inverse effectiveness. This means integration is more likely when cross-modal stimuli are presented at the same time or place. In this context, inverse effectiveness means that the strength of an individual unimodal stimulus is inversely related to the strength of multisensory integration. A relatively weak response to stimuli presented in a unimodal setting can also enhance integration. Therefore the implementation of multimodal feedback has to be considered carefully, especially with regard to interferences between sensory inputs from different modalities. Car manufacturers incorporate additional acoustic feedback into haptic user interfaces. Tikka and Laitinen (2006) found the biasing effect of audio feedback on perceived haptic strength in piezo actuated devices to be weaker than anticipated. Haptic intensity evaluation was biased more with higher sound levels than with lower sound levels. Presenting redundant information on more than one perceptual channel enhances user experience in interaction situations (Pitts et al., 2009, 2012b). Reddy et al. (2009) showed that multisensory redundancy increased speed and accuracy in user interfaces for elderly users. Multisensory information may ease and speed up processing due to processes such as familiarity and mere-exposure (Zajonc, 1968; Jakesch and Carbon, 2012).

MacLean (2008) concludes that for multisensory interfaces, enhancement as well as inhibition effects need to be discussed. Depending on its quality, subsequent stimuli can inhibit or facilitate a prior perceived one. But also primary stimuli can influence the perception of subsequent input, which is called sensory adaptation. For example, Kahrimanovic et al. (2009) found that textures felt after a rough stimulus felt smoother compared to textures felt after smooth stimuli. Breitschaft and Carbon (2016) found that adaptation effects may also be evoked in visuo-haptic settings.

Haptic Information: Confirmation Cues

Crucial haptic information in the usage phase are confirmation cues. The information is directly linked to the operation of the control element. In translational control elements, such as buttons or rocker switches, the transition from one state to another is characterized by a button snap. Input gestures on touch-sensitive surfaces, such as sliding, can also be supported by confirmation cues, for example by using active haptic systems. In rotational control elements, detents felt by turning usually indicate the change of an increment in the respective function. Button snaps or detents need to trigger a clear and distinct haptic feedback. A weak feeling might lead to ambiguity as to whether or not the control has been operated. Haptic feedback in passive translational or rotational control elements can be precisely determined with force-displacement-curves (see **Figure 3**). Numerous studies have researched the connection between physical parameters and subjective assessments to give an optimal feedback in translational (Reisinger, 2009) and rotational control elements (Kühner, 2014) for confirmation haptics. Specific force-displacement-characteristics can be used to evoke specific emotions (Rösler et al., 2009) to create a certain user experience in car interiors (for example, sporty vs. luxury). Furthermore, customers are able to differentiate between different button-feelings (Wellings et al., 2008). Wellings et al. (2010) found that participants used factors like "image," "build quality," and "clickiness" to characterize and differentiate between multiple buttons.

There is some research on the subjective evaluation of active haptic feedback technologies. Koskinen et al. (2008) found that a tactile click for a virtual button on a mobile device produced by a piezo actuator felt slightly more pleasant than a vibration motor. Salminen et al. (2011) studied affective evaluations of piezo actuated haptic and auditory feedback. Haptic stimuli with a longer rise time were found to be pleasant. Most of these studies are done in the context of mobile devices, but implementation of active haptics systems in car interiors is different, which is why generalizability to an automotive context is limited (Schneider et al., 2017).

Additionally, confirmation cues need to be easily separable from search and identification cues, in order to decrease ambiguity of haptic cues. Haptic cues can become more ambiguous if search and confirmation cues are generated by the same actuator, for example in active haptic systems. This lack of precise differentiation, for example between the feeling of a button area and the feeling of the button snap, may lead to dissatisfaction. Passive haptic feedback solutions are less susceptible to this problem, as search and confirmation cues already yield a fairly different haptic sensation. Passive search cues, such as textures and shapes, are clearly separated from confirmation cues, such as a button snap. This analogy could be applied to active haptic systems, which mean haptic feedback in both cases should yield a clear and distinctive haptic experience.

Desired Action

The output of the framework is an integrated mental model of haptic feedback impulses in the car. This leads to the previously desired action. After an ongoing evaluation of different haptic stimuli during interaction, the user not only reached the appropriate control element but also changed it to the required operation status. The interaction process has ended. Insights gained from the complete interaction process are integrated into previous cognitive models, further expectations, and knowledge that are exploited in future interaction situations (see "Level of Integration" in **Figure 4**).

Affective Evaluation

Aesthetic evaluation is an important part of user experience design. At the end of the interaction process, the user has integrated haptic information from single phases into a holistic mental model of the interface. In addition to functional evaluation of the haptic information, the user is evaluating haptic information based on personal preferences (Carbon and Jakesch, 2013). These insights are integrated into the previously formed mental model of the interface. It was already mentioned that especially material properties, for example, wood, leather, metal, or plastic, have an impact on pleasantness and liking (Gallace and Spence, 2011a). Also latency and timing seem to be an important factor, influencing perceived quality of an interface (Kaaresoja et al., 2014). These affective evaluations play a role in reoccurring interaction processes as they influence expectations.

APPLICATION OF A FRAMEWORK OF HAPTIC PROCESSING IN USER INTERFACES

The above-propagated framework describes the perception process of haptic information involved in controlling a car's function (**Figure 5**). It gives insights on perceptual and cognitive processes during haptic interaction, which is a rather theoretical approach. However, one aim of this model is to provide guidelines on how to optimally utilize haptic information during the design process of automotive user interfaces by including already existing literature. Basic guidelines can already be drawn (see **Table 2**) from the framework. Further studies are required to deduct more precise guidelines at single phases of processing. In this section, we would like to show how this framework can already facilitate the design process of tangible user interfaces in cars. Looking at the different user interfaces in **Figure 1** demonstrates which guidelines aid the effective design of haptic feedback in automotive interfaces. Passive haptic control panels in recent cars often already follow these design principles (see **Figures 1A,B**). For example, visual and haptic feedback information are present, as are edges and joints. Additionally, confirmation feedback, mostly through button pressing or knob turning is vastly different from search haptic feedback. Particularly in seamless touch-sensitive and touchscreen-based surfaces, the following guidelines may be useful (see **Figure 1C**), as such interfaces often lack haptic feedback.

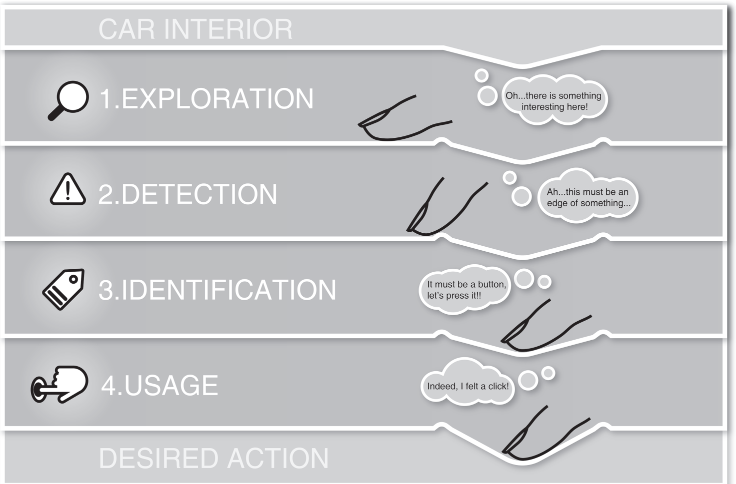

FIGURE 5 | Application of the framework of haptic processing in automotive user interaction in an exemplified interaction situation. This figure shows the four different phases of the framework with the respective actions performed by the user.

TABLE 2 | Connection of phases of the framework and a first set of derived guidelines.

Phase	Guideline	Description
Exploration	Holistic user experience	Make use of the haptic experience that is inherently connected with certain technologies
Detection	Clarity	Make transitions between different semantic areas feelable
Identification	Intuitiveness	Make use of affordances posed by certain technologies to indicate interactivity
Usage	Discriminability	Make search and confirmation cues distinct from each other to avoid ambiguity

Holistic User Experience

In an automotive context haptic feedback, first and foremost, needs to ensure safety of use, reduce cognitive load and distraction. Usability research mostly covers objective and measurable aspects of haptic feedback. As shown in Pitts et al. (2012b) perceived strength of haptic impulses are of great importance for a positive UX. The proposed framework helps to understand how haptic feedback can be successfully integrated into tangible user interfaces by dividing the perception process into *Exploration*, *Detection*, *Identification,* and *Usage*. Haptic feedback that guides and supports interaction enhances user experience.

Several studies show that incorporating haptic feedback into user interfaces also increases acceptance among users (Pitts et al., 2009, 2010; Weddle and Yu, 2013) and adds value to a product. Active haptics allows more aesthetically pleasing interfaces compared to passive haptic counterparts (Tunca et al., 2016). Designers also need to take aesthetical evaluations of haptic feedback into account (haptic aesthetics). Switches not only need to work, but also need to feel high quality in order to yield pleasure and fascination (Carbon and Jakesch, 2013).

One aspect contributing to a high quality UX is latency, which is especially crucial in haptics and even more in the automotive context. Schneider et al. (2017) emphasized the importance of latency and timing. Not only does haptic feedback need to be delivered fast, but also needs to be synchronized with other feedback modalities, such as a confirmation sound and a haptic click. Kaaresoja et al. (2014) found that in the tactile domain, the point of subjective simultaneity of two stimuli is 5 ms. Furthermore, the perceived quality significantly drops if latency is higher than 70 ms from interaction to feedback. They suggest a latency of 5–50 ms for tactile, 20–70 ms for audio and 30–85 ms for visual feedback. These values are in line with the conclusion drawn by Weddle et al. (2013) who performed an automotive-specific study. Jay and Hubbold (2005) point out that users' seem to tolerate higher haptic feedback latency if an easy task is at hand.

Haptic feedback has the potential to create unique and brand-specific design features. One of the earliest and most widely used examples in the automotive industry is the *iDrive* controller by BMW (Bernstein et al., 2008). Using touchscreens and touch-sensitive surfaces limit these idiosyncratic, brand-specific design features ("Formensprache" as called by Carbon, 2010).

Clarity

In recent years, there has been a staggering increase in touchscreens and touch-sensitive surfaces in cars. Design surfaces become interactive without any visible borders between control panels. Especially with a hidden-till-light effect, user interfaces are at times invisible (Aito, 2018). This impairs blind control and forces users to look where their finger is placed. However, in control panels buttons should at least remain perceptible through touch. For example, using piezo-actuated systems, the edges of buttons could be indicated by a simple "click" sensation that is triggered when crossing a virtual boarder. Nevertheless, an interactive area could also be represented by a texture that is felt by sweeping across a surface. It is not yet clear which haptic information is most suitable to enable users an easy detection of control elements on seamless surfaces.

Parameters have to be set in a way that impulses are always perceivable to avoid confusion. For active haptic stimuli, this means not only the strength but also waveform and temporal aspects, such as line width (Palani and Giudice, 2016), of an impulse. In in-car applications, especially when using vibrotactile stimuli, external factors, such as vehicle vibration, need to be taken into account when setting impulse parameters. Thus, perception thresholds reported in lab settings are a mere starting point in interface design. Beruscha et al. (2016) are currently working toward user requirements for touch screen interactions.

Intuitiveness

Haptic feedback in automotive user interfaces can support intuitiveness of user interfaces. Especially with touch-sensitive interfaces, there is an increasing number of input possibilities than mere pressing. This may be confusing for users, because they do not understand how to interact with a plane interface. Employing signifying design features, such as found by Breitschaft et al. (2019), Götz (2007) and Mueller (2016) for passive haptic stimuli, ease interaction. Designers should make of user's association and affordances of shapes and impulses during haptic perception to increase ease-of-use. For example, an on/off function should be manifested in a recess or ridge. If users scan across a surface, almost falling into a recess with the finger is associated with pressing.

Discriminability

In previous sections, we described that haptic processing in user interfaces is a staged process with crucial phases. In order not to confuse users, haptic stimuli should be designed to distinguishably meet requirements set in each phase. More precisely, search cues need to feel differently than confirmation cues. For passive haptic interfaces, discriminability is relatively easy to obtain as search haptics yields a fairly different haptic experience as confirmation haptics. If only one active haptic actuator solution is used in the interface, discriminability becomes an issue. Even though development kits of various tech suppliers offer a wide variety of adjustable parameters, haptic impulses may feel rather similar. Similar to passive haptic control elements, designers should aim for eliciting a distinct haptic experience. For example, in technologies involving vibration, waveforms of impulses could be set in a way that the confirmation feels like pressing a real button, whereas search haptics could feel like a sharper impulse, as if one would go over an edge.

Future Work

This paper summarized findings from research in the field of haptic feedback, with the aim of generating guidelines to aid in the design of automotive interfaces. It also identified areas with open research questions. For example, it remains unclear which parameters are best suited to differentiate between search and confirmation cues. The framework could also be used as a model of haptic information processing. However, empirical data on the validity of various phases, and the model itself, are not yet available. Future research aims to check the sequential structure of the model and the importance of single phases. A target-select-and-confirm paradigm could include a number of different haptic feedback scenarios, involving both search and confirmation haptics. Video recording or a think-aloud approach could yield insights into how users explore surfaces and how they utilize haptic information. An example of concrete hardware to be used in the study could be a touchscreen or a touchpad with haptic feedback, programmed to interact with a graphical user interface. Various items could be coded with different haptic feedback patterns. The goal of the study would be to determine the optimal haptic representation of certain elements for a variety of use cases involving search, identification and confirmation feedback.

Future research could also involve gathering feedback on the proposed framework from experts, both within the automotive industry, as well as other industries that deal with the design of seamless interfaces.

CONCLUSION

Studies on automotive haptic feedback mostly focus on increasing driving safety and blind operation in control elements. They show that haptic feedback can positively enrich in-car user experience. However, the scope of these studies is mostly to validate a certain technological solution. Little research deals with the optimal design of haptic features and how haptic feedback can support the user in searching for control elements. The theoretical framework presented in this paper describes the process of haptic perception and points to crucial phases in perception that need to be addressed by interaction and technological concepts. It also gives rough guidelines as to how distinctively designed haptic features can support the interaction process and enhance user experience. This gets even more important with the surface integration of control elements, where functional and aesthetical aspects of haptic perception are even more connected. Psychologically motivated models on haptic perception, such as the one proposed in this paper, may support practitioners such as designers and engineers as well as empirical researchers in understanding the shortcomings and capabilities of human haptic perception in automotive user interfaces.

AUTHOR CONTRIBUTIONS

SB had the initial idea to harmonize findings in automotive haptic feedback in a common framework and terminology. C-CC brought insights from haptic aesthetic processing and perception research in automotive contexts. SB did the main part of the research, mainly wrote the manuscript and worked on rough drawings of figures. SB, SC, and C-CC worked further on the manuscript.

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REFERENCES

Aito (2018). *Touch. Click. Feel.: Solutions*. Available at: https://aito-touch.com/solutions (Accessed June 04, 2018).

Albrecht, S., and Carbon, C.-C. (2014). The fluency amplification model: fluent stimuli show more intense but not evidently more positive evaluations. *Acta Psychol.* 148, 195–203. doi: 10.1016/j.actpsy.2014.02.002

Alps Alpine Co., L. (2019). *Switch for automotive selection*. Available at: https://www.alps.com/prod/info/E/HTML/SearchList/SearchList1000_list1.html (Accessed January 09, 2019).

Banter, B. (2010). Touch screens and touch surfaces are enriched by haptic force-feedback. *Inform. Disp.* 26, 26–29. doi: 10.1002/j.2637-496X.2010.tb00231.x

Bau, O., Poupyrev, I., Israr, A., and Harrison, C. (2010). "TeslaTouch: electrovibration for touch surfaces" in *Proceedings of the 23rd annual ACM symposium on user interface software and technology*. (New York: ACM), 283–292. doi: 10.1145/1866029.1866074

Baumgartner, E., Wiebel, C. B., and Gegenfurtner, K. R. (2013). Visual and haptic representations of material properties. *Multisens. Res.* 26, 429–455. doi: 10.1163/22134808-00002429

Bergmann Tiest, W. M. (2010). Tactual perception of material properties. *Vis. Res.* 50, 2775–2782. doi: 10.1016/j.visres.2010.10.005

Bernstein, A., Bader, B., Bengler, K., and Künzner, H. (2008). "Visual-haptic interfaces in car design at BMW" in *Human haptic perception: Basics and applications*. ed. M. Grunwald (Basel: Birkhäuser), 445–451.

Beruscha, F., Brosi, C., Krautter, W., and Altmüller, T. (2016). Deriving user requirements for haptic enhanced automotive touch screen interaction. *SID Symp. Dig. Tech. Pap.* 47, 271–273. doi: 10.1002/sdtp.10663

Beruscha, F., Krautter, W., Lahmer, A., and Pauly, M. (2017). "An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens" *In 2017 IEEE World Haptics Conference* (*WHC*). (Munich: IEEE), 201–206. doi: 10.1109/WHC.2017.7989901

Biet, M., Giraud, F., and Lemaire-Semail, B. (2007). Squeeze film effect for the design of an ultrasonic tactile plate. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 54, 2678–2688. doi: 10.1109/TUFFC.2007.596

BMW Group (2015). *Der neue BMW 6er: zusätzliches bildmaterial*. https://www.press.bmwgroup.com/deutschland/article/detail/T0208842DE/der-neue-bmw-6er-%E2%80%93-zusaetzliches-bildmaterial (Accessed May 29, 2018).

BMW Group (2017). *The BMW Concept 8 Series: unadulterated dynamics and modern luxury – the essence of a BMW coupe*. Available at: https://www.

press.bmwgroup.com/global/article/detail/T0271136EN/the-bmw-concept-8-series-unadulterated-dynamics-and-modern-luxury-%E2%80%93-the-essence-of-a-bmw-coupe?language=en (Accessed May 29, 2018).
BMW Group (2018). *The BMW vision iNEXT. Future focused*. Available at: https://www.press.bmwgroup.com/global/article/detail/T0284904EN/the-bmw-vision-inext-future-focused (Accessed January 09, 2019).
Breitschaft, S. J., and Carbon, C.-C. (2016). Multisensory adaptation: how visual are haptics? *Perception* 45:147. doi: 10.1177/0301006616671273
Breitschaft, S. J., Clarke, S., and Carbon, C.-C. (2019). Using haptic shapes for orientation and identification in automotive user interfaces. in *IEEE World Haptics Conference 2019*. (Tokyo: IEEE).
Bubb, H., Bengler, K., Breuninger, J., Gold, C., and Helmbrecht, M. (2015). "Systemergonomie des Fahrzeugs" in *ATZ/MTZ-Fachbuch. Automobilergonomie.* 2015th edn. ed. H. Bubb (Wiesbaden: Springer Vieweg), 259–344.
Budiu, R. (2019). *Tesla's touchscreen UI: A case study of car-dashboard user interface*. Available at: https://www.nngroup.com/articles/tesla-big-touchscreen/ (Accessed May 24, 2019).
Burnett, G., and Irune, A. (2009). "Drivers' quality ratings for switches in cars" in *Proceedings of the 1st international conference on automotive user interfaces and interactive vehicular applications*. (New York, NY: ACM), 107. doi: 10.1145/1620509.1620530
C&K Switches. (2019). *Automotive switches*. Available at: https://www.ckswitches.com/markets/automotive/ (Accessed January 09, 2019).
Carbon, C.-C. (2010). The cycle of preference: long-term dynamics of aesthetic appreciation. *Acta Psychol.* 134, 233–244. doi: 10.1016/j.actpsy.2010.02.004
Carbon, C.-C., and Jakesch, M. (2013). A model for haptic aesthetic processing and its implications for design. *Proc. IEEE* 101, 2123–2133. doi: 10.1109/JPROC.2012.2219831
Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav. Brain Sci.* 36, 181–204. doi: 10.1017/S0140525X12000477
Culbertson, H., Schorr, S. B., and Okamura, A. M. (2018). Haptics: the present and future of artificial touch sensation. *Annu. Revi. Contr. Robot. Auton. Sys.* 1, 385–409. doi: 10.1146/annurev-control-060117-105043
Ernst, M. O., and Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends Cogn. Sci.* 8, 162–169. doi: 10.1016/j.tics.2004.02.002
Etzi, R., Spence, C., and Gallace, A. (2014). Textures that we like to touch: an experimental study of aesthetic preferences for tactile stimuli. *Conscious. Cogn.* 29, 178–188. doi: 10.1016/j.concog.2014.08.011
Gaffary, Y., and Lécuyer, A. (2018). The use of haptic and tactile information in the car to improve driving safety: a review of current technologies. *Front. ICT* 5:445. doi: 10.3389/fict.2018.00005
Gallace, A., and Spence, C. (2011a). Tactile aesthetics: towards a definition of its characteristics and neural correlates. *Soc. Semiot.* 21, 569–589. doi: 10.1080/10350330.2011.591998
Gallace, A., and Spence, C. (2011b). To what extent do Gestalt grouping principles influence tactile perception? *Psychol. Bull.* 137, 538–561. doi: 10.1037/a0022335
Gershon, P., Klatzky, R., Palani, H., and Giudice, N. (2016). Visual, tangible, and touch-screen: comparison of platforms for displaying simple graphics. *Assist. Technol.* 28, 1–6. doi: 10.1080/10400435.2015.1054566
Gibson, J. J. (1979). *The ecological approach to visual perception*. (Boston: Houghton Mifflin Harcourt).
Glohr, T., Wahn, N., Fritz, M., and Maier, T. (2015). Haptics as an aspect of the perceived quality of control devices in trucks. *Proced. Manufact.* 3, 5535–5542. doi: 10.1016/j.promfg.2015.07.721
Götz, M. (2007). Die Gestaltung von Bedienelementen unter dem Aspekt ihrer kommunikativen Funktion. dissertation. München: Technische Universität. Available at: https://mediatum.ub.tum.de/632979 (Accessed March 13, 2018).
Grane, C., and Bengtsson, P. (2012). Haptic addition to a visual menu selection interface controlled by an in-vehicle rotary device. *Adv. Hum. Comp. Interact.* 2012, 1–12. doi: 10.1155/2012/787469
Harley, A. (2018). Visibility of system status. Available at: https://www.nngroup.com/articles/visibility-system-status/ (Accessed June 21, 2019).
Heijboer, S., Breitschaft, S. J., and Carbon, C.-C. (2019). "Characterization of active haptic feedback for user interface design and development" in *IEEE 2019 world haptics conference* (*WHC*). (Tokyo: IEEE).
Jakesch, M., and Carbon, C.-C. (2012). The mere exposure effect in the domain of haptics. *PLoS One* 7:e31215. doi: 10.1371/journal.pone.0031215
Jakesch, M., Zachhuber, M., Leder, H., Spingler, M., and Carbon, C.-C. (2011). Scenario-based touching: on the influence of top-down processes on tactile and visual appreciation. *Res. Eng. Des.* 22, 143–152. doi: 10.1007/s00163-010-0102-5
Jay, C., and Hubbold, R. (2005). "Delayed visual and haptic feedback in a reciprocal tapping task" in *First joint eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems*. (Pisa: IEEE), 655–656. doi: 10.1109/WHC.2005.29
Kaaresoja, T., Brewster, S., and Lantz, V. (2014). Towards the temporally perfect virtual button: touch-feedback simultaneity and perceived quality in mobile touchscreen press interactions. *ACM Trans. Appl. Percept.* 11, 1–25. doi: 10.1145/2611387
Kahrimanovic, M., Bergmann Tiest, W. M., and Kappers, A. M. L. (2009). Context effects in haptic perception of roughness. *Exp. Brain Res.* 194, 287–297. doi: 10.1007/s00221-008-1697-x
Kappers, A., and Bergmann Tiest, W. M. (2015). Haptic saliency. *Scholarpedia* 10:32734. doi: 10.4249/scholarpedia.32734
Kern, D., and Pfleging, B. (2013). Supporting interaction through haptic feedback in automotive user interfaces. *Interactions* 20, 16–21. doi: 10.1145/2427076.2427081
Kerzel, D., and Schönhammer, J. (2013). Salient stimuli capture attention and action. *Atten. Percept. Psychophysiol.* 75, 1633–1643. doi: 10.3758/s13414-013-0512-3
Klatzky, R., Giudice, N., Bennett, C. R., and Loomis, J. M. (2014). Touch-screen technology for the dynamic display of 2D spatial information without vision: promise and progress. *Multisens. Res.* 27, 359–378. doi: 10.1163/22134808-00002447
Klatzky, R., and Lederman, S. J. (1993). Toward a computational model of constraint-driven exploration and haptic object identification. *Perception* 22, 597–621. doi: 10.1068/p220597
Klatzky, R., and Lederman, S. J. (1995). Identifying objects from a haptic glance. *Percept. Psychophys.* 57, 1111–1123. doi: 10.3758/BF03208368
Klatzky, R., Lederman, S. J., and Matula, D. E. (1993). Haptic exploration in the presence of vision. *J. Exp. Psychol. Hum. Percept. Perform.* 19, 726–743. doi: 10.1037/0096-1523.19.4.726
Klatzky, R., Lederman, S. J., and Reed, C. (1987). There's more to touch than meets the eye: the salience of object attributes for haptics with and without vision. *J. Exp. Psychol. Gen.* 116, 356–369. doi: 10.1037/0096-3445.116.4.356
Klatzky, R., Pawluk, D., and Peer, A. (2013). Haptic perception of material properties and implications for applications. *Proc. IEEE* 101, 2081–2092. doi: 10.1109/JPROC.2013.2248691
Klatzky, R., and Peck, J. (2012). Please touch: object properties that invite touch. *IEEE Trans. Haptics* 5, 139–147. doi: 10.1109/TOH.2011.54
Koskinen, E., Kaaresoja, T., and Laitinen, P. (2008). "Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button" in *Proceedings of the 10th international conference on multimodal interfaces–IMCI'08*. eds. V. Digalakis, A. Potamianos, M. Turk, R. Pieraccini, and Y. Ivanov (New York, USA: ACM Press), 297.
Kühner, M. (2014). Haptische Unterscheidbarkeit mechanischer Parameter bei rotatorischen Bedienelementen. dissertation. München: Technische Universität. Available at: https://mediatum.ub.tum.de/?id=1145031 (Accessed April 26, 2018).
Lederman, S. J., and Klatzky, R. (1997). Relative availability of surface and object properties during early haptic processing. *J. Exp. Psychol. Hum. Percept. Perform.* 23:1680. doi: 10.1037/0096-1523.23.6.1680
Lederman, S. J., and Klatzky, R. (2009). Haptic perception: a tutorial. *Atten. Percept. Psychophysiol.* 71, 1439–1459. doi: 10.3758/APP.71.7.1439
Lust, M., and Schaare, R. (2016). Bedienoberflächen mit aktivem haptischem feedback. *ATZ* 118, 48–53. doi: 10.1007/s35148-016-0043-z
MacLean, K. E. (2008). Haptic interaction design for everyday interfaces. *Rev. Hum. Fact. Ergonom.* 4, 149–194. doi: 10.1518/155723408X342826
Matysek, M., Lotz, P., Winterstein, T., and Schlaak, H. F. (2009). "Dielectric elastomer actuators for tactile displays." *In World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. (Salt Lake City, UT: IEEE), 290–295. doi: 10.1109/WHC.2009.4810822

Meyer, D. J., Wiertlewski, M., Peshkin, M. A., and Colgate, J. E. (2014). "Dynamics of ultrasonic and electrostatic friction modulation for rendering texture on haptic surfaces" in *2014 IEEE haptics symposium, HAPTICS*. (Houston, TX: IEEE), 63–67. doi: 10.1109/HAPTICS.2014.6775434

Mueller, S. (2016). Das optimale Bedienelement und der optimale Bedienort für eine Nutzerfunktion. dissertation. München: Technische Universität. Available at: https://mediatum.ub.tum.de/node?id=1227514 (Accessed March 13, 2018).

Muth, C., Raab, M. H., and Carbon, C.-C. (2016). Semantic stability is more pleasurable in unstable episodic contexts. On the relevance of perceptual challenge in art appreciation. *Front. Hum. Neurosci.* 10:43. doi: 10.3389/fnhum.2016.00043

Ng, A., and Brewster, S. A. (2016). "Investigating pressure input and haptic feedback for in-car touchscreens and touch surfaces" in *Proceedings of the 8th international conference on automotive user interfaces and interactive vehicular applications*. (New York, NY: ACM), 121–128. doi: 10.1145/3003715.3005420

Ng, A., Brewster, S. A., Beruscha, F., and Krautter, W. (2017). "An evaluation of input controls for in-car interactions" in *Proceedings of the 2017 CHI conference on human factors in computing systems*. (ACM), 2845–2852.

Nielsen, J. (1994). 10 Heuristics for User Interface Design: Article by Jakob Nielsen. Available at: https://www.nngroup.com/articles/ten-usability-heuristics/ (Accessed June 21, 2019).

Norman, D. A. (2013). *The design of everyday things: Revised and expanded edition*. (New York: Basic Books).

Palani, H. P., and Giudice, N. A. (2016). Usability parameters for touchscreen-based haptic perception *In 2016 IEEE Haptics Symposium* (*HAPTICS*). (Philadelphia, PA, USA: IEEE). https://umaine.edu/vemi/publication/usability-parameters-touchscreen-based-haptic-perception/

Palani, H. P., Giudice, G., and Giudice, N. (2018). "Haptic information access using touchscreen devices: design guidelines for accurate perception of angular magnitude and line orientation" in *Lecture notes in computer science. Universal access in human-computer interaction. methods, technologies, and users*. eds. M. Antona, and C. Stephanidis, vol. 10907 (Cham: Springer International Publishing), 243–255.

Palmer, S. E. (1975). The effects of contextual scenes on the identification of objects. *Mem. Cogn.* 3, 519–526. doi: 10.3758/BF03197524

Petermeijer, S. M., Abbink, D. A., Mulder, M., and de Winter, J. C. F. (2015). The effect of haptic support systems on driver performance: a literature survey. *IEEE Trans. Haptics* 8, 467–479. doi: 10.1109/TOH.2015.2437871

Pitts, M. J., Burnett, G. E., Williams, M. A., and Wellings, T. (2010). "Does haptic feedback change the way we view touchscreens in cars?" in *International conference on multimodal interfaces and the workshop on machine learning for multimodal interaction*. (ACM), 38.

Pitts, M. J., Burnett, G., Skrypchuk, L., Wellings, T., Attridge, A., and Williams, M. A. (2012a). Visual–haptic feedback interaction in automotive touchscreens. *Displays* 33, 7–16. doi: 10.1016/j.displa.2011.09.002

Pitts, M. J., Skrypchuk, L., Wellings, T., Attridge, A., and Williams, M. A. (2012b). Evaluating user response to in-car haptic feedback touchscreens using the lane change test. *Adv. Hum. Comp. Interact.* 2012, 1–13. doi: 10.1155/2012/598739

Pitts, M. J., Williams, M. A., Wellings, T., and Attridge, A. (2009). "Assessing subjective response to haptic feedback in automotive touchscreens" in *Proceedings of the 1st international conference on automotive user interfaces and interactive vehicular applications*. (New York, NY: ACM), 11–18. doi: 10.1145/1620509.1620512

Preh (2018). Car HMI. Available at: https://www.preh.com/produkte/automotive/car-hmi.html (Accessed 09 January 2019).

QUAD Industries (2018). How smart surfaces are reshaping human machine interaction. Available at: https://www.quad-ind.com/why-smart-surfaces-will-reshape-human-machine-interaction/ (Accessed 09 January 2019).

Reddy, G. R., Blackler, A. L., Popovic, V., and Mahar, D. P. (2009). "Redundancy in interface design and its impact on intuitive use of a product in older users." *In Proceedings of the IASDR 2009: Rigor and Relevance in Design*. (Seoul, Korea: Korean Society of Science Design), 209.

Reisinger, J. (2009). Parametrisierung der Haptik von handbetätigten Stellteilen. dissertation. München: Technische Universität. Available at: https://mediatum.ub.tum.de/654165 (Accessed March 26, 2018).

Richter, H., Ecker, R., Deisler, C., and Butz, A. (2010). HapTouch and the 2+1 state model. In *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. (New York, NY: ACM). 72–79. doi: 10.1145/1969773.1969787

Rösler, F., Battenberg, G., and Schüttler, F. (2009). Subjektive Empfindungen und objektive Charakteristika von Bedienelementen. *ATZ* 111, 292–297. doi: 10.1007/BF03222068

Rydström, A., Grane, C., and Bengtsson, P. (2009). "Driver behaviour during haptic and visual secondary tasks" in *Proceedings of the 1st international conference on automotive user interfaces and interactive vehicular applications*. (New York, NY: ACM), 121–127. doi: 10.1145/1620509.1620533

Salminen, K., Surakka, V., Lylykangas, J., Rantala, J., Laitinen, P., and Raisamo, R. (2011). "Evaluations of piezo actuated haptic stimulations" in *Lecture notes in computer science. Affective computing and intelligent interaction*. Vol. 6974, eds. S. D'Mello, A. Graesser, B. Schuller, and J.-C. Martin (Berlin, Heidelberg: Springer), 296–305.

Schneider, O., MacLean, K., Swindells, C., and Booth, K. (2017). Haptic experience design: what hapticians do and where they need help. *Int. J. Human Comp. Stud.* 107, 5–21. doi: 10.1016/j.ijhcs.2017.04.004

Sonneveld, M. H., and Schifferstein, H. N. J. (2009). "The tactual experience of objects" in *Product experience*. eds. H. N. J. Schifferstein and P. Hekkert (Amsterdam: Elsevier), 41–67.

Stein, B. E., and Rowland, B. A. (2011). Organization and plasticity in multisensory integration: early and late experience affects its governing principles. *Prog. Brain Res.* 191, 145–163. doi: 10.1016/B978-0-444-53752-2.00007-2

Swindells, C., MacLean, K. E., Booth, K. S., and Meitner, M. J. (2007). "Exploring affective design for physical controls" in *Proceedings of the SIGCHI conference on human factors in computing systems*. (New York, NY: ACM), 933–942. doi: 10.1145/1240624.1240765

Tikka, V., and Laitinen, P. (2006). "Designing haptic feedback for touch display: experimental study of perceived intensity and integration of haptic and audio" in *Haptic and audio interaction design: first international workshop, HAID 2006*. eds. D. McGookin, and S. Brewster (Berlin, Heidelberg: Springer), 36–44.

Tunca, E., Fleischer, R., Schmidt, L., and Tille, T. (2016). "Advantages of active haptics on touch surfaces" in *Proceedings of the 8th international conference on automotive user interfaces and interactive vehicular applications*. (New York, NY: ACM), 137–144. doi: 10.1145/3003715.3005406

van Erp, J. B. F., and van Veen, H. (2001). "Vibro-tactile information presentation in automobiles" in *Proceedings of eurohaptics*. Vol. 2001 (Paris, France: Eurohaptics Society), 99–104.

Vollrath, M., and Krems, J. F. (2011). *Verkehrspsychologie: Ein Lehrbuch für Psychologen, Ingenieure und Informatiker* 1. Aufl. Kohlhammer Standards Psychologie. (Stuttgart: Kohlhammer).

Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., et al. (2012a). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure-ground organization. *Psychol. Bull.* 138, 1172–1217. doi: 10.1037/a0029333

Wagemans, J., Feldman, J., Gepshtein, S., Kimchi, R., Pomerantz, J. R., van der Helm, P. A., et al. (2012b). A century of Gestalt psychology in visual perception: II. Conceptual and theoretical foundations. *Psychol. Bull.* 138, 1218–1252. doi: 10.1037/a0029334

Weddle, A. B., and Yu, H. (2013). Confirmation haptics for automotive interfaces: Cadillac CUE User Study. Available at: https://www.immersion.com/wp-content/uploads/2015/10/CUE-whitepaper_jun13v1.pdf

Weddle, A. B., Yu, H., and Moreno, M. (2013). UX impacts of haptic latency in automotive interfaces: literature review and user study. Available at: https://pdfs.semanticscholar.org/de7c/0c19188642cc925c256608f048163ea5973d.pdf (Accessed January 15, 2019).

Welch, R. B., and Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychol. Bull.* 88, 638–667. doi: 10.1037/0033-2909.88.3.638

Wellings, T., Williams, M. A., and Pitts, M. J. (2008). Customer perception of switch-feel in luxury sports utility vehicles. *Food Qual. Prefer.* 19, 737–746. doi: 10.1016/j.foodqual.2008.03.004

Wellings, T., Williams, M., and Tennant, C. (2010). Understanding customers' holistic perception of switches in automotive human-machine interfaces. *Appl. Ergon.* 41, 8–17. doi: 10.1016/j.apergo.2009.03.004

Zajonc, R. B. (1968). Attitudinal effects of mere exposure. *J. Pers. Soc. Psychol.* 9, 1–27. doi: 10.1037/h0025848

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A.4 Using Haptic Shapes for Orientation and Identification in Automotive User Interfaces

Using haptic shapes for orientation and identification in automotive user interfaces

Stefan J. Breitschaft, Stella Clarke, Claus-Christian Carbon

Haptic feedback is a crucial part of secure and easy to operate automotive user interfaces. These interfaces are changing through surface-integrated buttons and switches, allowing higher degrees of freedom in haptic design. Passive haptic shapes not only enable the ease of finding control elements without looking, but also aid in the identification of functionality. This paper presents preliminary findings of a series of studies examining the perceived functionalities of surface-integrated haptic shapes. Via multidimensional scaling we showed that there is a variability of associated functionality within a set of preselected shapes, depicting mainly three clusters of functionality: on/off, more-or-less and selection. This knowledge can be used to systematically optimize haptic design, and thus the fast and secure operating of automotive interfaces.

I. INTRODUCTION

In the automotive industry, there is a recent trend towards seamless integration of control elements in user interfaces, leading to clean and often monolithic-looking interiors. Despite the visually pleasing design, these interior surfaces typically lack haptic information or feedback, thus impairing the ability to blindly operate while driving. Haptic feedback has been proven to be useful not only for safe driving and distraction minimization [1], but also to enrich user experience [2]. Smart surface technologies enable the seamless integration of switches into design surfaces, with a wide variety of appearances and materials. This increases freedom in the haptic design of interior surfaces, such as the use of shapes to ensure the blind finding, and identification, of control elements. Research until now has mainly focused on edges and joints as search haptic cues. We aim to examine surface-integrated shapes with respect to the influence of perceived functionality in the context of automotive user interfaces.

II. HAPTIC SHAPES AS SIGNIFYING DESIGN ELEMENTS

Götz [3] examined the communicative functions of control elements in an automotive user interface context. He found that certain design aspects of switches evoke links to specific functionalities, and influence how users expect to interact with them. Based on Gestalt psychology ideas, Norman [4] calls such design features “signifying” design elements. However, control elements have since undergone significant technological changes. Additionally, focus was on the visual previews of control elements, and not haptics, which is particularly relevant when the element is used in a secondary task, as in driving. For example, Tiab and Hornbæk [5] examined how shape-changing buttons can be used in user interfaces to convey easy-to-understand information on the underlying functionality. This paper reports the findings of the second of three studies, examining the influence of shapes on their underlying functionalities as haptically perceived by users.

III. METHOD

A. Stimuli and Apparatus

20 different haptic shapes were used (see Figure 1). The shapes were chosen based on the findings from a prestudy in which an exploration and drawing-paradigm was used. Stimuli consisted of 50×50×4 mm polycarbonate plates (see Figure 1) which were laser-engraved to create protruded (white) or recessed (black) areas. A greyscale gradient indicates a slope. Stimuli were presented in a “touch box” with a curtain in front, enabling participants to haptically explore the shapes without seeing them. An opening in the back ensured the smooth exchange of stimuli (see Figure 1).

B. Participants and Procedure

14 right-handed participants (m_{age}=29.8 years, range: 21-57 years; 6 female) were seated next to the touch box, which was situated in a position similar to the middle console for a driver. Each participant received and introduction to the study and experimental procedure. A clear reference to the automotive context of the study was provided, including examples of possible user interfaces. In a training session consisting of three trials, participants familiarized themselves with the experimental procedure and general design of the shapes. The task at hand was to explore two adjacent shapes. In a pairwise-comparison, participants had to rate the similarity of the perceived functionality of the shapes on a scale of 1 (*not similar at all*) to 7 (*very similar*), using the following question: “How similar are both shapes according to their perceived functionality?” There was no time restriction. In total, each participant completed 190 pairwise-comparisons to cover all possible pair-combinations of the 20 shapes. Afterwards, a questionnaire with a list of all shapes was handed to participants, from which they could choose the functions they associated the according shapes with. The number of participants was limited by availability and is in line with the exploratory nature of this study.

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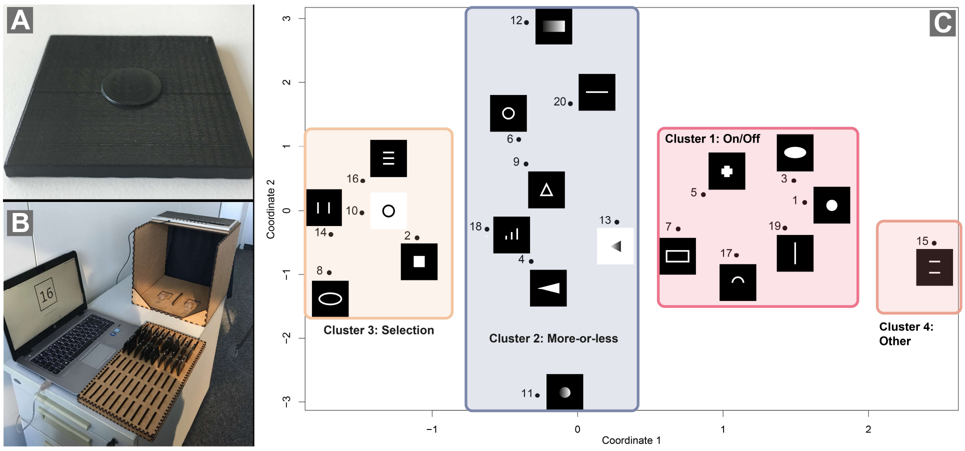

Figure 1. The experimental stimuli were made from laser-cut polycarbonate (A) and presented in a specially prepared touchbox (B). C depicts the visual representation of the MDS procedure with the corresponding shapes. The numbers correspond to the shape ID. The white color depicts protruded areas in the tactile plates.

IV. Results and Discussion

The ratings were prepared to perform a metric multidimensional scaling (MDS) procedure using the *cmdscale()*-function in the statistical software R. An a priori stress test revealed that four dimensions are sufficient to represent the original space (stress-1<0.2). The resulting MDS configuration is shown in Figure 1, with each shape copied in to aid visual interpretation. The MDS configuration reveals that there *does* seem to be shapes that users associate with certain functionalities. Looking at the data, and including the verbal questionnaire descriptions, three clusters with the following functional categories can be identified: (1) on/off-function mostly with regard to confirmation by pushing, (2) more-or-less with regard to sliding and rocker type switches, and (3) scrolling and pushing with regard to selecting items from a horizontal or vertical list. This is a categorization scheme in accordance with Götz [3]. Cluster four consist solely of shape 15 and appears to be an outlier, because no common functionality was confirmed by the data. Variance within clusters may be explained by how users explored the shapes. For example, shapes such as 11 and 12 are associated with a more-or-less-function, but differ in operating-principle, with 11 acting as rocker switch type element, and 12 as a slider. However, not all shapes entirely seem to fit into this categorization. For example, shape two (rectangle), was mostly reported to be an on/off and push function, but in the MDS configuration it is situated in the cluster of shapes that were predominantly reported to be selection functions. Thus, it seems possible that some users focused on the actual shapes instead of their associated functionality.

V. Conclusion and Future Work

This paper aimed to explore the underlying functional qualities of various shapes that can be used in car interiors. The MDS showed that shapes can be categorized into different functional qualities. However, it gives a mere insight into which functionalities are associated with the corresponding shapes. There seems to be three different functional qualities: on/off, more-or-less, and selection. A next study aims to assess fitting of functionality, describe how users interact with a selected set of these shapes, and determine which haptic features make each of the functional categories distinct – similar to the approach of Götz [3]. These insights can aid user interface designers and engineers.

References

[1] S. M. Petermeijer, D. A. Abbink, M. Mulder, and de Winter, J. C. F., “The effect of haptic support systems on driver performance: A Literature Survey,” *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 467–479, 2015.

[2] M. J. Pitts, M. A. Williams, T. Wellings, and A. Attridge, “Assessing subjective response to haptic feedback in automotive touchscreens,” in *Proceedings of the 1st international Conference on Automotive User interfaces and interactive Vehicular Applications*, 2009, pp. 11–18.

[3] M. Götz, “Die Gestaltung von Bedienelementen unter dem Aspekt ihrer kommunikativen Funktion”, Ph.D dissertation, Departement of Mechanical Engineering, Technical University, Munich, 2007.

[4] D. A. Norman, *The design of everyday things: Revised and expanded edition*. New York: Basic Books, 2013.

[5] J. Tiab and K. Hornbæk, “Understanding Affordance, System State, and Feedback in Shape-Changing Buttons,” in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, Santa Clara, California, USA, 2016, pp. 2752–2763.

USING HAPTIC SHAPES FOR ORIENTATION AND IDENTIFICATION IN AUTOMOTIVE USER INTERFACES

HAPTIC SHAPES IN AUTOMOTIVE UI.

In the automotive industry there is a trend towards seamless integration of control elements which is aesthetically pleasing but lacks haptic information, and thus impair the ability to blindly operate while driving. Haptic feedback has proven to increase driving safety and performance [1]. Research has mainly focused on edges and joints as search haptic cues. The „framework of haptic processing in automotive user interfaces“ [2] proposes haptic feedback can be designed not only to help users find certain control elements and give confirmation on input action, but also to support identification of the functionality of control elements. Götz [3] examined communicative function of control elements, more precisely the association of specific design features and their perceived functionality. He focused on visual previews, whereas little is known about specific haptic design for identification of contorl elements. We aimed to examine surface-integrated shapes with respect to the influence of perceived functionality in the context of automotive user interfaces.

METHOD.

14 right-handed participants (mage=29.8 years, range: 21-57 years; 6 female) rated 20 different haptic shapes made of laser-engraved polycarbonate plates based on their similiarity with regard to perceived functionality. The task at hand was to blindfoldedly explore two adjacent shapes inside the a touchbox. In a pairwise-comparison, participants had to rate the similarity of the perceived functionality of all shape pair combinations on a scale of 1 (not similar at all) and 7 (very similar). A post-experiment questionnaire was used to gain first insights which functionalities users associated with respective shapes.

RESULTS AND DISCUSSION.

A multidimensional scaling procedure (MDS) using the similarity data revealed that there does seem to be shapes that users associate with certain functionalities. More precisely is seems to be the four underlying clusters, which was also indicated by an a priori perfomed stress test (stress-1<0.2): (1) on/off-function with regard to confirmation by pushing, (2) more-or-less with regard to sliding or rocker switches, and (3) selecting items from a list with regard to scrolling and pushing. Cluster four solely consists of one unspecific shape, which seems to be an outlier. Variances within clusters could be explained by means of operating, such as shape 11 (pressing) and shape 12 (sliding).

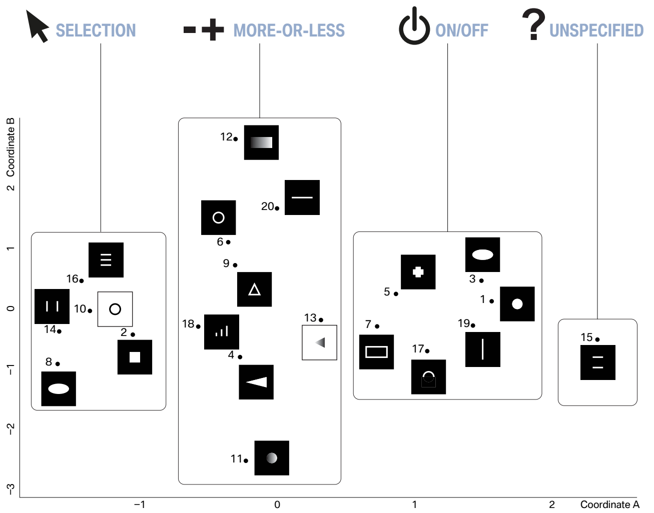

Fig. 1. The experimental stimuli were made from laser-cut polycarbonate and presented blinfolded in a touchbox. The MDS configuration shows four fclusters with their corresponding shapes and ID. The white color depicts protruded areas in the tactile plates.

FUTURE WORK.

We explored underlying functional qualities of various shapes that can be used in car interiors. The MDS showed that shapes can be categorized into different functional qualities, which seem to cover basically three clusters: On/Off, More-or-less, Selection. A next study seeks to assess fitting of functional quality, describe how users interact with a selected set of these shapes, and determine which haptic features make each of the functional categories distinct. These insights can aid user interface designers and engineers.

REFERENCES.

[1] S. M. Petermeijer, D. A. Abbink, M. Mulder, and J. C. F. de Winter, "The effect of haptic support systems on driver performance: A Literature-Survey," IEEE transactions on haptics, vol. 8, no. 4, pp. 467–479, 2015.
[2] S. J. Breitschaft, S. Clarke, and C.-C. Carbon, "A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering," Frontiers in psychology, vol. 10, no. 1470, https://www.frontiersin.org/articles/10.3389/fpsyg.2019.01470/abstract, 2019.
[3] M. Götz, "Die Gestaltung von Bedienelementen unter dem Aspekt ihrer kommunikativen Funk-

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A.5 Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design

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Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design

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Novel tangible user interface technologies facilitate current trends toward seamless user interfaces. They enable the design of yet unseen interfaces and thus the creation of a new kind of haptic language. In order to use the benefits of a touch-and-feel design for a positive user experience, carefully designed haptic feedback plays an important role by providing aesthetically pleasing and sustainable product features. Haptic feedback may exceed mere acquiring of buttons and input-confirmation but enable orientation and even identification of functionality governed by the haptic impression. We employed the aesthetic association principle as a deeply grounded psychological mechanism that assists effective linkage between haptic form factors and associated functional attributes. In order to illustrate this powerful principle, we analyzed the specific associations between certain main haptic surface qualities and associated functional aspects. In a series of three subsequent studies (Pre-Study 1: *perception*, Pre-Study 2: *similarity*, and Main Study: *association*), we explored paradigmatic associations of that kind to develop guidelines which forms are distinct to be used in interfaces. We show how forms are implicitly categorized into functional qualities (on/off, more-less, selection), using a multidimensional scaling procedure and explore explicit form-functionality associations, using a think-aloud method in the context of an automotive interface. For a series of forms, we revealed clear associative relations to specific functions. We will discuss the general value and opportunities of an association-based approach to user experience in order to create intuitive user interfaces. We will also develop ideas for specific areas of applications.

Keywords: haptic design, user interface, haptic experience, haptic aesthetics, aesthetic association principle, functionality, haptic feedback

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INTRODUCTION—THE PHYSICAL EMPIRE FIGHTS BACK

Technological advancements in the area of tangible user interface technologies and an increasing desire for dynamic and programmable interfaces capable of dealing with an ever-growing number of functionalities led to the ongoing digitalization of user interfaces—among others in the automotive industry. This digitalization of user interfaces is characterized by a fusion of an interactive and decorative surface, leading to the reduction and extinction of dedicated analog interfaces to create seamless and harmonic interfaces. Analog interfaces are increasingly replaced by seamless touch-sensitive areas at the expense of classical passive haptic controls. Yet, the digitalization of user interfaces comes at a price. Featureless interfaces surfaces neglect the subtlety and hands-on qualities of well-designed haptic surfaces. Mainly, we miss the touch-and-feel aspects we need to create a great user experience and to ensure an efficient and low-error use even in eyes-free operation. This becomes imminent in safety-relevant contexts, such as automotive, in which haptic feedback in touchscreen interfaces could massively improve distraction and eyes-free operation. Usability and user experience are limited to mainly visual information. Hence, an innate part of product experience and also brand identity is lost. Not only since several carmakers are focusing in-car interaction on a single touchscreen, but there is also a call for reinforcing the sense of touch in seamless user interfaces by haptic feedback (Stockburger, 2013). Some carmakers are slowly following backward trends at least for some functionalities (Burgess, 2020). The title of a recent Fjord's (a major design consultancy) campaign explains the comeback of the sense of touch in design very well: "Physical Fights Back" (Fjord., 2020).

Increasing fidelity of haptic technologies, expanding mere vibrations to a rendering of complex surface materials (Breitschaft et al., 2020) and also novel technological manufacturing processes (combining different layers of sensing, lighting, and haptics with a single small-package component), enables unprecedented types of interfaces. Haptics will play a key factor in interface design, becoming an essential part of the identity of a brand and a discriminating factor among different competing products as it has already done quite successfully in the past. An example is an iDrive controller of BMW as a dedicated multifunctional input device for in-vehicle infotainment that soon afterward has been adopted by an array of different brands (Bernstein et al., 2008). Since then, the haptic community has been revolving primarily around technical and functional aspects rather than the experience aspect of haptics. Yet resourceful active haptic technology was used to yield a rather simple, analog metaphor—a button click. With novel haptic technologies, haptic experience in interfaces may not only be restricted to confirmation but give orientation toward otherwise featureless interfaces and help acquiring buttons. By triggering functional associations, they may even enable identification *via* haptics (Heijboer et al., 2019a; Breitschaft et al., 2019b). Obviously, this requires a new kind of haptic language for interface design, which integrates seamlessly with the rest of the user interface, thereby creating a whole new level of experience and aesthetics. In his recent paper "Psychology of Design," Carbon (2019) promotes the importance of a psychological perspective for optimization of current and development of a novel design. Following the framework of Carbon, in this research, we will take a fundamental psychological turn to assist the path of optimizing the quality and intuitiveness of haptics. A major principle within this framework will be the strategic application of the so-called *aesthetic association principle*, which dates back to the experimental founding of psychology in the 1860s and seems to represent the basis of how we perceive and assess design items.

NEED FOR HIGH-QUALITY HAPTIC FEELING

For a very long time, the development of haptic interfaces in the automotive industries was dominated by the necessity of clear, functional, precise, and pleasing user feedback. In the pre-digital era, this was mostly realized *via* mechanical buttons and switches; later, these properties were simulated by electromechanical devices (Lust and Schaare, 2016). Nowadays, in the drive-by-wire times of digitalization, more and more programmable user interfaces are introduced, mostly being without haptic feedback. But even with the advent of devices with programmable active haptic technologies, which offer a great variety of modes and functions, we lack real haptic feedback as the devices do only provide movements in the dimensions of microns, so are quite marginal in everyday usage. The haptics of mechanical devices still seem to be an important benchmark of high-quality user interface. There engineers try to recreate the feeling of such devices in a digital framework. Creating the feeling of handling something manually gives us the opportunity to use deeply rooted and often practiced mechanical routines. This helps us to reduce the cognitive load and to rely on tactile modes only without compromising our cognitive and visual-perceptual capacities (Grane and Bengtsson, 2013; Petermeijer et al., 2015). This is a promising prerequisite for fast, safe, and errorless handling. The joy of handling mechanical devices, furthermore, adds to the user experience by triggering aesthetic aha moments, increased liking, and even fascination in very well-applied cases (Breitschaft et al., 2019a).

Even the finest crafted mechanical interfaces still show an essential problem: They were hard to keep apart. Although excellently engineered buttons feel great, placed side by side, they feel just the same. What we needed and still need is a clear scheme to distinguish them. And, as we are not interested in investing much time and effort to learn the association between specific haptic qualities (e.g., characteristic form) and the function, which is linked with the specific device, we should use already existing associations—associations that are typical, which are deeply rooted in us. In his early writing called "The Aesthetic Association Principle," Gustav Theodor Fechner, the pioneer of psychophysics and empirical aesthetics, proposed a modern view on perception by emphasizing the power of associations (Ortlieb et al., 2020). The *Aesthetic Association Principle* (AAP) is based on meaning and purpose that is attached to certain objects by experience. As such, perception of an object is not only based on a pure sensory experience, but everything that is cognitively attached to it: "We do not perceive it with the physical eye, but with a mental eye" (Ortlieb et al., 2020). Context and previous experiences become an inherent part of this exact object. As such, Fechner explained the strength of his approach, comparing the aesthetic quality of an orange compared with a visually similar wooden orange ball. If we trigger very common associations, the *aesthetic association principle* offers the ideal playground to develop a general framework of specific haptic qualities, which can be assigned to certain functions.

THE AESTHETIC ASSOCIATION PRINCIPLE IN HAPTIC INTERFACE DESIGN

The *aesthetic association principle* (AAP) has been widely used in several areas of cognitive sciences, mostly in visual perception, although most authors never mentioned Fechner as the originator of these ideas (see **Table 1**). Most prominently, Palmer and Schloss (2010) provided a powerful explanatory approach for color preferences based on affective responses of participants to color-associated objects. For example, blue has high preference ratings as it is generally associated with positively connoted objects, such as clear skies. Later on, the same group of researchers also found systematic associative links between different styles of music and color (Palmer et al., 2013; Whiteford et al., 2018).

Fechner already stated that the AAP is not restricted to the visual domain. It is a powerful tool for other domains, such as haptic perception as it constitutes great parts of social communication and interaction (Grunwald, 2017). The sense of touch is also called the "intimate sense" and offers an additional layer of emotionality to be taken care of in UI-Design. This goes way beyond a mere psychophysical approach to map subjective perception of haptic impulses to physical parameters. The AAP has already been widely used in a variety of contexts in haptic research, especially focusing on cross-modal associations. Guest et al. (2011) examined associations between tactile sensory descriptions and semantic as well as emotional descriptions to establish an evidence-based tactile lexicon. For example, comfort was reported with decreasing roughness. Generally, there seem to be systematic links between colors and haptic/tactile stimuli and descriptions (Simner and Ludwig, 2012; Ludwig and Simner, 2013; Jraissati et al., 2016). For example, pink was associated with softness; black was associated with hardness. Jraissati et al. (2016) argue that brightness, chroma, and hue have an influence of color-haptic association. For example, colors associated with adjectives like softness and lightness were brighter than those associated with their verbal counterparts. Iosifyan et al. (2017) examined cross-modal associations of haptic materials with complex multimodal stimuli. The participants were asked to match movie snippets with a certain type of haptic material, e.g., sandpaper and silk. In accordance with previously mentioned studies, softer materials, such as silk, were linked to movies, containing notions of beauty, whereas rough materials, like sandpaper, were linked to movies with notions of ugliness. Similar results for color-haptic associations could even be found with electrically induced electrostatic friction impulses (Hasegawa et al., 2018). Rösler et al. (2009) examined the relationship of force-displacement curves in mechanical buttons and their subjective assessment. For example, a longer button stroke induced a heavier button feeling. Regal et al. (2014) leveraged the implicit association between haptic surface properties and user experience evaluations to use haptic materials for UX assessments instead of questionnaires, i.e., a negative experience was represented by rough sandpaper.

There are different types of methods to reveal semantic associations between semantic and perceptual information (see also **Table 1**). One of the most used methods involves matching tasks. Participants are required to assign or match the most fitting/consistent descriptors for a specific perceptual stimulus, for example, choose the most consistent color when exploring a particular haptic stimulus. Other approaches involve ranking tasks (Iosifyan et al., 2017). Hasegawa et al. (2018) used a mapping task to check for color-tactile associations. Some studies used a free association (think-aloud) task during stimulus exploration. Association patterns are analyzed by establishing a post-study categorization system for the qualitative descriptions (Heijboer et al., 2019a). Another method to reveal underlying semantic qualities is using a multidimensional scaling procedure (MDS). MDS is a statistical method to visualize similarity/dissimilarity data in a multidimensional space. Similarity data can, for example, be gathered, using a similarity estimation method, classification, or a semantic differential method (Okamoto et al., 2013). A well-established psychological procedure, which offers measurement of implicit attitudes, is the implicit association test (IAT) by Greenwald et al. (1998). Subsequent developments include the multidimensional IAT (md-IAT) (Gattol et al., 2011), the go/no-go-association test (GNAT) (Nosek and Banaji, 2001) or the single-category-IAT (SC-IAT) (Karpinski and Steinman, 2006). All these implicit association test variants assume participants react faster when they perceive strongly associated semantic information. Reaction times are used to determine the strength of association.

With the advent of novel interface technologies, the relationship of device-specific technical parameters and affective evaluations are still not fully understood. Yet development is focused on superficial psychophysical relations of parameters rather than holistic aesthetic evaluations. This is hindering the transition from functional to emotional interfaces (Heijboer et al., 2019b). Heijboer et al. (2019a) found that participants mostly describe piezo-actuated haptic feedback, using affective descriptions. They showed that haptic stimuli consisting of different vibration patterns have the potential to convey emotion- and semantically-rich experiences, like "squeezing a spring" and "crunching a snowball." The notion of using vibration feedback to convey semantic and functional information in user interfaces has already been followed by multiple research laboratories (Brewster and Brown, 2004; MacLean, 2008; MacLean and Hayward, 2008). They propose the use of *tactons* or *haptic icons* (a systematic vibration pattern based on *amplitude*, *frequency*, and *duration*) to convey abstract and metaphorical messages, such as systems errors. However, *tactons* do not always follow deeply rooted associations but rather arbitrary connections of vibrational patterns and menu actions, which require learning. Yet MacLean and Hayward (2008) propose measures on how to create an easy-to-learn stimulus set.

In interaction design, the term *affordances*—introduced by Norman (2013) and originating from Gibson (1979) *Ecological Approach to Visual Perception*—is used as a main descriptor for the usability of a product. Affordances describe the association of object properties to functional characteristics of a product.

TABLE 1 | A brief overview of studies that are compatible with the aesthetic association principle as proposed by Fechner in the year 1866 (Ortlieb et al., 2020).

Citation	Modality	Association	Method	Results
Palmer and Schloss (2010)	Visual	Color preference—Valence of color related objects	Free association	Color preference (for example blue) can be explained by valence ratings of color-related object associations, such as skies and water
Palmer et al. (2013)	Visual-Audio	Color-Music	Choose 5 most and least consistent color for music pieces	e.g., faster, major-mode music was linked to brighter and more saturated colors, whereas as
Whiteford et al. (2018)	Visual-Audio	Color-Music	Matching 3 best word samples to music	e.g., loud/heavy music relates to darker/more saturated colors
Guest et al. (2011)	Visual-Haptic	Tactile Surface Attributes-Emotional Descriptions	Pairwise Comparison Multidimensional Scaling	e.g., participants reported more comfort with decreasing roughness
Ludwig and Simner (2013)	Visual-Haptic	Color-Tactile stimuli	Assign color best fitting color to tactile stimuli	e.g., softness was associated with pink
Jraissati et al. (2016)	Visual-Haptic	Color-Haptic Adjectives	Two opposing haptic descriptions, Assign/rate fitting haptic descriptions (1–5) to color patch	e.g., hard and heavy objects were associated with black colors
Iosifyan et al. (2017)	Multimodal-Haptic	Movie-Tactile Surfaces	Rate material and movies using semantic differential Choose best-matching sample to movie	e.g., films tackling the notion of beauty were associated with silk
Hasegawa et al. (2018)	Visual-Haptic	Color-Electrostatic Haptic Feedback	Russel's psychological plane Map stimuli on the coordinate system	e.g., low-frequency impulses were associated with colder colors
Götz (2007)	Visual	Surface design features-UI-functionality	Free association	Certain surface features are linked to a specific interaction
Heijboer et al. (2019a)	Haptic	Vibrational Pattern-Semantic Content	Free association	Specific vibrational pattern were linked to alarm, whereas others produced associations like a spring
Mlakar and Haller (2020)	Visual-Haptic	Textile surface Features-UI-functionality	Observation	e.g., protrusion feels like a button

Norman (2008) later revised the term "affordance" and proposed to use *signifiers* to refer to interactive clues as it refers to the initially intended meaning of *perceived affordances* of Norman, i.e., the interactivity of a product, depending on context and a perspective of a user. It is the task of the designer to provide interactive clues and which product properties are suited best for certain kinds of interactions. Carefully designed signifying elements are of special importance in cognitive demanding, multitask environments, such as aviation and transportation. For example, in the "Advisory Circular No. 20–175," the US Federal Aviation Administration proposes to use consistent surface textures, shapes, and other haptic surface features to make interfaces in aviation cockpits detectable, distinguishable, identifiable, and predictable to ensure efficient, errorless and safe interaction (Federal Aviation Administration, 2011). Mlakar and Haller (2020) presented similar design recommendations for textile interfaces, which also consider using unambiguous forms as a clear call for interaction. They propose a preliminary differentiation of forms that indicate an actuation in the normal or tangential direction. Yet they do not provide an in-depth view on form-functionality associations. In this respect, Götz (2007) speaks about "communicative functions" of traditional automotive control elements, which refer to the signifying character of specific design features for the interaction of basic functional principles: on/off, more/less, cursor/selection. In his study, he found reliable associations between different types of functionality and specific interface design features in the context of "traditional" car interiors. For example, a convex surface geometry invited pressing, whereas a cylindrical form with knurling on the side invited to use as a rotary control. Götz argues visual information is a primary source of making interfaces more usable. In an experimental approach focusing on visual stimuli, the participants were not able to physically interact with the virtually modeled stimuli. This approach neglects the influence of visual-haptic information and, hence, the notion of eyes-free operation that focuses on haptic design to alleviate a visual load. Additionally, previous work on signifying interaction features in an automotive context (Götz, 2007; Mueller, 2016), which dates back to the late 2000s, focused on purely mechanical in-vehicle control elements. Interface technologies, design premises, and, most importantly, interaction habits (note the first iPhone was introduced in 2007) changed quite drastically since then, which makes revisiting the signifying character of a potentially novel form language indispensable. The increasing use of interactive surfaces with little to no haptic feedback increases visual distraction by deteriorating orientation in interfaces (Rümelin, 2014; Eren et al., 2015; Beruscha et al., 2017). Passive haptic form features can be a powerful design feature to ease orientation in switch and seamless interfaces. So-called search haptics (Breitschaft et al., 2019a) has primarily been focusing on providing the ability of eyes-free operation by a mere discrimination of buttons, using arbitrary form and edges. By utilizing the AAP to understand the functional character of haptic design features in specialized contexts, such as user interfaces, we suppose that haptic forms can also be used for the identification of basic functional principles. In a preliminary study, Breitschaft et al. (2019b) found differences in the implicit functional associations of different shapes, using a multidimensional scaling procedure.

The goal of this research is to explore signifying haptic forms, more precisely the association of carefully selected forms and their perceived functionality in a user interface context. By applying a multistage experimental study setup (Pre-Study 1: *Perception*, Pre-Study 2: *Similarity* and Main Study: *Association*) we try to (1) to extend the AAP to functional-based associations in haptic design research, (2) give guidelines on discrete, distinguishable, and signifying haptic surface features (see Pre-Study 1), (3) explore the design space of form-functionality associations (see Pre-Study 2 and Main Study), (4) discuss the general value of an association-based approach to user experience design (see section General Discussion), and (5) develop ideas for specific applications on the basis of the concrete associations carved out by our study (see section Ideas for Application).

MULTISTAGE EXPERIMENTAL SETUP OF THE PRESENT STUDY

This paper presents a tripartite multistage approach, consisting of three subsequent studies "*Perception*, *Similarity*, and *Association*," as shown in **Figure 1**. To increase comprehensibility, we will refer to the *Perception* and *Similarity* Studies as Pre-Study 1 and Pre-Study 2 and the Association Study as Main Study.

The initial stimulus set included 80 forms in Pre-Study 1, which was subsequently reduced to 20 forms in Pre-Study and 12 in the Main Study. The restrictions were mainly implemented due to methodological reasons: (1) to ensure an adequate and manageable number of stimuli at every stage and (2) to ensure that, in the Main Study, only a set of highly recognizable and distinguishable forms is used. This research was not intended to provide a fully systematic examination of form-functionality descriptions but to provide an initial implementation of the AAP in a haptic design context.

Pre-Study 1 (see section Pre-Study 1—Perception), *Perception*-Study, was carried out to examine which forms are easy to explore, recognize, and discriminate, using an exploration-and-drawing task. As a result, 20 recognizable and distinguishable forms were identified to be used as stimuli for Pre-Study 2.

Pre-Study 2 (see section Pre-Study 2—Similarity), *Similarity*-Study, utilized a multidimensional scaling (MDS) procedure to explore a general underlying pattern of form-functionality (dis-)associations between different forms. Do they differ at all based on their perceived functionality? A similar approach to "perceptually optimize" a set of stimuli has been reported by MacLean and Hayward (2008). As a result, 12 forms were identified to be used in the Main Study.

Even though having a preliminary character, Pre-Study 1 and Pre-Study 2 yield important insights and prerequisites for the examination of form-functionality associations, which is why they play an inherent part within our highly systematic research approach. In addition, to make the complete stimulus selection process more transparent, the Pre-Studies will be described in more detail. Insights from Pre-Studies 1 and 2 were used to refine and reduce the initial set of 80 forms to 12 highly distinguishable forms that were used in the Main Study.

The Main Study (see section Main Study—Association and Fitting), *Association*-Study, uses a final set of 12 forms and examines explicit form-functionality associations. In the first part of the Main Study, the participants freely reported functional associations, using a think-aloud method. In the second part, they rated the fitting of the forms for functionality categories defined in Pre-Study 2.

In the following section, all the Pre-Studies are described with respect to the implemented method, results, and stimulus selection. The Main Study includes a description of the method, results, as well as a discussion of specific form-functionality associations. The general experimental premises were the same for all three studies: (1) Haptic stimuli were concealed within a touchbox while haptic exploration, (2) the same room, apparatus, and haptic stimuli and general procedure (washing hands, consent form, post-session feedback, etc.) were used during all three studies and (3) all the studies included an introduction focusing on an automotive interaction context to provide a concrete scenario, following the idea of *scenario-based touching* (Jakesch et al., 2011).

PRE-STUDY 1—PERCEPTION

Haptic forms in user interfaces should be detectable effortlessly within short haptic glances (Klatzky and Lederman, 1995). Moreover, forms need to be distinguishable to retain their unique character (Federal Aviation Administration, 2011; Mlakar and Haller, 2020). In Pre-Study 1, we primarily used qualitative as well as quantitative data to explore design guidelines for the design of haptic forms and to select stimulus material for Pre-Study 2.

Method

Participants

Ten right-handed participants took part in Pre-Study 1. They were between 19 and 36 years old ($M_{age} = 27.1$ years, $SD = 4.4$); six participants were female. All the participants worked in the automotive sector; five had prior experience with haptic feedback. The participants were naïve to the aims of the study and had not gone through special training in haptic perception or drawing. All the participants were right-handed.

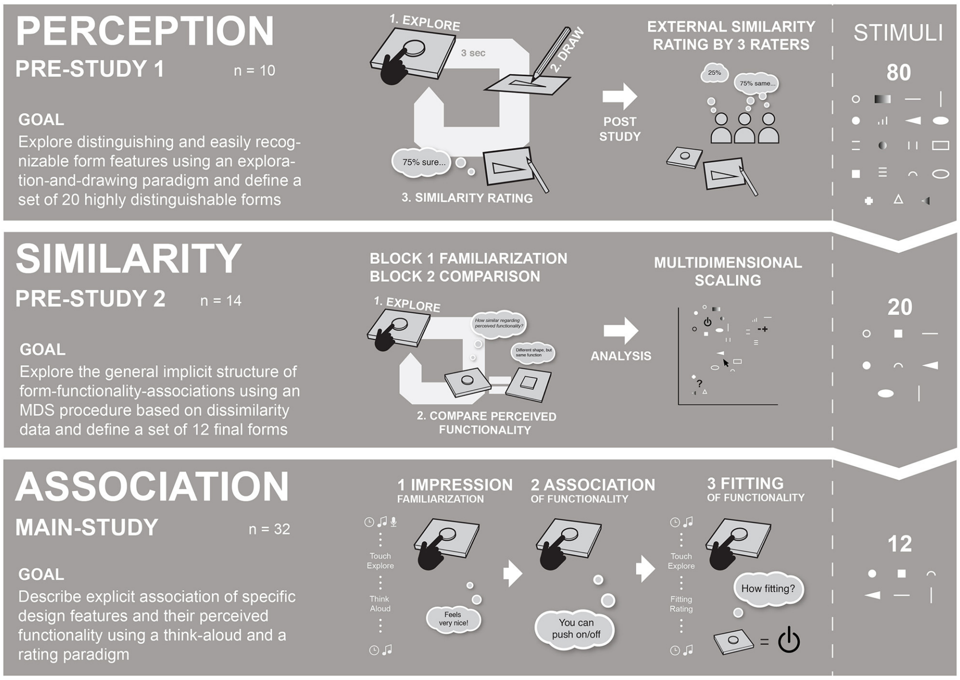


FIGURE 1 | This research utilized a tripartite setup of three subsequent studies: (1) *Perception* included an exploration-drawing paradigm, (2) *Similarity* included a comparison paradigm and (3) *Association* included a think-aloud paradigm.

Apparatus

Stimuli were presented in a touchbox with a curtain in front and an opening in the back (see **Figure 2A**). The touchbox was positioned like a center console of a car and adjusted to the handedness of the participants. A black curtain prevented the participants to see the stimulus material and enabled them to focus on their haptic impression (see **Figure 2**). The opening in the back of the box enabled the experimenter to easily exchange stimuli. Different inlays were used over the course of the three studies to accommodate a varying number of stimuli. A little recess in front of every form position on the inlay helped orientation and was used as a common starting point for the exploration phase in all experiments.

Stimuli

In Pre-Study 1, an initial set of 80 a priori-designed stimuli was used (**Figure 3**). This study employed a within-subject design, meaning all the participants explored all 80 shapes. The haptic forms were created during a workshop with experts from different professions, including psychology, design, usability, and engineering to create a wide variety of potentially suitable and appealing forms. The set of 80 forms was not based on a fully exhaustive and systematic variation of physical parameters as this was not the goal of this study. Object properties, such as height in the z-axis, size, and surface geometry were deliberately excluded during the process of stimulus creation as it would have increased stimulus complexity. As the stimulus set was refined over the course of this research, numbers of forms indicated in all figures change with every experiment.

The experimental stimuli were made of 50 × 50-mm polycarbonate (pc) plates. The forms were maximum 15 × 15 mm (e.g., Forms 1 and 2), 30 × 15 mm (e.g., Forms 3 and 77–80) or 15 × 30 mm (e.g., Forms 69 and 75) in size. The authors are aware that recognition of forms may depend on the size of haptic forms. The size was chosen based on a compromise of design and usability aspects. A laser engraver was used to manufacture the physical forms, which were previously created in Adobe Illustrator (files are available upon request). The thickness of the pc-plates is 4.11 mm. Engraved areas (depicted in white in all figures) of the pc-plates were 3.66 mm thick, which results in a height

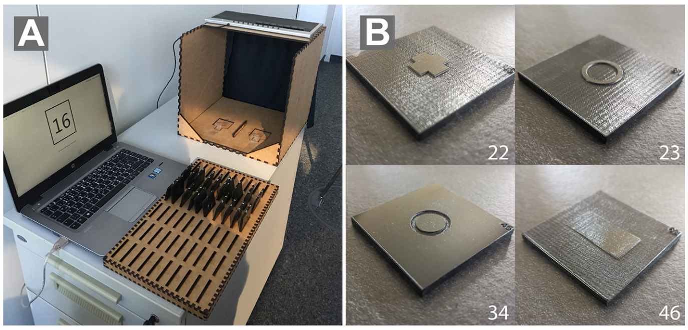


FIGURE 2 | (A) The figure shows the view of the experimenters. Haptic stimuli were presented in a custom-made touchbox with a curtain on the side of the participants to ensure pure haptic exploration. **(B)** shows an exemplary stimulus used in the studies. Numbers correspond to the forms from Pre-Study 1.

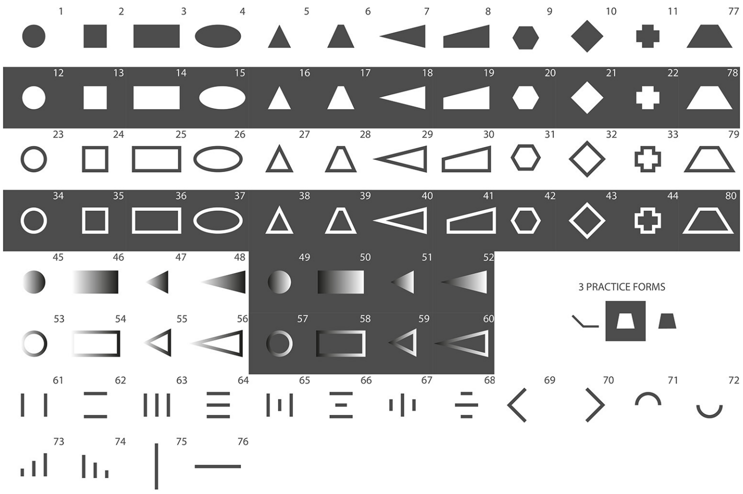


FIGURE 3 | These stimuli present the initial set of 80 stimuli, which was used in Pre-Study 1. Gray areas equal protruded (non-engraved), and white equals laser-engraved areas.

of 0.45 mm for the protruded areas (depicted in gray in all figures). Using a laser engraver made the production of forms easy and efficient. Furthermore, polycarbonate is very resistant to abrasion. Engraving created a slight texture on the top surface of the pc-plates. A subtle texture was applied to the protruded areas of the pc-plates in order to reduce friction of the pc surface and create a homogenous feeling while exploring the surface. **Figure 2B** depicts four exemplary forms that were used in the study.

Procedure

Pre-Studies 1 and 2 and the Main Study were conducted in the same silent and separated room. Before every experimental session, the participants washed their hands for hygienic reasons and gave consent for taking part in the study before data collection. The participants were seated next to the touchbox, which was placed on a storage container to provide a comfortable height for the participants to explore the stimuli and adjusted to the handedness of the participants. The participants were told to find a comfortable position to reach the stimuli in the touchbox and comfortably switch to the drawing after haptic exploration. A folder containing empty pages to collect the drawings of the participants was placed on a table to the left side of the participants. The participants were introduced to the background and procedure of this pre-study and were instructed how to draw the explored three-dimensional forms. They were told to focus on two-dimensional geometry of the forms in their drawings and to use pencil shading to indicate protruded or recessed areas of the stimuli. Darker shading indicated recessed areas, whereas lighter shading and blank spaces indicated protruded areas of the form (see **Figure 4**). A short training session, including three forms, helped the participants to practice the drawing procedure. A single trial included a tripartite task: (1) haptic exploration in 3 s, (2) drawing the explored shaped, and (3) a subjective rating (see **Figure 1**). The experimenter started the trial once the participants placed their fingers on the starting point in the touchbox. The first acoustic signal marked the beginning of the trial. The participants explored the respective form for 3 s with their index fingers. A second acoustic signal marked the end of the 3-s-exploration phase. Afterward, the participants drew the explored form. Following the drawing, the participants were asked to judge the perceived similarity of the drawn and explored form on a scale from 1, "very different," to 7, "very similar," using the following question: "How similar is the form you drew compared with the one you explored?." In total, every participant completed 80 experimental trials (80 different forms). All haptic forms were presented in a randomized order for every participant. A complete session took ∼1 h.

Results and Stimulus Selection

Ahead of data analysis, drawings, as well as ratings, were preprocessed, which included scanning and cropping the images. To gain objective similarity ratings, three independent raters (who did not take part in the study) were given all 800 pairs of the drawings and engraving templates of the forms in a post-experimental rating. The task of the rater was to judge the similarity of the two adjacent forms on a seven-point scale with 1 being "very different" and 7 being "very similar," following this question: "How similar are both forms?." Mean values for the participants' (subjective) and post-experimental (objective) similarity ratings were calculated (see **Figure 5**). Due to the limited space, only those parts of the data that were relevant to the stimulus selection were considered and subsequently described on a qualitative level.

In general, the participants performed well in this exploration-and-drawing task. Despite a very short 3-s exploration time, most of the form drawings showed a strong resemblance to the presented stimuli. A general finding was that the quality of form drawing deteriorated with more complex forms. Comparably easy forms, such as a horizontal line (the mean of subjective rating, 6.30/the mean of objective rating, 6.60) and a raised-line circle (6.00/6.80), scored much higher similarity ratings as more complex forms, such as the fully protruded cross (3.4/3.33). A comparison of subjective and objective similarity ratings for the forms that were chosen to be used in Pre-Study 2 is given in **Figure 5**. Orientation and aspect ratios of forms seem to get lost by drawing. For example, the diamond-shaped stimuli were often recognized as simple squares. Rectangular forms were reproduced with distorted aspect ratios in a lot of cases—mostly as squares—making them easier to confuse with squared forms. Raised-line figures that consisted of a multitude of differently sized lines were also not reproduced correctly in many cases (#61–#74 in **Figure 3**). Another common observation was that forms with dull angles, such as the upper parts of trapezes, were drawn as semicircles, replacing edges by rounding.

Forms were selected based on criteria, such as (1) subjective and objective similarity ratings, (2) distinctiveness from other forms (e.g., rectangular and squared forms were often confused) and (3) advice from tangible user interface experts regarding suitability and feasibility in user interfaces. **Figure 6A** shows the 20 forms that were selected to be used in Pre-Study 2.

PRE-STUDY 2—SIMILARITY

Pre-Study 2 focused on examining general underlying form-functionality associations of 20 previously described haptic forms, using a multidimensional scaling procedure (MDS). Similarity data were collected, using a form-comparison paradigm. We also used Pre-Study 2 to select a set of 12 final stimuli for the Main Study.

Method

Participants

Fourteen right-handed participants took part in Pre-Study 2. They were between 21 and 57 years old (M_{age} = 29.9 years, $SD = 9.1$). Six participants were female. All the participants worked in the automotive sector. The participants were naïve to the goals of the study. Three participants already took part in Pre-Study 1. Four participants had prior experience with haptic technology. All the participants were right-handed.

Apparatus and Stimulus

Pre-Study 2 utilized the same apparatus, general setting experimental material as in Pre-Study 1. The inlay of the touchbox was adapted to fit two adjacent forms. The forms were separated by a small detent. The touchbox was adapted to the dominant hand of the participants. The MDS procedure requires similarity data from all form pair combinations. The stimulus set derived from Pre-Study 1 consisted of 20 forms (see **Figure 6**), resulting in 190 (undirected) pair combinations and comparisons.

Procedure

The participants were introduced to the background and procedure of Pre-Study 2. They were asked to imagine encountering these shapes in a future user interface. The experiment included a familiarization and comparison phase. In the familiarization phase, the participants were able to familiarize themselves with the stimulus set. They were instructed to freely explore all the forms one by one, using their index fingers and think of which kind of functionality the forms could represent in a user interface without speaking out loud. In the comparison phase, two adjacent forms were presented simultaneously. All

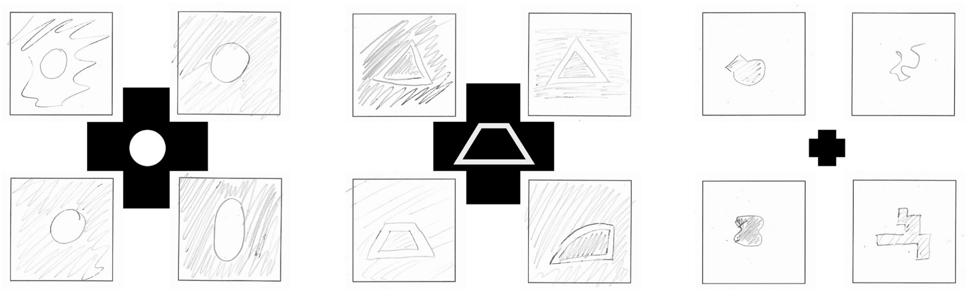


FIGURE 4 | Examples of participant's form drawings in Pre-Study 1. The middle form depicts which form the participants explored.

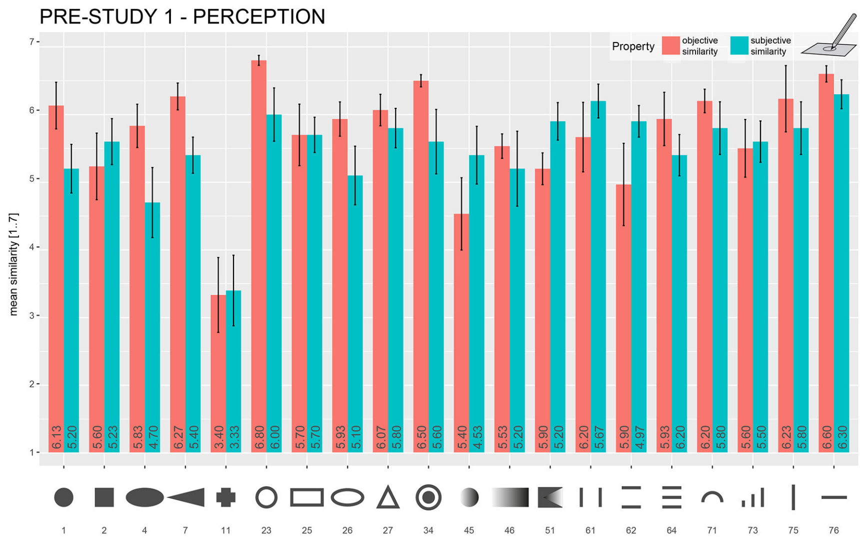


FIGURE 5 | Mean objective and subjective similarity ratings for the explored forms in Pre-Study 1 (*Drawing*) that were chosen to be used in further studies. The mean objective and subjective similarity rating is represented in each bar. Error bars = ±1 standard error of the mean.

haptic forms were presented in a randomized order for each block. The participants were asked to freely explore both forms. There was no time restriction for the exploration phase. The participants were asked to answer the following question after exploration: "How similar are both forms in terms of their perceived functionality on a scale from 1 (not similar at all) to 7 (very similar)?" After completion of all the comparisons, the participants were given a short questionnaire, containing illustrations of all the forms. The participants were asked to write down their initial form-functionality associations. These insights were gathered to have an initial starting point for the interpretation of the multidimensional scaling procedure. A complete session took ~75 min.

Data Analysis and Results

The multidimensional scaling procedure (MDS) allows to explore implicit similarity structures of different objects and visualize their reciprocal relationship based on pairwise (dis-)similarity measures (Jaworska and Chupetlovska-Anastasova, 2009). The MDS has previously been used to understand basic principles in haptic perception (Cooke et al., 2010; Okamoto et al., 2013). In the context of this study, the MDS was used to explore

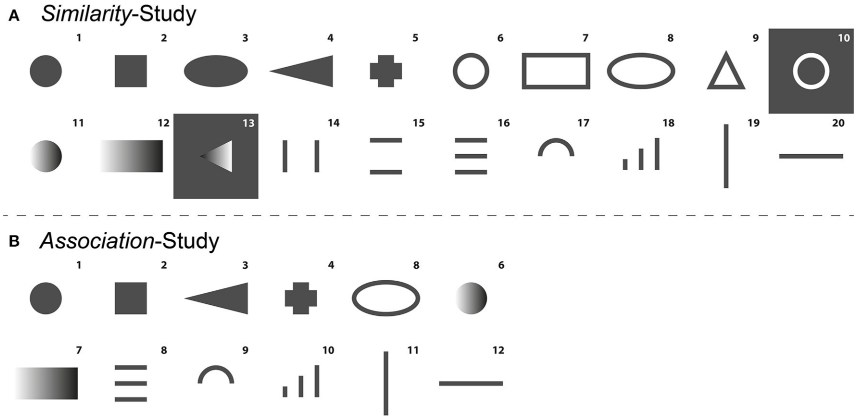


FIGURE 6 | **(A)** Forms ($k = 20$) that were selected to be used in Pre-Study 2. **(B)** Forms ($k = 12$) that were selected to be used in the *Association*-Study. Gray areas equal protruded (non-engraved), and white equals laser-engraved areas.

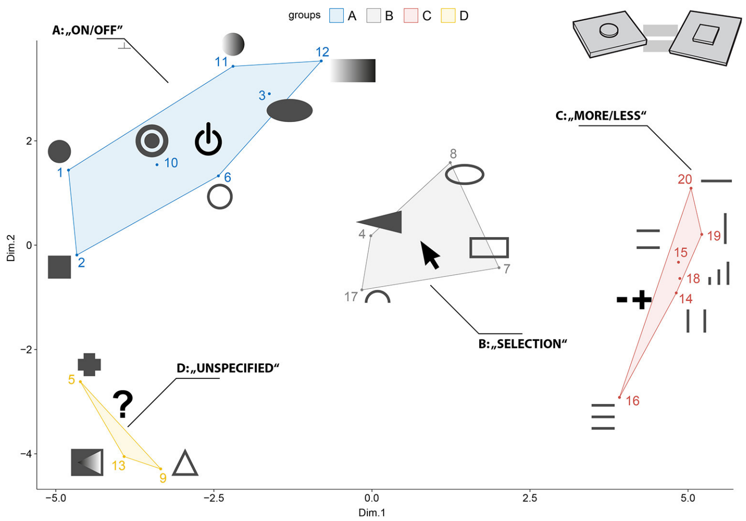


FIGURE 7 | The MDS procedure yielded four clusters that were interpreted with the following functional categories: **(A)** "on/off," **(B)** "selection," **(C)** "more/less," **(D)** "unspecified".

the general, underlying association pattern of forms and their perceived functionality. For data preparation, ratings of the pairwise comparisons were averaged across all the participants. Afterward, the data were transformed into a dissimilarity matrix, representing empirical distances between each of the form combinations. The MDS was performed on the dissimilarity matrix, using the *cmdscale()*-function in the statistical software R version 4.0.2 (R Core Team., 2021). We also used the *goeveg* (Friedemann and Schellenberg, 2021) and *igraph*-package (Csardi, 2019). An a priori stress test was performed to determine the number of clusters that needed to be extracted. The stress test (Kruskal's *Stress-1* < 0.2) revealed four clusters to be a reasonable number of clusters to represent the original space of stimuli. **Figure 7** depicts the configuration gained from the MDS. For ease of interpretation, the forms were directly embedded in the visual presentation of the MDS configuration. Using the initial impressions of the participants reported in the post-experimental questionnaire, and also results from Götz (2007) and Mlakar and Haller (2020), we interpreted the four clusters, using the following categories: (A) "on/off," (B) "selection," (C) "more/less," (D) "unspecified" (see **Table 2**).

Discussion and Stimulus Selection

Pre-Study 2 aimed to investigate the general implicit structure of form-functionality associations. Judging from the MDS plot (see **Figure 7**), there seem to exist four distinguishable clusters with respect to form-functionality associations: (A) "on/off," (B) "selection," (C) "more/less," and (D) "unspecified."

Different forms within a cluster share a common functional association, for example, different raised-line patterns—regardless of orientation—seem to invite sliding. It also seems reasonable to assume that there is an underlying pattern of interaction within the MDS configuration. Dimension 1 might correspond to spaceness of form and Dimension 2 to the roundness of form. Forms that were mostly related to sliding can be found on the positive side of the x-axis, whereas forms on the negative side of the x-axis were mostly related to pushing in the initial impressions of the participants. Forms within the "unspecified" cluster either do not activate specific functionality associations due to the fact of being too complex or contain a multitude of signifying design features, which makes them ambiguous with respect to functionality and interaction.

Only a selection of forms from every functional cluster was used in the Main Study. Forms were chosen based on (1) their location in the MDS configuration, (2) their distinguishing character and (3) feasibility in a user interface. In addition, forms 10 and 13 were the only forms, including recesses, and thus were excluded from the selection to avoid any biases in the final *Association*-Study. Based on the MDS configuration, the following forms were selected: 1, 2, 4, 5, 8, 11, 12, 16, 17, 18, 19, and 20 (see **Table 2**).

MAIN STUDY—ASSOCIATION AND FITTING

The MDS procedure in the previous *Similarity*-Study only depicts the configuration of the underlying similarity structure of the haptic forms. It is a mere description and does not provide any information as to which forms and design features correspond to which functional associations. The following *Association*-Study seeks to explicitly describe form-functionality relationships, using verbal descriptions and fitting ratings for functionality categories based on the 12 stimuli that were selected in *Pre-Study 2*.

Method

Participants

Thirty-two participants took part in the main *Association*-Study. They were between 21 and 57 years old (M_{age} = 32.3 years, $SD = 3$). Thirteen participants were female. All the participants worked in the automotive sector. The participants were naïve to the goals of the study. Thirteen participants had prior experience with haptic technology. There was one left-handed participant in the study. Seven participants took part in one of the previous studies.

Apparatus and Stimulus

The apparatus and experimental setup was the same as in Pre-Studies 1 and 2. The touchbox was fitted to house a single form at a time. The participants explored the form with their dominant hand. A special-purpose keyboard (consisting of number keys 1–7 for respective ratings only) to prevent distraction and an audio-microphone to capture verbal recordings were fitted onto the touchbox. A refined stimulus set, consisting of 12 forms based on the results from the *Similarity*-Study, was used (see **Figure 6B**).

Procedure

The participants were introduced to the procedure of the main *Association*-Study. They were asked to imagine encountering the forms in the context of an automotive user interface. The Main Study consisted of three experimental blocks: *Impression*, *Association*, and *Fitting* (see **Figure 1**). The blocks were presented in the same order. All 12 stimuli were presented randomly in each of the three blocks, so the participants touched all the forms three times within a single test session. An audio click indicated the start and the end point of the trial and audio recording. The audio was only recorded in the first two blocks. There was no time restriction in either of the blocks. All haptic forms were presented in a randomized order for each block. The first block *Impression* used a think-aloud method. The participants were asked to verbally describe their initial experiences with the form when touching the form for the first time. The participants were instructed to give spontaneous answers. This block was used as a familiarization block. The second block *Association* also used a think-aloud method to gain insight into the relationship between haptic forms and associated functionalities. In this block, the participants were again asked to freely explore the haptic forms and describe functional aspects they associated upon exploration. This also included how they would interact with the forms in an interface, e.g., by pressing or sliding. The third block *Fitting* used a rating procedure to gain insights into the perceived fitting ratings of the participants of the presented forms regarding the three functionality clusters that were being described in Pre-Study 2. After a haptic exploration period, the participants were given three questions: "How fitting is this form to be used as a control element for (1) on/off, (2) adjusting more or less or (3) selection?." The participants rated fitting of the three functionality categories, respectively, on a scale from one to seven (1 = *not suitable at all*, 7 = *very suitable*). After completing all the experimental blocks, there was a short post-study questionnaire that asked for any difficulties posed by the experimental design. The participants also had the chance to give any further annotations to the study. A test session lasted about 60 min.

TABLE 2 | Preliminary interpretation of the MDS results as given in **Figure 7**.

Cluster	Description	Forms
A	**On/Off** regarding confirmation by pushing	**1**, **2**, 3, 6, 10, **11**, **12**
B	**Selection** regarding selecting items from a horizontal or vertical list by pushing or sliding	**4**, 7, **8**, **17**
C	**More-or-Less** regarding sliding and rocker type switches	14, 15, **16**, **18**, **19**, **20**
D	**Unspecified** with ambiguous associations	**5**, 9, 13

Form numbers in bold indicate forms that were chosen to be further used in the Main Study.

Data Analysis and Results

During the *Association*-Study, two types of data were recorded: qualitative data covering verbal descriptions from the *Impression* and *Association* blocks and quantitative data covering rating data from the *Fitting* block. The verbal descriptions from each trial were transcribed to be used in further analysis. Verbal descriptions were given in German but will be translated to English in this paper. As the *Impression* block was conceptualized as a familiarization phase, we did not include those descriptions in the further analysis.

Association Data

For the preparation and analysis of the qualitative data from the *Association* block, we used a similar approach as Muth et al. (2018). They categorized verbal descriptions of artworks based on predefined categories to derive frequency values for the use of specific descriptive categories. Despite having an already predefined set of functionality clusters from Pre-Study 2, we again reviewed all verbal descriptions. Functional categories that were mentioned by most of the participants were on/off, more or less, and selection. The participants reported, in some cases, that a form does not yield any specific functionality association but might be used as search haptic cues as described by Breitschaft et al. (2019a). The participants also explicitly mentioned that there is no specific functionality at all in some cases. An initial list of categories defined by each of the authors separately was discussed and resulted in the following coding scheme: on/off, more or less, selection, search cues, and no functionality.

Three independent raters categorized each of the verbal descriptions (32 participants × 12 forms = 384 descriptions per rater) based on the created coding scheme. The raters were given an extensive explanation for each of the categories. The raters could freely assign each description to only one category or more than one category. If the participants did not associate a specific functionality, the raters were instructed to assign the "no functionality" category. In total, there were 1,247 category assignments. In 312 cases, all three raters were assigned the same category; in 98 cases, only two of the raters used the same category assignment, and, in 115 cases, only one rater used the category assignments for a specific description. For further analysis, only the verbal descriptions in which all three raters coincided with their category assignment were used. **Figure 8** shows the relative frequencies of the functionality-based category assignments per form. For ease of readability in the following sections, form numbers will be given in numbers.

Forms 1, 2, 6, 7, and 9 were most often described by words belonging to the on/off category (e.g., confirmation, button, and push button). Form 1 (circle) and Form 2 (square) were almost exclusively described as being an on/off push button (96 and 91%, respectively). Forms 6, 7, and 9 were mostly being described with respect to on/off functionality (48, 48, and 36%, respectively). The most-used words for describing Forms 3, 5, 8, 10, 11, and 12 were related to more-or-less functionality (e.g., slider, volume, and temperature), ranging from 30 to 79%. The selection-category was the second most assigned functional category for forms 4 (32%), 5 (25%), and 8 (21%). Close to 37% of the descriptions for form 4 included references of the form being useful for detection purposes.

In addition to the perceived functionality, the participants also often described how they would interact (i.e., pressing, sliding, and touching) if the form was represented in a user interface. The previous categorization procedure was repeated with the same three raters and verbal descriptions from the *Association* block to focus on interaction-based descriptions. The coding scheme included the following interaction categories: "push (in z-axis)," "slide (as swiping on a touchscreen)," "push and slide (as moving a physical slider control)," and "no movement." **Figure 9** shows frequency plots of interaction-based category assignments for all forms. Most of the forms, for example, Forms 1, 2, 11, and 12 can clearly be assigned to a single type of interaction. Manipulation by pushing was the most used category for Forms 1 (100%), 2 (93%), 3 (44%), 4 (65%), 6 (64%), 7 (48%), and 9 (37%). Sliding-related descriptions were most used for Forms 5 (52%), 8 (48%), 10 (36%), 11 (70%), and 12 (64%). Form 7 has quite often been described by sliding as well (45%), in addition to pressing (48%). Form 10 was often described as being with no specific movement (36%) as it was with sliding (36%). About 28% would want to use Form 10 by pressing. Form 9 was one of the most ambiguous forms (push, 37%; slide, 26%; push and slide, 16%; and no movement, 21%).

Fitting Data

Fitting data from the *Fitting* block were analyzed, using the statistical software R version 4.0.2 (R Core Team., 2021), as well as the *ggplot2* (Wickham, 2016), and *effsize* package (Torchiano, 2020). **Figure 10** and **Table 4** show the averaged fitting values grouped by functionality and form. Forms 1 (6.88), 2 (6.25), and 4 (5.00) scored highest on the on/off category, with a high discrepancy to the next functionality category. Form 1 and Form

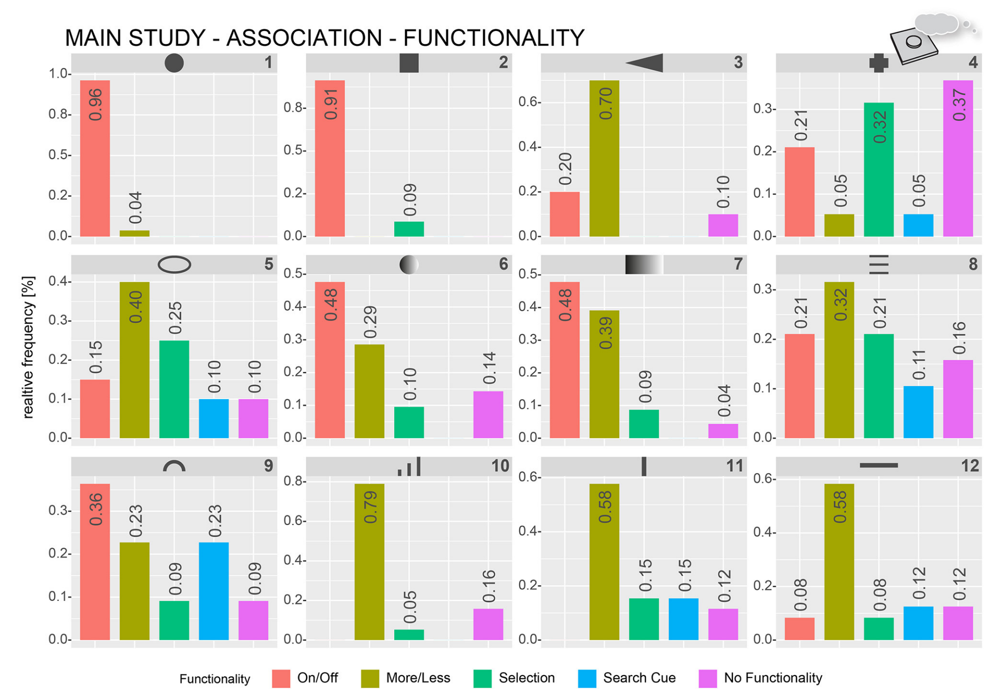


FIGURE 8 | Relative frequencies of how often specific functionality-based categories were assigned by the raters to describe verbal functionality associations of the participants. The numbers represent the relative frequency per category.

2 scored the highest mean values overall. Forms 6 (3.91) and 9 (4.12) scored highest on the on/off category but did not seem to differ from the more-or-less category. Forms 3, 7, 8, 10, and 12 scored highest in the more-or-less category (4.69, 4.09, 4.53, 5.22, and 5.56), but only Forms 3 and 10 differed from the next highest category. Forms 5 and 11 scored highest on the selection category (4.72, 5.72), but there were no relevant differences from the more-or-less category.

We established the uniqueness fitting score (UFS) to compare the fitting of specific forms for certain functionalities. It describes the clarity of a form in terms of perceived functionality and is based on the effect size (reported in *Cohen's d*) between the fitting values of the highest and second best-fitting functionality category. The higher the UFS, the clearer association of a form in terms of functionality. The lower the UFS, the more ambiguous the form-functionality association. **Table 4** describes the UFSs as well as the effect sizes to the least fitting category for every form. The UFSs yielded large effects sizes (Cohen's $d \geq .8$), except for Forms 5 ($d = 0.22$, small), 7 ($d = 0.35$, small), 8 ($d = 0.15$, small) 9 ($d = 0.38$, small), 11 ($d = 0.10$, small), and 12 ($d = 0.37$, small).

Discussion of Form-Functionality Associations

The major aim of the main *Association*-Study was to further explore the general implicit form-functionality pattern found in Pre-Study 2 and describe explicit form-functionality associations. We used a think-aloud method (qualitative) as well as a rating task (quantitative), which were both already used in previous studies, using association-based paradigms (for a more-detailed explanation, see **Table 1**). In general, combining both data collection strategies yields a strong indication for specific form-functionality relationships. Yet some forms seem to convey clearer functionality associations than others, for example, see Forms 1 and 2 vs. Forms 7 and 9.

Forms 1 and 2 yielded the clearest association pattern. In the *association* as well as the *fitting* task, the protruded square and circle forms yielded the highest scores in the on/off category (see **Figures 8**, **10**) and the highest UFS (each > 3). In most cases, the participants wanted to press these forms (see **Figure 9**). Typical descriptions included "it just feels like a normal button" or "It's a protruded form I would just like to press." The

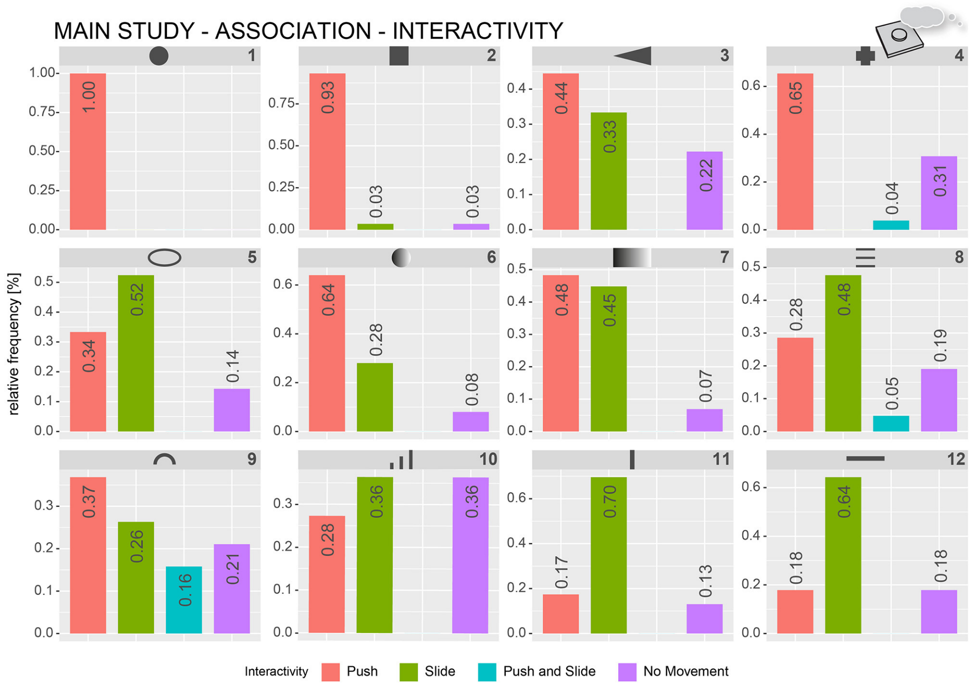


FIGURE 9 | Relative frequencies of how often specific exploration-based categories were assigned by the raters to describe verbal interactivity associations of the participants. The numbers represent the relative frequency per category.

protruded circular and squared form seems to strongly resemble a "traditional button."

Form 3 displayed a more/less functionality for most of the participants (UFS = 0.72). As opposed to most of the other more/less-associated forms, it seems to be ambiguous regarding interaction. Roughly 40% would press, while roughly 33% of the participants would slide to adjust values. The triangular form potentially reminded the participants of a volume element ("It reminds me of increasing/decreasing as the shape converges to a point.").

Form 4 (cross) seems to be clearly associated with an on/off functionality (UFS = 1.33) that is activated by pressing (65%). However, the verbal associations also pinpoint a selection functionality (32%), as the cross seems to remind the participants of the control pad on a Gameboy. The selection can be made by pressing on one side or the other. Yet the *Perception* Study showed that this form is hard to recognize, which potentially leads to a lot of people having no specific functionality association at all (37%). For the other participants, a mere protrusion may have yielded the association of something that can be pressed—no matter the form.

Form 10, with its triangular geometrical shape, clearly indicated a more/less functionality. The UFS (1.48) indicates a large effect. In almost 80% of the cases, the participants described Form 10, using a more/less functionality. For some participants, the tripartite structure (multiple raised lines increasing in size) yielded an even more detailed association with distinct and increasing levels of intensities ("3 stages," "*3 different intensities*"; see **Table 3**). However, interactivity seems to be ambiguous. A third of the participants would like to slide; another third did not report any interaction movement, whereas roughly 25% reported they would want to press.

Forms 6 and 9 are quite similar with respect to their association patterns. Their UFS ranges between 0.32 and 0.38, which represents a small effect. The on/off category is the most fitting functionality category for Forms 6 and 9. Almost 50% described Form 6, using on/off related, while roughly 30% used more/less-related descriptions. Form 9 seems to be even more ambiguous. About 36% used on/off related, and 23% used more/less-related descriptions. The same number of the participants frequently reported this form in conjunction with being a mere search cue with no further functionality.

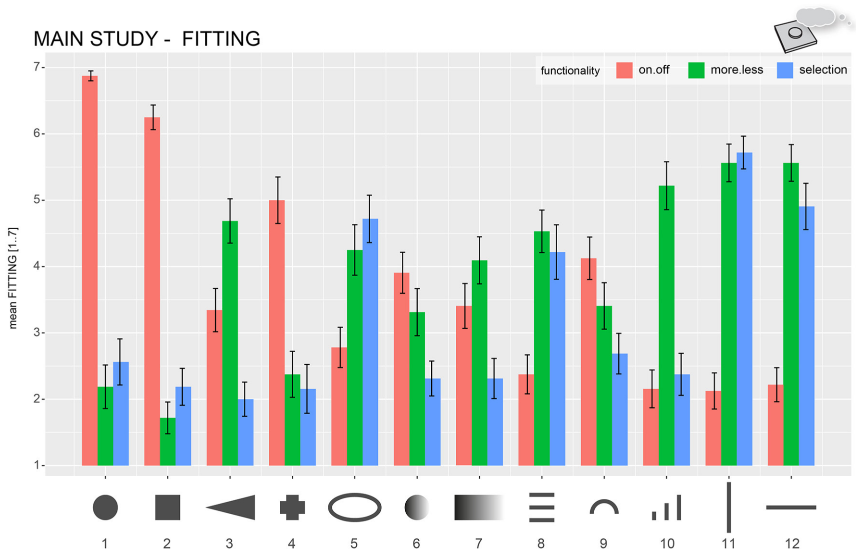


FIGURE 10 | Mean fitting values for all functionality categories (on/off, more/less, selection) for each haptic form. Error bars indicate ± 1 standard error of the mean.

A similar pattern can be observed for Forms 7 and 8, only that the most fitting category was more/less (UFS = 0.35 and 0.15, respectively). Judging from the qualitative association data, Form 7 was frequently associated with an on/off (48%) as well as a more/less functionality (39%). Interactivity descriptions for Form 7 show an equally ambiguous pattern for pressing (48%) vs. sliding (45%). Although some of the participants reported associating Form 8 with a "burger menu icon" was mostly connected to a more/less and selection functionality that is primarily activated by sliding (48%). The ambiguity of Forms 6, 9, 7, and 8 possibly results from the integration of multiple signifying design features. The participants described the gradient of Form 6 to have the form of a "ramp that you just want to swipe up." However, the edge of the ramp also invited the participants to push ("I want to make the form flush"). The physically longer gradient in Form 7 seemed to reinforce the sliding and, hence, the more/less impression of the form. Form 9 seems to integrate a mixture of possible signifying design features as well. The half-cut circle clearly represented the boundaries of a button for several participants: "It's like a dead end for the finger," "finger guidance," "the arc feels like a search haptic cue." The "half-moon" created a "natural contour for a button area," which probably invites users to press. However, in some cases, the arc-like appearance was also associated with a two-way more/less functionality ("slide on half-moon").

Forms 5, 8, 11, and 12 are among the lowest UFS (0.22, 0.15, 0.10, and 0.37). Each of the forms scored low on the on/off category and high on both the more/less and selection functionality categories with regard to its mean fitting rating. All those forms have in common that almost half of the participants described an interaction *via* sliding during exploration. Forms 11 and 12 were characterized by sliding by 70 and 64% of the participants. Generally speaking, raised-line forms, regardless of their appearance (horizontal, vertical, or a closed circular form), are likely to be interpreted as slider elements. The participants describe protruded contours as "anchors" or "guidance and orientation for the finger." Looking at the qualitative data in **Figure 8**, all forms show higher frequency values for the more/less than the selection category. The elliptical shape of Form 5 reminded the participants of the circular click-wheel on older iPods used for scrolling playlists. Although some participants interpreted Form 8 as a "burger menu icon" or a push button with three discrete intensities, most of the participants would use the three horizontally arranged lines as a slider to either scroll lists or adjust temperature and volume. The participants were reminded of a flat and modern-looking interpretation of a knurl element that can regularly be found as a scroll element on automotive steering wheels. The vertical and horizontal arrangements of Forms 11 and 12 both seem to trigger the association of a slider to scroll lists or adjust a more/less continuum. We assume the functionality itself depends on the implementation into the user interface.

GENERAL DISCUSSION

The major aim of this study was to explore functional-based associations of haptic forms based on a highly systematic tripartite (*perception*, *similarity*, *association*) multi-study approach. Both Pre-Studies were mainly used to select a set of distinguishable and recognizable forms to be used in the Main Study. Even though having a preliminary character, both Pre-Studies yield insights and prerequisites for examining form-functionality associations. With an open-ended, exploratory approach, we aimed to apply the so-called "aesthetic association principle," which is one of the basic principles of psychology (1) to a purely haptic domain and (2) in a utility-based rather than an aesthetic-based setting (Carbon and Jakesch, 2013). By doing, so we advocate the integration of a deeper psychological turn in haptic interface design (Carbon, 2019).

Form-Functionality Associations

One general conclusion is that haptic forms in a user interface context seem to convey signifying functional aspects (see **Figure 11**). At a first glance, this seems quite intuitive, but it is important to realize that, first of all, we have to test this intuitive thinking by means of systematic empirical testing. Even more important, this routine has proved to be of great assistance to detect clusters of associations. The MDS procedure in Pre-Study 2 suggests functional-based dissociation of different forms based on four implicit clusters, which we interpreted regarding the following functional categories: on/off, more or less, selection, and unspecified. The verbal association and fitting data from the main *Association*-Study (study 3) revealed explicit form-functionality associations, indicating communicative characteristics of haptic design features. For a detailed description and discussion of association patterns, see section Procedure. In the following section, form numbers refer to the forms in the *Association* Study.

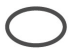
Some forms and haptic design features revealed a strong association with perceived functionality, regardless of interactivity. Forms 3 and 10, both with a triangular shape, were associated mostly with a more/less functionality as it seems to remind the participants of a typical volume symbol. Also, the circular and rectangular shapes (Forms 1 and 2) seem to clearly indicate an on/off functionality. Other forms yielded a strong invitation for interaction but are potentially ambiguous toward functionality. A protrusion—either in the form of fully protruded form (as in Forms 1 and 2) or single salient edges (as in Forms 6 and 7)—seems sufficient to convey a push functionality. Forms including elongated raised lines, such as Forms 11 and 12, clearly afford a sliding interaction no matter the functionality ("It gives guidance and orientation for the finger."). The Creative Zen Vision: M and the Toshiba Gigabeat MP3-Players are examples of how forms have already been used to facilitate a scroll interaction by sliding (Saffer, 2009).

We suppose the functionality association is not entirely triggered by geometrical shape alone but depends on integration with other design features. Forms 6 and 7 both incorporated a protruded edge and a prolonged "ramp-like" gradient. The edge was often interpreted as a call to push ("I am tempted to make the edge disappear."), while the gradient invited the participants to slide ("I would like to slide toward the elevation."), making the form somewhat ambiguous. Possibly, ambiguous forms, such as Forms 6, 7, and 9, incorporate a multitude of signifying design elements, which fail to pronounce a "key interaction." Indeed, haptic forms that entailed a distinct protruded element, such as Form 1 or "[the] ramp with an edge" (Forms 6 and 7), made the participants frequently think of "something [they] would like to make flush with the surroundings." Data indicate that the longer "ramp-like" gradient in Form 7 affords sliding as well as more/less impression, while the "edge of the ramp," which is more pronounced in form 6, invites pressing. The implementation of specific design features, such as size, gradient, and protrusion already seem to pose an interactive context that facilitates or suppresses the functional character of specific geometrical shapes.

This research incorporated simple implementations of the forms, which only provided a generic interaction context (e.g., location of the interface, integration of forms into the interface possible interaction with a GUI, etc.). The forms were presented individually and not embedded in a physical interface (see **Figure 2**). We suppose that associative strength is influenced by the overall haptic impression of a physical interface—a localized haptic context. Protruded elements seemed to be connected to a push functionality. This is, at least, partly, due to the saliency of the protrusion in an otherwise flat surface. Salient stimuli are said to be highly efficient and informative in perception as they grab attention (Itti, 2007; Kerzel and Schönhammer, 2013), which makes them a value source of information. A "bumpier" interface might decrease the saliency of a form and suppress its associative strength. The same applies to triangular forms (which indicated a more/less functionality). In the presence of a bumpier surface geometry, they blend with the rest of the interface and lose their associative strength. Context variables, such as the implementation of functional elements within non-functional parts of the user interface elements and the interplay of haptic information with multisensory, especially additional visual information like symbols information, impact saliency and thus associative strength. Being aware of modulating factors is essential during the haptic design process to avoid ambiguity and facilitate the intended functional interpretation (Jakesch et al., 2011; Carbon and Jakesch, 2013). Further studies may investigate the modulating influence of additional context information, such as visual symbols on the perceived affordance of haptic forms.

In general, the participants found it difficult to differentiate between a more-or-less and selection functionality (indicated by a small UFS) for some haptic features. The given context and thus associative strength of the forms were probably too weak or too ambiguous to elicit a clear association. Even though Forms 5, 8, 11, and 12 are highly associated with a sliding interaction and more/less functionality, the UFS is low for all of these forms (0.22, 0.15, 0.10, and 0.37). Effect sizes compared

TABLE 3 | Exemplary verbal descriptions by the participants in the *Association* Study.

	Form	Exemplary descriptions
1		"A protruded area. Just a simple button," "A circle. I would just like to press it"
2		"You'll get stuck on the protruded surface," "I just want to press it, because it's protruded."
3		"The triangle is a complicated shape," "It reminds me of increasing/decreasing as the shape converges to a point," "could be used for climate control or volume."
4		"it' complicated," "reminds me of a joystick and directional pad," "could be an iDrive replacement"
5		"it's exactly like the click-wheel of the first iPods," "could be used for navigating in a center display," "multifunctional," "contours invite sliding," "pressing in-between contours"
6		"slide from left to right," "I would like to slide along the rising area," "The edge invites pressing," "it's like sliding and then pressing at the end"
7		"intensity adjustment," "reminds me of a rocker key," "sliding toward rising area," "I am tempted pressing the protruded edge"
8		"slide control to open the sun-roof," "menu-button," "reminds me of a knurl," "3-staged element," "haptic separation between buttons"
9		"like a dead-end for the finger," "finger guidance," "slide on half-moon," "natural contour for button area," "the arc feels like search cue"
10		"3 stages," "more/less," "WiFi-Button," "Volume- control," "three increasing buttons," "three different intensities"
11		"guidance," "increase/decrease," "slider," "separation between buttons"
12		"temperature," "volume," "climate control," "slider," "guidance and orientation for the finger," "more/less," "zoom in/out on a map"

*The number of forms corresponds to the forms in **Figure 6B**. Gray values correspond to protruded areas.*

with the least fitting the on/off category were high for all those forms (1.03, 1.24, 2.44, and 2.21; see **Table 4**). The raised-line contours clearly afforded a sliding interaction regardless of the underlying functionality ("finger guidance," "you snap onto the contour"). Hence, the raised-line forms seem to incorporate user expectation and a stronger underlying interactive metaphor toward interaction rather than functionality. Mlakar and Haller (2020) already proposed to use a straight stitched line to indicate an interaction *via* sliding. The convergence of more/less and the selection functionalities might also be undermined by the conceptual similarities between both functionalities. While the more/less functionality is characterized by the incremental adjustment of ordinally scaled values (e.g., temperature/volume) on a dimension with two extremes (min/max), the selection is characterized by adjusting nominal data in a list. Despite the conceptual overlap, above-mentioned forms are highly suitable in interface contexts, as the context and consequently associative strength toward a specific functionality can be modulated *via* additional graphical information. Forms may probably be interpreted as more/less functions if the form is implemented as a standalone interface element, e.g., like temperature sliders in the VW ID.3 (Volkswagen., 2020) or

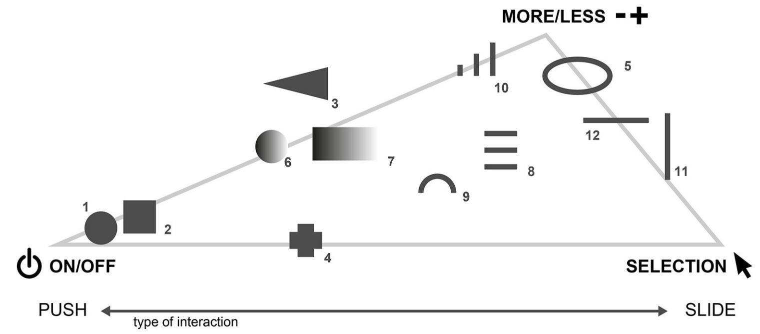


FIGURE 11 | Form-functionality associations based on the forms and functional categories in the Main Study. Some shapes also show a clear tendency toward how the participants would want to interact.

TABLE 4 | Uniqueness fitting score (UFS) and effect sizes for fitting ratings for each of the forms across the functionality categories on/off, more/less, and selection.

Form	Most fitting	Mean	Least fitting	Mean	*Effect size*	2nd best fitting	Mean	*UFS*
1	On/Off	6.88	More/Less	2.19	3.48 *(H)*	Selection	2.56	3.03 *(H)*
2	On/Off	6.25	More/Less	1.72	3.75 *(H)*	Selection	2.19	3.04 *(H)*
3	More/Less	4.69	Selection	2.00	1.60 *(VL)*	On/Off	3.34	0.72 *(M)*
4	On/Off	5.00	Selection	2.16	1.40 *(VL)*	More/Less	2.38	1.33 *(VL)*
5	Selection	4.72	On/Off	2.78	1.03 *(L)*	More/Less	4.25	0.22 *(S)*
6	On/Off	3.91	Selection	2.31	0.98 *(L)*	More/Less	3.31	0.32 *(S)*
7	More/Less	4.09	Selection	2.31	0.96 *(L)*	On/Off	3.41	0.35 *(S)*
8	More/Less	4.53	On/Off	2.38	1.24 *(VL)*	Selection	4.22	0.15
9	On/Off	4.12	Selection	2.69	0.81 *(L)*	More/Less	3.41	0.38 *(S)*
10	More/Less	5.22	On/Off	2.16	1.67 *(VL)*	Selection	2.38	1.48 *(VL)*
11	Selection	5.72	On/Off	2.12	2.44 *(H)*	More/Less	5.56	0.10
12	More/Less	5.56	On/Off	2.22	2.21 *(H)*	Selection	4.91	0.37 *(S)*

UFS, uniqueness fitting score. Mean values range from 1 to 7. Effect sizes and UFS are reported in Cohen's d. The higher the UFS score, the clearer functionality association of a form. $d \geq 0.2$ = S/small, $d \geq 0.5$ = M/medium, $d \geq 0.8$ = L/large, $d \geq 1.2$ = VL/very large, $d \geq 2$ = H/huge.

the molded touch modules to control airflow temperature in the BMW 7 Series (BMW Group., 2019). An additional screen might afford a scrolling/selecting type of interaction, comparable to an automotive rotary controller or the Click Wheel on the early iPods.

Interestingly, for some of the forms, the participants already described very specific functional associations. Form 10 reminded some of the participants of the cell reception icons on their phones. It thus represented "setting up a wireless connection." We argue that some frequently used symbols in graphical interfaces, such as a prototypical antenna symbol or a musical note, could also be used as haptic shortcut elements for functions, such as connectivity or entertainment. Haptic symbols or pictograms have shown to improve the accessibility of interfaces for visually impaired people (Harder and Michel, 2002; Gual et al., 2015).

The required precision for a robust recognition of haptic icons is still subject to discussion. Mlakar and Haller (2020) used familiar UI-symbols (star, home, phone, and heart) that were stitched onto a textile and concluded, that while the star was recognized best, the participants found it rather difficult to correctly name the symbol after eyes-free exploration. Ueda et al. (2016) propose a haptic symbol size of around 120–150 mm^2 for optimized recognizability. Results from the *Perception*-Study indicate that drawing and thus recognition performance is worse with more complex forms (for an example, see **Figure 4**), which possibly applies to complex haptic symbols as well. Weak discriminability and recognizability might also decrease the associative character of haptic symbols. We advise designers to use basic and simple forms to ease discriminability and thus maximize saliency in contexts that require efficient and easy-to-use interfaces.

We followed a bottom-up study approach to explore user associations. We examined associative descriptions, using a think-aloud method based on a set of easily recognizable and distinguishable forms whose selection process we described in detail. A more top-down approach has been followed by Van den Bogaert and Geerts (2020) as well as Wobbrock et al. (2009). They used a so-called "end-user elicitation study" to examine affordances of gesture-specific mid-air-haptic feedback and gestures for surface computing. Villarreal-Narvaez et al. (2020) provide an extensive review of gesture elicitation studies. A similar approach was used by Ali et al. (2019) but added an additional evaluation loop and fed back user-elicited symbols in a separate study back to the participants with the task to identify the most fitting representatives for specific certain UI categories. Carbon (2019) emphasized that evaluation of novel and unfamiliar products requires user familiarization to gain valid data on longer-termed user experiences. This might be a limiting factor in elicitation studies: "If you ask people about the future, they will talk about the world of today" (Carbon, 2019, p. 6). Our bottom-up oriented approach seems to be an effective yet convenient and easy-to-execute task for the participants as it focuses on personal learning history of the participants. Experimental data generated by employing the AAP is concrete and allows for direct application. Yet we encourage designers to apply the AAP to their specific field application (visual, as well as audio design) to derive use-case specific guidelines.

Toward a Deeper Psychological Turn in Haptic Design

Insights from the *perception-*, *similarity-*, and *association*-study underscore the notion of Carbon notion of the subjective, predictive, dynamic, experience-based, context-sensitive, task-dependent, associative, and multisensory nature of perception (Carbon, 2019). We propose the AAP to be an important and fundamental underlying psychological principle, contributing to the formation of affordances through constant perception, evaluation, and integration of experience. Being aware of the associative relationship between design features and functionality fosters interface design from a functional as well as aesthetical perspective. It also means gaining a deeper understanding of the expectations of users. Creating predictable interfaces by facilitating user associations alleviates cognitive demand and positively influences customer satisfaction (Pohlmeyer et al., 2009). It also complies with one of the basic usability parameters "conformity to expectations" (Heimgärtner, 2017). Future studies might want to explore factors facilitating and suppressing the adoption of associative relationships. In this respect, research should take an even closer look at the role of context ("Are there context-insensitive functional associations?," "How does additional visual information, such as the presence of a screen, change the functional affordance of a haptic form?," etc.) and feedback on the adaptation of interaction habits ("Which type of feedback facilitates establishing functional associations?").

Understanding the experiences of users (i.e., the personal learning history) with haptic interfaces is especially important in understanding the metaphorical value of traditional analog interfaces and how they can be transferred to the digital age. The AAP enables practitioners to gain insight into metaphors governing this switch from analog to digital interfaces, for example, how to design active haptic impulses to retain the rich tactual experience known from traditional button interfaces. Heijboer et al. (2019a) applied the AAP to examine how participants interpret a broad number of piezo-actuated impulses. Also, Breitschaft and Carbon (2020a) aimed to identify haptic analogies in the context of electrostatic friction displays. Form 5 (an ellipse with a raised-line contour) was often associated with the Click-Wheel rotary control found on an early version of the iPod (Apple, 2020). Some participants suggested using such the "elliptical ring" as a modernized interpretation of traditional in-vehicle rotary knobs. Interestingly, something similar happened when the participants explored form 8, which looks like a haptic symbol of a "burger" menu button (which, indeed, was a common association, "that's like a menu shortcut"). Yet the associative data indicate that the participants are more likely drawn toward interaction by sliding. The verbal data reveal that some participants compared form 8 with a reminiscence of a classic "knurl" —comparable to visual signifying cues described in Götz (2007).

The concepts we employed in the study partly remind us of the notions of Gibson and Norman of "affordances." In a later article, Norman (2008) advocated for using "signifying design features" instead of "(perceived) affordances" to refer to the usability of products to emphasize their context dependency. However, the approach of Norman seems to be more prominent for a posteriori explanation of usable products in the sense of usability heuristics. The approach we propose in the present paper allows to examine and explain the effectiveness of some haptic forms in user interfaces—the approach also explores user expectations to create more compelling interfaces in the first place. Literature still lacks concrete guidelines on how to mindfully incorporate functionality-driven haptic design features in the design process of high-quality and safe-to-use active and passive haptic interfaces (Breitschaft and Carbon, 2020a; Breitschaft et al., 2020). Our work extends findings on signifying surface features in traditional automotive control elements (Götz, 2007) and will hopefully, also, inspire more work on this important topic.

LIMITATIONS

Despite the systematic approach we applied here in terms of a multistep research process, there are limitations of the study. First and foremost, the forms have not yet been integrated and evaluated in a holistic user interface. Hence, important context cues are missing. During the study, no haptic feedback upon confirmation was given—the forms remained static. This was done because we were only interested in examining the initial identifying character of haptic forms as described in the *Identification* phase of the "Framework of Haptic Processing in Automotive User Interfaces" (Breitschaft et al., 2019a).

Also, the given interaction context was too generic compared with diverse real-world interface context demands (e.g., safety in automotive, experience in CE). Context fundamentally influences user associations. We focused on examining general potentially context-independent functional categories rather than interface-specific functions. Another goal was to demonstrate the general effectiveness as well as the ease of use of the AAP in an interface design context. Nonetheless, the participants reported very specific functional associations for some forms ("WiFi," "First Aid Button"). Future research needs to examine the influence of different context factors on form-functionality associations.

This study used a limited set of generic forms in the *Association* Study, which needs further adaptation for the application in consumer-ready interfaces and potentially lacked representativeness regarding a fully systematic form-functionality approach. We mainly implemented a prototypical and restricted set of forms due to the overwhelming abundance of physical material properties to create haptic forms. We chose to select the initial set of 80 haptic forms (which seemed to be feasible in pilot studies for Pre-Study 1) also based on experience from tangible user interface experts. We opted to take a more application-focused approach with respect to which forms might be applicable in the future interfaces. Another related limitation refers to the number of stimuli we employed in each of the studies. Pre-Study 1 included 80 forms, which were reduced to 20 in Pre-Study 2. The Main Study used 12 forms. These restrictions were based on methodological reasons. Each of the studies was designed to last about 60–90 min, which we found to be the maximum for the untrained participants in haptic studies. We decided on the number of stimuli based on what seemed to be manageable for the participants within this time frame. Indeed, choosing different quantities of stimuli, or making a different stimulus selection might have ended in different results. A larger number of stimuli per stage might influence the overall quality of the results. However, this research was not intended to exhaustively report form-functionality descriptions but to explore common user associations for frequently implemented prototypical forms, rest their examination on a systematic theoretical foundation, and emphasize the importance of a psychology-based perspective of haptic design. A similar issue regarding a manageable sample size and how to optimize the perceptual space have been described by MacLean and Hayward (2008). We followed the approach of MacLean (2008) and implemented a tripartite perception-based form selection process, which underscores important facets during the haptic design process—*recognition and detectability*, *distinctiveness*, and *semantic significance*. Further studies might examine functionalities, using broader and more systematically generated stimuli. Pre-Study 1 and Pre-Study 2 included 10 and 14 participants, respectively. The sample size might appear lower than comparable studies but needs to be considered within the context of the entire multistep research approach. The first two studies were designed as Pre-Studies and not as standalone experiments. We described the Pre-Studies in more depth to provide practitioners with an easy-to-implement procedure to support their design workflow. Pre-Study 1, which was based on a qualitative judgment of drawings, might have benefited from a greater number of participants to derive valid design guidelines. Also, the MDS in Pre-Study 2 might have yielded a more precise representation of actual associative patterns. Even though we explore haptic design guidelines, the main goal of the Pre-Studies was to provide a very general foundation for stimulus selection. MacLean and Hayward (2008) describe a similar approach of "perceptually optimizing" a larger set of stimuli within their research on haptic icons. They argue that a few participants might already generate a sufficient amount of dissimilarity data.

IDEAS FOR APPLICATION

The current set of stimuli consisted of a homogenous material in terms of hardness and surface texture. Mlakar and Haller (2020) already examined signifying features in textile interfaces. They showed that surface features, such as stitching, and also concave or convex surface geometries, are associated with a call for action. Götz (2007) gives an extensive overview of visual-based affordances of traditional automotive control panels. Additionally, other haptic material qualities, such as temperature, hardness, and slipperiness, seem promising to be used in UI contexts but have not yet been examined with respect to their signifying character. For an extended review of haptic material qualities, see Bergmann Tiest (2010) and Klatzky et al. (2013). Iosifyan et al. (2017) already found semantic associations between haptic material, such as silk or wood and multisensory stimuli, such as movie snippets. Especially surface features, such as compliance, may elicit a profound "call for pressing" in the z-direction due to the compliant surface material. Besides haptic features, also the dynamics of shape-changing interfaces may be useful for interface design to display system state and an affordance (Tiab and Hornbæk, 2016; Petersen et al., 2020).

Applying a more profound psychological perspective by employing semantic analogies has the potential to benefit a broad spectrum of applications, such as novel haptic technologies and automotive tangible user interface design. Haptic experience constitutes more than a mere technical perspective of haptic technologies. It is embedded into a reciprocal interaction of context, user, and technology. Methodological approaches, such as shown in the *perception*-, *similarity*-, and *association*-study, promote understanding of the perception of the users of innovative haptic devices (Breitschaft and Carbon, 2020b) and support a truly human-centered approach to haptic interface design (Breitschaft et al., 2020). Automotive user interfaces may especially profit from a cognitive-driven design process as they need to meet a multitude of different requirements, ranging from a safe and efficient interaction to a highly aesthetic appearance. Integrating an association-driven haptic form language into seamless tangible user interfaces may not only enable orientation but also already identification of interface elements, reduce driver distraction by alleviating cognitive demand, and positively impact user experience due to conformity with user expectations (Carbon and Jakesch, 2013; Breitschaft et al., 2019a). It may also guide familiarization and ease of use with novel technologies as association potentially triggers deeply rooted routines (Breitschaft et al., 2019a), especially in cases of eyes-free operation. Future research should aim to test the usability of an association-based user interface in an applied automotive setting. Following an association-based perspective may also improve usability and product appreciation in other domains of haptic design, such as consumer electronics, transportation, virtual reality, and robotics. Even though we focused on form-functionality associations, the *aesthetic association principle* might also be applied in haptic aesthetics to provide a cognitive-driven explanation why certain material properties are appealing to touch.

CONCLUSION

This series of studies reinforces the need for the implementation of a stronger psychological and contextual perspective in haptic interface design. We depicted how the mindful integration of psychological paradigms from the early ages of psychology in the nineteenth century, such as *aesthetic association principle*, has fundamental repercussions on new-age design disciplines, like haptic interaction design. Focusing on a psychological rather than purely technical reality opens new perspectives for refining the current design and pathing the way for rethinking and readjusting established design and engineering practices to govern the transformation from analog tangibility to a digital virtuality. The adaptation of psychological paradigms is a key challenge in the human-centered design process. It is an important stepping stone toward successfully following of a holistic "Psychology-of-Design" approach to design.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SB and C-CC had the initial idea to apply the aesthetic association principle to the haptic interaction domain and worked further on the manuscript. SB conceptualized the design of experiments, manufactured haptic stimuli, did the main part of the research, conducted the studies, mainly wrote the manuscript, and created graphical content. Both authors contributed to the article and approved the submitted version.

REFERENCES

Ali, A. X., Morris, M. R., and Wobbrock, J. O. (2019). "Crowdlicit: a system for conducting distributed end-user elicitation and identification studies," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, eds S. Brewster, G. Fitzpatrick, A. Cox, and V. Kostakos (New York, NY: ACM Press), 1–12. doi: 10.1145/3290605.3300485

Apple (2020). *iPod-Modell Bestimmen*. Retrieved from: https://support.apple.com/de-de/HT204217

Bergmann Tiest, W. M. (2010). Tactual perception of material properties. *Vis. Res.* 50, 2775–2782. doi: 10.1016/j.visres.2010.10.005

Bernstein, A., Bader, B., Bengler, K., and Künzner, H. (2008). "Visual-haptic interfaces in car design at BMW," in *Human Haptic Perception: Basics and Applications,* ed M. Grunwald (Basel: Birkhäuser), 445–451. doi: 10.1007/978-3-7643-7612-3_36

Beruscha, F., Krautter, W., Lahmer, A., and Pauly, M. (2017). "An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens," in *2017 IEEE World Haptics Conference (WHC)* (Munich: IEEE), 201–206. doi: 10.1109/WHC.2017.7989901

BMW Group. (2019). *THE 7 - BMW 7er Limousine*. Retrieved from: https://www.bmw.de/de/neufahrzeuge/7er/limousine/2019/bmw-7er-limousine-entdecken.html

Breitschaft, S. J., and Carbon, C. C. (2020a). *An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context*. Leiden: Poster presented at EuroHaptics 2020.

Breitschaft, S. J., and Carbon, C. C. (2020b). *Semantic Differentiation of Haptic Edges rendered on an Electrostatic Friction Modulation Display*. Leiden: Poster presented at EuroHaptics 2020.

Breitschaft, S. J., Clarke, S., and Carbon, C. C. (2019a). A theoretical framework of haptic processing in automotive user interfaces and its implications on design and engineering. *Front. Psychol.* 10:1470. doi: 10.3389/fpsyg.2019.01470

Breitschaft, S. J., Clarke, S., and Carbon, C. C. (2019b). "Using haptic shapes for orientation and identification in automotive user interfaces," in *IEEE World Haptics Conference 2019* (Tokyo: IEEE).

Breitschaft, S. J., Heijboer, S., Shor, D., Carbon, C. C., and Tempelman, E. (2020). *Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design*. Leiden: Poster presented at EuroHaptics 2020.

Brewster, S. A., and Brown, L. M. (2004). "Tactons: structured tactile messages for non-visual information display," in *Australian Computer Society (Chair), AUIC'04 Proceedings of the Fifth conference on Australasian User Interface* (Dunedin). doi: 10.1145/985921.985936

Burgess, R. (2020). *Honda Bucks Industry Trend by Removing Touchscreen Controls*. Retrieved from: https://www.autocar.co.uk/car-news/motor-shows-geneva-motor-show/honda-bucks-industry-trend-removing-touchscreen-controls

Carbon, C. C. (2019). Psychology of design. *Des. Sci.* 5:339. doi: 10.1017/dsj.2019.25

Carbon, C. C., and Jakesch, M. (2013). A model for haptic aesthetic processing and its implications for design. *Proc. IEEE*, 101, 2123–2133. doi: 10.1109/JPROC.2012.2219831

Cooke, T., Wallraven, C., and Bülthoff, H. H. (2010). Multidimensional scaling analysis of haptic exploratory procedures. *ACM Trans. Appl. Percept.* 7, 1–17. doi: 10.1145/1658349.1658356

Csardi, G. (2019). *Igraph - The Network Analysis Package*. Retrieved from: https://igraph.org/

Eren, A. L., Burnett, G., and Large, D. R. (2015). "Can in-vehicle touchscreens be operated with zero visual demand? An exploratory driving simulator study," in *The 4th International Conference on Driver Distraction and Inattention* (Sydney, NSW).

Federal Aviation Administration (2011). *Advisory Circular*. Washington, DC: Federal Aviation Administration.

Fjord. (2020). *Phyiscal Fights Back*. Retrieved from: https://trends18.fjordnet.com/physical-fights-back/

Friedemann, G., and Schellenberg, J. (2021). *Goeveg: Functions for Community Data and Ordinations*. Retrieved from: https://cran.r-project.org/web/packages/goeveg/index.html

Gattol, V., Sääksjärvi, M., and Carbon, C.-C. (2011). Extending the Implicit Association Test (IAT): assessing consumer attitudes based on Multi-Dimensional Implicit Associations. *PLoS ONE* 6:e15849. doi: 10.1371/journal.pone.0015849

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Boston, MA: Houghton Mifflin Harcourt.

Götz, M. (2007). *Die Gestaltung von Bedienelementen Unter Dem Aspekt Ihrer Kommunikativen Funktion* (Dissertation). Technische Universität, München, Germany.

Grane, C., and Bengtsson, P. (2013). Driving performance during visual and haptic menu selection with in-vehicle rotary device. *Trans. Res. F Traff. Psychol. Behav.* 18, 123–135. doi: 10.1016/j.trf.2012.12.011

Greenwald, A. G., McGhee, D. E., and Schwartz, J. L. K. (1998). Measuring individual differences in implicit cognition: the implicit association test. *J. Pers. Soc. Psychol.* 74, 1464–1480. doi: 10.1037/0022-3514.74.6.1464

Grunwald, M. (2017). *Homo Hapticus: Warum Wir Ohne Tastsinn Nicht Leben Können*. München: Droemer.

Gual, J., Puyuelo, M., and Lloveras, J. (2015). The effect of volumetric (3D) tactile symbols within inclusive tactile maps. *Appl. Ergonom.* 48, 1–10. doi: 10.1016/j.apergo.2014.10.018

Guest, S., Dessirier, J. M., Mehrabyan, A., McGlone, F., Essick, G., Gescheider, G., et al. (2011). The development and validation of sensory and emotional scales of touch perception. *Atten. Percept. Psychophys.* 73, 531–550. doi: 10.3758/s13414-010-0037-y

Harder, A., and Michel, R. (2002). The target-route map: evaluating its usability for visually impaired persons. *J. Vis. Impair. Blind.* 96, 711–723. doi: 10.1177/0145482X0209601003

Hasegawa, H., Itoh, K., Okamoto, S., Elfekey, H., and Yamada, Y. (2018). "Colorful tactile stimuli. association between colors and tactile-display stimuli on russell's psychological plane," in *Lecture Notes in Electrical Engineering. Haptic Interaction,* eds S. Hasegawa, M. Konyo, K. U. Kyung, T. Nojima, and H. Kajimoto (Singapore: Springer Singapore), 47–52. doi: 10.1007/978-981-10-4157-0_8

Heijboer, S., Breitschaft, S. J., and Carbon, C. C. (2019a). "Characterization of active haptic feedback for user interface design and development," in *IEEE World Haptics Conference 2019* (Tokyo: IEEE).

Heijboer, S., Schumann, J., Tempelman, E., and Groen, P. (2019b). "Physical fights back," in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct Proceedings - AutomotiveUI '19,* eds C. P. Janssen, S. F. Donker, L. L. Chuang, and W. Ju (New York, NY: ACM Press), 93–98. doi: 10.1145/3349263.3351510

Heimgärtner, R. (2017). "Usability-engineering," in *Interkulturelles User Interface Design,* ed R. Heimgärtner (Berlin; Heidelberg: Springer Berlin Heidelberg), 81–133. doi: 10.1007/978-3-662-48370-1_4

Iosifyan, M., Korolkova, O., and Vlasov, I. (2017). Emotional and semantic associations between cinematographic aesthetics and haptic perception. *Multisens. Res.* 30, 783–798. doi: 10.1163/22134808-00002597

Itti, L. (2007). Visual salience. *Scholarpedia* 2:3327. doi: 10.4249/scholarpedia.3327

Jakesch, M., Zachhuber, M., Leder, H., Spingler, M., and Carbon, C. C. (2011). Scenario-based touching: on the influence of top-down processes on tactile and visual appreciation. *Res. Eng. Des.* 22, 143–152. doi: 10.1007/s00163-010-0102-5

Jaworska, N., and Chupetlovska-Anastasova, A. (2009). A review of multidimensional scaling (MDS) and its utility in various psychological domains. *Tutor. Quant. Methods Psychol.* 5, 1–10. doi: 10.20982/tqmp.05.1.p001

Jraissati, Y., Slobodenyuk, N., Kanso, A., Ghanem, L., and Elhajj, I. (2016). Haptic and tactile adjectives are consistently mapped onto color space. *Multisens. Res.* 29, 253–278. doi: 10.1163/22134808-00002512

Karpinski, A., and Steinman, R. B. (2006). The single category implicit association test as a measure of implicit social cognition. *J. Pers. Soc. Psychol.* 91, 16–32. doi: 10.1037/0022-3514.91.1.16

Kerzel, D., and Schönhammer, J. (2013). Salient stimuli capture attention and action. *Attent. Percept. Psychophys.* 75, 1633–1643. doi: 10.3758/s13414-013-0512-3

Klatzky, R. L., and Lederman, S. J. (1995). Identifying objects from a haptic glance. *Percept. Psychophys.* 57, 1111–1123. doi: 10.3758/BF03208368

Klatzky, R. L., Pawluk, D., and Peer, A. (2013). Haptic perception of material properties and implications for applications. *Proc. IEEE* 101, 2081–2092. doi: 10.1109/JPROC.2013.2248691

Ludwig, V. U., and Simner, J. (2013). What colour does that feel? Tactile–visual mapping and the development of cross-modality. *Cortex* 49, 1089–1099. doi: 10.1016/j.cortex.2012.04.004

Lust, M., and Schaare, R. (2016). Bedienoberflächen mit aktivem haptischem Feedback. *ATZ* 118, 48–53. doi: 10.1007/s35148-016-0043-z

MacLean, K. E. (2008). Haptic interaction design for everyday interfaces. *Rev. Hum. Fact. Ergonom.* 4, 149–194. doi: 10.1518/155723408X342826

MacLean, K. E., and Hayward, V. (2008). Do it yourself haptics: part II [Tutorial]. *IEEE Robot. Autom. Mag.* 15, 104–119. doi: 10.1109/M-RA.2007.914919

Mlakar, S., and Haller, M. (2020). "Design investigation of embroidered interactive elements on non-wearable textile interfaces," in *Proceedings of CHI '20: CHI Conference on Human Factors in Computing Systems (CHI '20)* (New York, NY: ACM). doi: 10.1145/3313831.3376692

Mueller, S. (2016). *Das Optimale Bedienelement und der Optimale Bedienort für eine Nutzerfunktion* (Dissertation). Technische Universität, München, Germany.

Muth, C., Hesslinger, V. M., and Carbon, C. C. (2018). Variants of semantic instability (SeIns) in the arts: a classification study based on experiential reports. *Psychol. Aesthet. Creat. Arts* 12, 11–23. doi: 10.1037/aca0000113

Norman, D. A. (2008). Signifiers, not affordances. *Interactions* 15:18. doi: 10.1145/1409040.1409044

Norman, D. A. (2013). *The Design of Everyday Things: Revised and Expanded Edition*. New York, NY: Basic Books.

Nosek, B. A., and Banaji, M. R. (2001). The go/no-go association task. *Soc. Cogn.* 19, 625–666. doi: 10.1521/soco.19.6.625.20886

Okamoto, S., Nagano, H., and Yamada, Y. (2013). Psychophysical dimensions of tactile perception of textures. *IEEE Trans. Hapt.* 6, 81–93. doi: 10.1109/TOH.2012.32

Ortlieb, S. A., Kügel, W. A., and Carbon, C. C. (2020). Fechner (1866): the aesthetic association principle—A commented translation. *I-Perception* 11:204166952092030. doi: 10.1177/2041669520920309

Palmer, S. E., and Schloss, K. B. (2010). An ecological valence theory of human color preference. *Proc. Natl. Acad. Sci. U.S.A.* 107, 8877–8882. doi: 10.1073/pnas.0906172107

Palmer, S. E., Schloss, K. B., Xu, Z., and Prado-León, L. R. (2013). Music-color associations are mediated by emotion. *Proc. Natl. Acad. Sci. U.S.A.* 110, 8836–8841. doi: 10.1073/pnas.1212562110

Petermeijer, S. M., Abbink, D. A., Mulder, M., and Winter, J. C. F. de (2015). The effect of haptic support systems on driver performance: a Literature Survey. *IEEE Trans. Hapt.* 8, 467–479. doi: 10.1109/TOH.2015.2437871

Petersen, M. G., Rasmussen, M. K., and Trettvik, J. (2020). "Affordances of shape-changing interfaces," in *Proceedings of the 2020 ACM Designing Interactive Systems Conference,* eds R. Wakkary, K. Andersen, W. Odom, A. Desjardins, and M. G. Petersen (New York, NY: ACM), 1959–1971. doi: 10.1145/3357236.3395521

Pohlmeyer, A. E., Hecht, M., and Blessing, L. (2009). User experience lifecycle model ContinUE [continuous user experience]. *Der Mensch Im Mittepunkt Technischer Systeme. Fortschritt Berichte VDI Reihe* 22, 314–317.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing (Version 4.0.2) [Computer Software]*. Vienna: R Foundation for Statistical Computing. Retrieved from: https://www.R-project.org/

Regal, G., Busch, M., Hochleitner, C., Wokerstorfer, P., and Tscheligi, M. (2014). "TACTUX: a tactile user experience assessment board," in *The 8th Nordic Conference,* eds V. Roto, T. Olsson, K. Väänänen-Vainio-Mattila, J. Häkkilä, E. Hvannberg, and O. Juhlin (Helsinki: Chairs). doi: 10.1145/2639189.2670256

Rösler, F., Battenberg, G., and Schüttler, F. (2009). Subjektive Empfindungen und objektive Charakteristika von Bedienelementen. *ATZ* 111, 292–297. doi: 10.1007/BF03222068

Rümelin, S. (2014). *The Cockpit for the 21st Century (München, Ludwig-Maximilians-Universität, Diss., 2014)*. München: Universitätsbibliothek der Ludwig-Maximilians-Universität.

Saffer, D. (2009). *Designing Gestural Interfaces*. Sebastopol, CA: O'Reilly.

Simner, J., and Ludwig, V. U. (2012). The color of touch: a case of tactile-visual synaesthesia. *Neurocase* 18, 167–180. doi: 10.1080/13554794.2011.568503

Stockburger, C. (2013). *Touchscreens Sind Unmännlich*. Retrieved from: https://www.spiegel.de/auto/fahrkultur/interview-mit-martin-grunwald-ueber-haptik-design-im-auto-a-895416.html

Tiab, J., and Hornbæk, K. (2016). "Understanding affordance, system state, and feedback in shape-changing buttons," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, eds J. Kaye, A. Druin, C. Lampe, D. Morris, and J. P. Hourcade (New York, NY: ACM Press), 2752–2763. doi: 10.1145/2858036.2858350

Torchiano, M. (2020). *Package 'Effsize'*. Retrieved from: https://cran.r-project.org/web/packages/effsize/effsize.pdf

Ueda, A. U., Sawada, Y., Murakami, T., Saito, M., and Tsutsui, S. (2016). Preliminary investigation of the optimal size on tactile pictogram for visually impaired persons. *Bull. Jpn. Soc. Sci. Des.* 63, 29–36. doi: 10.11247/jssdj.63.3_29

Van den Bogaert, L., and Geerts, D. (2020). "User-defined mid-air haptic sensations for interacting with an AR menu environment," in *Haptics: Science, Technology, Applications*, eds I. Nisky, J. Hartcher-O'Brien, M. Wiertlewski, and J. Smeets (Cham: Springer International Publishing). doi: 10.1007/978-3-030-58147-3_3

Villarreal-Narvaez, S., Vanderdonckt, J., Vatavu, R. D., and Wobbrock, J. O. (2020). "A systematic review of gesture elicitation studies," in *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, eds R. Wakkary, K. Andersen, W. Odom, A. Desjardins, and M. G. Petersen (New York, NY: ACM), 855–872. doi: 10.1145/3357236.3395511

Volkswagen. (2020). *Der ID.3*. Retrieved from: https://www.volkswagen.de/de/modelle-und-konfigurator/id3.html

Whiteford, K. L., Schloss, K. B., Helwig, N. E., and Palmer, S. E. (2018). Color, music, and emotion: bach to the blues. *I-Perception* 9:2041669518808535. doi: 10.1177/2041669518808535

Wickham, H. (2016). *Ggplot2: Elegant Graphics for Data Analysis. Use R!*. Cham: Springer. doi: 10.1007/978-3-319-24277-4

Wobbrock, J. O., Morris, M. R., and Wilson, A. D. (2009). "User-defined gestures for surface computing," in *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09*, eds D. R. Olsen, R. B. Arthur, K. Hinckley, M. R. Morris, S. Hudson, and S. Greenberg (New York, NY: ACM Press), 1083. doi: 10.1145/1518701.1518866

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A.6 Characterization of Active Haptic Feedback for Design and Development

CHARACTERIZATION OF ACTIVE HAPTIC FEEDBACK FOR DESIGN AND DEVELOPMENT

INTRODUCTION.

As active haptic feedback technologies are increasingly embedded in user interaction (UI), next to its technological development, haptics also must form a coherent holistic UI for reasons of usability, safety and user experience [1]. Since haptics are very brand specific [2], their relation with the haptic experience are often unclear. Also, the variety of haptic technologies [3], novel components to UI language [4], and its repercussions on the design process complicate the UI development. Based on [6][7][8], piezo haptic impulses were described, categorized and analyzed in order to investigate if haptics can be described other than with (brand specific) parameters and code for aiding UI-designers and developers [5].

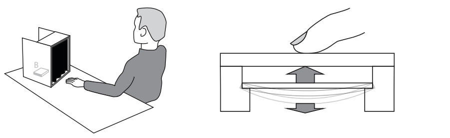

Fig. 1 . Participants were seated next to a touchbox (A) which comprise the feed - back system (B) which was actuated by pressing

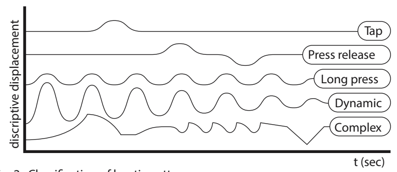

Fig. 2 . Classification of haptic patterns

	Category	Description	Examples
1		**Factual**	
1.1	Technical	use of jargon, or specific technical parameters	frequency, sinus, amplitude
1.2	Timing	descriptions involving temporal aspects	long, 2 seconds
1.3	Factual Adjective	adjective that seek to precisely describe the sensory experience in a factual way	subtle, too hard, deep, intensive, light, increasing
1.4	Rational	Rationnaly describing a haptic event without using any of the previous named categories	I feel many vibrations, it gives feedback
2		**Evocative**	
2.1	Action	percieved physical movement	It feels like knocking
2.2	Evocative Adjective	adjectives that seek to figuratively describe the sensory experience in an indirect way	preachy, funny, dangerous, exiting
2.3	Function	assumed or imagined function	it feels like a warning
2.4	Object	object or application related	like a printer, an electroshock
2.5	Sound	sound description or imitation	zooming, "bzzzz"

Table 1 . Categories of Haptic Description

METHOD

26 German-speaking participants (m_{age} = 30years, range: 21-58 years; 14 female) explored 30 different haptic patterns, triggered by pressing and/or releasing a smooth surface and actuated in the z-Axis by 4 piezo disks that simultaneously were driven by the ATH-700. Patterns were subsumed into five classes to cover various rhythm- and attack related values that the controller allows for. After a short training session, participants explored haptic impulses and described their experiences with no restriction in time and wording. The verbal descriptions were recorded.

RESULTS AND DISCUSSION

After transcribing the verbal descriptions, a workshop provided 16 initial categories on how participants described the haptic experiences. These categories were then assigned to all 780 descriptions by the authors independently and subsequently, rearranged into nine categories and two meta-categories. The refined categories were then assigned to the descriptions by three raters, and counted when all three had overlap to get an initial impression of the category distribution.

Factual description include rational and non-imaginary descriptions, with no associations to anything previously experienced. This study shows that factual descriptions acount for 15% and technical or timing terms are hardly used (e.g."approximately two seconds"). Evocative descriptions are linked to subjects' previous experiences and expressed poetically, symbolically or imaginatively. Within the evocative descriptions (85%), personalities are sometimes connected to functions ("Tapping your foot like waiting... this vibration is waiting"). Other findings show associations haptic pattern with objects (e.g. "machine gun").

CONCLUSION

This study aimed to explore how users describe haptics. Firstly, an initial categorization system shows that factual categories are either not used much, or not clearly detectable when rating. Future studies could elaborate on- and potentially confirm the category system. Also, descriptions could eventually be linked to technical haptic values (e.g. acceleration) and in this way potentially aid stakeholders in designing tools that ease prototyping.

REFERENCES

[1] E. Koskinen, T. Kaaresoja, and P. Laitinen, "Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button., " 2008, pp. 297–304.
[2] M. Sturdee and J. Alexander, "Analysis and Classification of Shape- Changing Interfaces for Design and Application-based Research," AC M Comput Surv, vol. 51, no. 1, pp. 2:1–2:32, Jan. 2018.
[3] X. Xie et al., "A Review of Smart Materials in Tactile Actuators for Information Delivery," C, vol. 3, p. 38, 2017.
[4] M. Hafez, "Tactile interfaces: technologies, applications and challenges," Vis. Comput., vol. 23, no. 4, pp. 267–272, Apr. 2007.
[5] Reisnick, "Rethinking learning in the digital age.," in The Global Information Technology Report 2001–2002, G. S. Kirkman, P. K. Corneli us, and J. D. Sachs, Eds. New York: Oxford University Press, 2002.
[6] M. Kwak, K. Hornbæk, P. Markopoulos, and M. Bruns Alonso, "The Design Space of Shape-changing Interfaces: A Repertory Grid Study, " in Proceedings of the 2014 Conference on Designing Interactive Systems, New York, NY, USA, 2014, pp. 181–190.
[7] M. K. Rasmussen, G. M. Troiano, M. G. Petersen, J. G. Simonsen, and K. Hornbæk, "Sketching Shape-changing Interfaces: Exploring Vo cabulary, Metaphors Use, and Affordances," in Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, New York, NY, USA, 2016, pp. 2740–2751.
[8] M. D. Augustin, J. Wagemans, and C.-C. Carbon, "All is beautiful? Generality vs. specificity of word usage in visual aesthetics," Acta Psyc hol. (Amst.), vol. 139, no. 1, pp. 187–201, Jan. 2012.
[9] "Aito reveals world's first HapticTouch controller for automotive applications | Aito." [Online]. Available: https://aito-touch.com/aito- rev eals-worlds-first-haptictouch-controller-automotive-applications. [Accessed: 18-Mar-2019].t

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A.7 Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Modulation Display

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EXAMINING DETECTABILITY OF VIRTUAL HAPTIC ITEMS RENDERED ON AN ELECTROSTATIC FRICTION DISPLAY

Fig. 1. Figure (A) shows the experimental screen during fixation. (B) shows the friction maps of the 12 different target textures that were used in the experiment. Grey values correspond to the available friction level with white being the maximum friction. (C) and (D) show mean values for the UX-Variables and Response Times. Error bars represent +/- 1 standard error of the mean.

SALIENCY OF VIRTUAL HAPTIC ITEMS.

Electrostatic friction modulation can be used to augment virtual user interface elements with haptic feedback, such as a home button. This might especially be useful for seamless user interfaces, such as displays or control panels, that require both high aesthetic quality and safe-to-use interactions. Haptic search paradigms have been exploited to reveal saliency of texture patches in passive haptics [1]. Zhang & Harrison [2] showed electrostatic textures can improve targeting performance in drag-and-drop tasks. UI-guidelines for creating easy-to-detect but also pleasing to touch elements are still scarse. We suspected high-frequent textures to be highly salient, but not very pleasing to touch. Goal of this study was to explore the impact of element size and texture on detectability and haptic experience (pleasantness, quality, precision, annoyance and fitting) of virtual elements that were haptically rendered via electrostatic friction modulation.

METHOD.

16 right-handed participants (M_{age}=25.3, SD_{age}=5.8, range 19 - 39 years, 12 female). Participants performed a "haptic search" task: After fixating the right index finger at the center of the screen, they searched for an electrostatically rendered (Tanvas MimoVue, SDK v2.0.1) but visually non-perceivable square-sized target that appeared at a randomized location on the screen. The screen-quadrant which entailed the target was primed during fixation. After every stimulus-block consisting of 12 trials participants were asked to rate pleasantness, quality, precision, annoyance and fitting of the target on a 7-point-scale. Stimuli included six different target textures in two different sizes: 10.2 and 15.3 mm. Figure 1 depicts the friction texture maps of each target. The high strength stimuli used the maximum friction level provided by the hardware unit (depicted by white areas in the friction maps in Fig. 1), whereas the low strength targets represented 20% of the maximum capable friction level.

RESULTS AND DISCUSSION.

In general, larger items were detected faster and yielded fewer errors than smaller items. Larger items also scored more positive on almost all UX variables. The "only contour" textures as well as a lower strength generally yielded more errors, produced longer response times and scored lower values on user experience variables as they were experienced as too soft and undefined by participants. Both high-strength as well as the high friction target (green) did not differ regarding error rate and response time. The high-strength textures scored higher than both low-strength and the only-contour texture regarding all UX-variables except for annoyance. Despite often being described as annoying in the post-experimental feedback session both high-frequency textures were not more annoying than all other textures. Based on our results, high-strength texture, independent from spatial frequency seem to be most suitable for "searching" virtual elements that are rendered via electrostatic friction modulation.

REFERENCES.

[1] Kappers, A., & Bergmann Tiest, W. M. (2015). Haptic saliency. *Scholarpedia*, 10(4), 32734. doi: 10.4249/scholarpedia.32734

[2] Zhang, Y., & Harrison, C. (2015). Quantifying the Targeting Performance Benefit of Electrostatic Haptic Feedback on Touchscreens. In N. Nunes, E. Costanza, P. Olivier, & J. Schöning (Eds.), *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces - ITS '15* (pp. 43–46). New York, New York, USA: ACM Press. doi: 10.1145/2817721.2817730

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SEMANTIC DIFFERENTIATION OF HAPTIC EDGES RENDERED ON AN ELECTROSTATIC FRICTION MODULATION DISPLAY

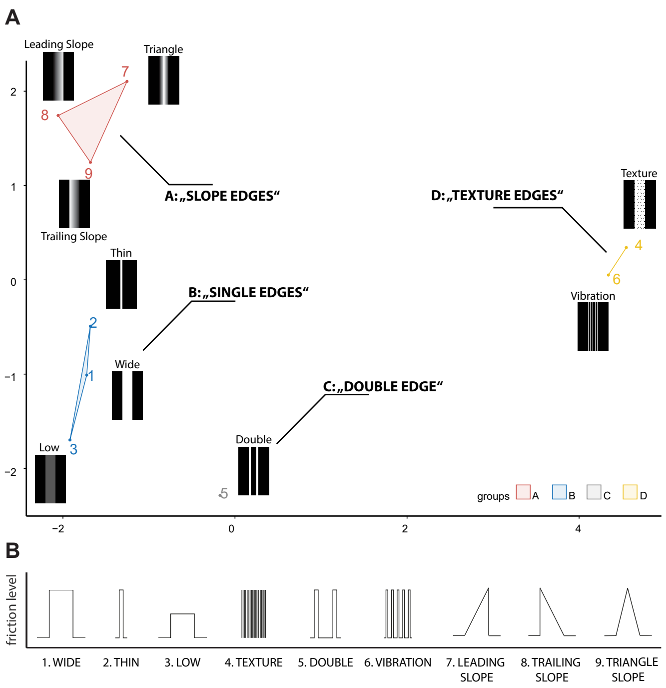

Fig. 1. (A) The MDS configuration shows four similarity clusters, each with their corresponding edges and accompanying friction maps. White bits in the friction map equal areas with maximum friction force provided by the unit. Figure (B) illustrates the friction levels of each transition.

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HAPTIC EDGES IN UI-DESIGN.

In recent years, there is a staggering demand for haptic devices embedded in seamless surfaces of high aesthetic quality. This is particularly the case for industries which ask for innovative yet safe-to-use and aesthetically pleasing interfaces, such as premium automotive brands. Variable friction displays enable haptic augmentation of virtual UI-elements, such as discontinuities between buttons as they play an important role for orientation, detection and discrimination of interactive elements in user interfaces [1]. There is research on psychophysical perception of friction modulation displays [2]. However there is only little research on guidelines and usability parameters [3] for the use of electrostatic friction modulation in haptic interface design. The present study was set out to examine which qualities of edges rendered on an electrostatic variable friction display are differentiated by participants.

METHOD.

21 participants (M_{age}=30.8, SD_{age}=7.8, range 22 - 52 years, 20 right-handed, 12 female) rated nine different types of haptic edges (see Figure 1) rendered on an electrostatic friction modulation display (Tanvas MimoVue, SDK v1.0.13) based on their perceptual similarity. The similarity of randomized stimuli pairs was evaluated one by one. The participants' task was to explore the adjacent edges and rate their perceptual similarity on a 7-point scale from 1 (*not similar at all*) to 7 (*very similar*). Physical width of all edges was 5mm (only thin edge 1mm) and covered a range of feasible edges to be used in a UI-context.

RESULTS AND DISCUSSION.

The nine different haptic edges can be separated into four distinct perceptual clusters, which was revealed by a multidimensional scaling procedure (MDS) following an a priori stress-test (stress-1<0.05). The results show four distinct clusters, that we refer to as (A) "Single Slope Edges" (leading/trailing slope, triangle), (B) "Single Sharp Edges" (wide, thin, low amplitude wide), (C) "Double Sharp Edges" and (D) "Texture Edges" (vibration, texture). We argue those transition qualities are highly suitable in haptic user interface design as they do not only rely on factors, such as different edge widths and strength levels and thus have a highly discriminative character.

FUTURE WORK.

We examined perceived similarity of haptic edges rendered on an electrostatic friction modulation display. These findings can be useful as best practices for haptic interface designers to create haptically augmented visual touch interfaces with comprehensible, yet easily differentiable haptic feedback elements. In future studies we aim to provide such best practices for other UI-elements, such as button textures as well.

REFERENCES.

[1] Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019). A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Impli cations on Design and Engineering. *Frontiers in Psychology*, 10(1470).
[2] Bau, O., Poupyrev, I., Israr, A., & Harrison, C. (2010). TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23nd Annual ACM Symposium on User interface Software and Technology* (pp. 283–292). New York: ACM. doi: 10.1145/1866029.1866074
[3] Palani, H. P., & Giudice, N. A. (2016). Usability parameters for touchscreen-based haptic perception. In *2016 IEEE Haptics Symposium*. Philadelphia, PA, USA: IEEE. Retrieved from https://umaine.edu/vemi/publication/usability-parameters-touchscreen-based-haptic-perception/

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AN EXPLORATORY EVALUATION OF PARTICIPANTS' REACTIONS TO ELECTROSTATIC FRICTION MODULATION IN A UI-RESEARCH CONTEXT

FRICTION HAPTICS IN UI-DESIGN.

Electrostatic friction modulation is a promising approach introducing a physical dimension to an array of digital applications, such as buttonless tangible user interfaces [1], tele-shopping and digital marketing. Psychophysical studies on electrostatic haptics deliver insights to possible use-cases, such as digitally recreating analog textures and improving target-selection performance (for a detailed review see [1]). Most studies in the field focus on functional and psychophysical aspects, resulting in a low ecological validity, which neglects the inherent user and more precisely haptic experience connected to electrostatic friction modulation. We seek to provide an initial set of user experience (UX) findings for electrostatics in interface design and derive a set of preliminary UX guidelines (Fig. 1) for the use of surface haptic technologies to enhance UX while reducing the chance of negative experiences with innovative haptic devices. This research sums up data from participants' post-experimental feedback that was given in two application-based studies incorporating friction haptics and delivers insights and recommendations based on them. The first study (n=16) entailed a single-task haptic search paradigm using a set of different low- and high-frequent textures. The second study (n=16) entailed a dual-task target-selection-paradigm with a primary lane-following task to emulate cognitive demands while driving a car. The TanvasTouch MimoVue (SDK v2.0.1) was used in the studies. All participants were first-time users.

INITIAL SET OF UX-RESULTS.

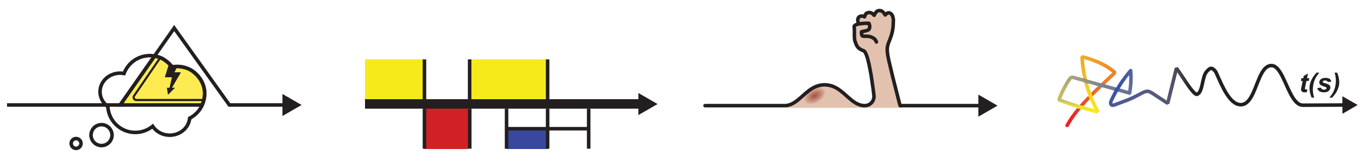
(1) In general, participants had **problems differentiating various haptic stimuli** and describing their actual feeling ("Something is different, but I cannot tell you exactly what it is").

(2) Using friction haptics was a **new and unexpected, yet innovative and fun experience** for most participants. In the beginning, participants felt unsure as to what exactly they were supposed to feel. A common problem was that participants attributed the "sticky feeling" to their finger involuntarily getting stuck to the screen instead of the feedback.

(3) Verbal reports indicate a **highly dynamic aesthetic experience**, as participants themselves reported a change in aesthetic and utilization evaluation of the haptic impression, for example perceived strength throughout the session.

(4) Some reports revealed **negative associations** ("feels like electroshocks") for "rougher" (high-frequent white noise textures) that could potentially lead to acceptance issues. Other often reported associations included "dry skin", "cotton cloth", "glue or adhesive", "sticky" and "sandpaper".

(5) **Soft feedback**, i.e. rendered textures and edges including a lower amplitude **caused insecurity** whether feedback was intentional.



1. Use Analogies
Analogies are based on user-associations. Understanding and deploying associations aids to create understandable and compelling feedback [3][4].

2. Keep it simple
Try to be straight-forward and restrict yourself to a very small set of very distinct haptic impulses.

3. Make it strong
Try to avoid soft feedback as it may cause confusion, try focus on strong impulses for relevant UI-content.

4. Consider Habituation
Make the user explore the interface and give them time to get used to the kind of feedback.

Fig. 1. Preliminary set of guidelines for the use of electrostatic friction modulation in haptic user interface design.

REFERENCES.

[1] Breitschaft, S. J., Clarke, S., & Carbon, C.-C. (2019). A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. *Frontiers in Psychology*, 10(1470).
[2] Basdogan, C., Giraud, F., Levesque, V., & Choi, S. (2020). A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces. *IEEE Transactions on Haptics*. Advance online publication. doi: 10.1109/TOH.2020.2990712
[3] Carbon, C.-C. (2019). Psychology of Design. *Design Science*, 5, 339. doi: 10.1017/dsj.2019.25
[4] Heijboer, S., Breitschaft, S. J., & Carbon, C.-C. (2019). Characterization of Active Haptic Feedback for User Interface Design and Development. In *IEEE World Haptics Conference 2019*. Tokyo: IEEE.

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A.10 Where's my Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces

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Where's My Button?

Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces.

Stefan Josef Breitschaft, Alexander Pastukhov & Claus-Christian Carbon

***Abstract*— Advancements in user interface technologies and demands of design engineering led to increasing implementation of large and mostly flat interactive surfaces in automotive. Recent discussions in the context of in-vehicle usage of touchscreens advocate for the use of haptic feedback to restore the explore- and feel-qualities typically experienced in traditional physical button interfaces that contribute to intuitive, eyes-free, and tactually rich interactions. Haptic technologies that include a friction modulation approach seem especially promising to convey a high-quality feeling. This research reports an experience-oriented evaluation of an electrostatic friction haptic display in an in-vehicle direct touch interaction context. The evaluation was based on an automotive multitask setting (primary driving-task and secondary target-selection-task) with a 2×2 feedback modality design (factors haptic/audio with levels absent/present). The objective variables (response time, errors, and performance on the primary task) did not differ between feedback modalities. Any additional feedback to a visual baseline enhanced the user experience, with the multimodal feedback being preferred by most participants. Surface haptics was perceived as a novel yet unexpected type of haptic feedback. We discuss the implications for the haptic design of programmable friction displays and provide an initial set of guidelines for this innovative technology.**

***Index Terms*— haptic design, haptic experience, user interface, haptic feedback, automotive, surface haptics, electrostatic friction modulation**

I. Introduction

Changing demands in future automotive mobility lead to disruptive transformation in automotive interior philosophy. In the age of autonomous driving, the influence of ubiquitous consumer electronic devices and advancements in user interface (UI) technologies ("smart surfaces") cars are expected to transform into rolling entertainment, communications, and recreation hubs with a lounge-like character. Traditional button interfaces cannot keep up with the needs expressed by consumers and stakeholders, such as programmability and compact package size. Nowadays, the design language is characterized by creating a monolithic and harmonic-looking interior using different materials (e.g., textile, wood, etc.), thus avoiding the rugged impression of traditional button interfaces. In short, automotive interiors already do and, in the future, will entail much more flat, seamless surfaces, hence reducing the physical impression from the traditionally rich experience of physical buttons to a mere contact between the finger and a flat display surface.

Automotive applications require interfaces not only with a high-quality impression, but also a safe, efficient, and potentially eyes-free operation. Paradoxically, the increasing functionality of dynamically changing visual interfaces coupled with the current focus on touch-only interactions requires even more visual attention, posing the risk of visual distraction [1], [2]. Its mere existence in the driver's parafoveal view might already be a source of distraction [3]. A recent German court decision, in which a Tesla driver was fined for an accident caused by adjusting the speed of the windscreen wipers on his Model 3's touchscreen during heavy rain, sparked a debate on the use of in-vehicle touchscreens among interface designers, usability experts, haptic advocates, and consumers [4], [5], [6]. Despite the growing sophistication of voice- and other input devices, the immediate feedback via direct haptic manipulation still seems to be an important feature of in-vehicle user experience (UX) [7].

The resurgence of tangibles amidst tactually poor interfaces is a recent trend in the consumer electronics (CE) market and is also considered as a way forward in automotive user interfaces [8], [9], [10]. This "tangible turn" [11] revolves around the question of how we can bridge the touch and feel of analogue button elements to the digital interface world. Haptic technologies that focus on friction modulation seem especially promising in restoring the tangibility and feel of analog buttons in tactually poor digital interfaces [9], [12], [13]. In contrast to current-state automotive haptic technologies that rely primarily on confirmation haptic feedback upon pressing, friction-based technologies are geared towards giving haptics to a dynamically moving finger, i.e., supporting "haptic search" and eyes-free operation [8]. Despite an automotive application of surface haptics, there are no user-oriented haptic studies that use variable friction displays based on electroadhesion in an automotive user context.

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TABLE I
OVERVIEW OF LITERATURE ON HAPTIC FEEDBACK IN AUTOMOTIVE USER INTERFACES

Author	Task	Conditions	Device	Main Outcome
Pitts, Williams, Wellings and Attridge (2009) [22]	1) LCT, 2) Touchscreen Use-cases	V, VH, VA, VHA	8.4-inch Haptic Touchscreen with TouchSense	No difference in driving and task performance; Acceptance higher for H than for V
Pitts, Skrypchuk, Weelings, Attridge and Williams (2012) [23]				No difference driving and task performance; preference for multimodal feedback
Pitts, Burnett, Williams and Wellings (2010) [24]	1) Vehicle Following in Driving Simulation, 2) 2D-Target-Selection (Feedback at push)	3 x 2 design, Visual: immediate, delayed, none; V only + VH		No difference in driving performance; Confidence and Hedonic Rating higher for H, perceived difficulty and driving interference lower for H; H reduced total glance time by 19% when V delayed or absent
Pitts, Skrypchuk, Attridge and Williams (2012) [25]				
Rydström, Grane and Bengtsson (2009) [26]	1) LCT, 2) Target-Selection	V, VH_{ridges}, $VH_{ridges+textures}$, $H_{ridges+textures}$	Rotary encoder	Driving performance and mental load did not differ across conditions
Grane and Bengtsson (2012) [27]	1) LCT, 2) Target-Selection	V only, partly corresponding VH, fully corresponding VH, H only	Rotary encoder	"some" haptics enhanced driving performance, H increased RT; No differences in mental workload
Grane and Bengtsson (2013) [28]	1) LCT, 2) Target-Selection		Rotary encoder	effectiveness depended on implementation of H; H reduces visual load
Tunca, Fleischer, Schmidt and Tille (2016) [29]	1) Driving Simulation, 2) Target-Selection (search)	Active + Passive Haptic, Blindfolded	Featureless Active + Passive Haptic control panel	No difference for RT, error, and lane deviation higher for active haptics, aesthetical appreciation higher for featureless panel
Tunca, Zoller and Lotz (2018) [30]	1) Driving Simulation 2) Target-Selection (search + push)	Haptic, Non-Haptic, Blindfolded	8-inch haptic touchscreen with four-button layout	lower error rates and response times and subjective operational stress for haptic vs non-haptic
Beruscha, Krautter, Lahmer and Pauly (2017) [3]	1) LCT, 2) Target-Selection (search + push)	V, VH, H	7-inch touchscreen with electrodynamic actuator	H reduced eye-off-road time and subjective mental workload
Mullenbach, Bloomer, Colgate and Peshkin (2013) [31]	1) Driving Simulation 2) 1D-Target-Acquisition	Visual, Haptic, Visual/Haptic	Ultrasonic Friction TPad	Negligible differences for task performance, H reduced eyes-off-road time by 19% and 39%, Participants preferred combined V and H
Weddle and Yu (2013) [32]	Use-cases in parked car	Cadillac Cue Haptic UI vs. non-haptic iPad UI		H perceived easier to use, more pleasant, more confident, more responsive, and more direct
Richter, Ecker, Deisler and Butz (2010) [33]	1) LCT, 2) Input phone number	V, H	8.4-inch screen with linear actuator	H reduced errors and response time; H was more preferred, but very small sample size (n=5)

Note: V = visual feedback, H = haptic feedback, A = visual-audio, M = Multimodal, LCT = Lane-Change-Task, RT = Response Time,

A. *Goal of the Study*

The main goal of this study was to provide an initial evaluation of a state-of-the-art electrostatic friction modulation (EFM) device in a dual-task setting with an automotive-related primary driving and a secondary in-vehicle 2D-target-selection task. We aimed to explore the effectiveness of EFM in an automotive setting and reveal strengths as well as weaknesses with respect to haptic feedback design. In contrast to previous studies, we focused on the evaluation of experience-based impressions. Due to the novel and unfamiliar character of EFM in an automotive setting, we were also interested in participants' first-hand responses.

II. A Tangible Turn in Automotive User Interfaces

There is an ample selection of industry-driven demonstrators geared towards a physically rich experience on flat surfaces – mainly in the context of so-called "smart surfaces" [14]. Most automotive OEMs, such as Audi, Mercedes, and Porsche, as well as automotive suppliers, have implemented haptic feedback using solenoid and voice-coil actuators into touchscreens and seamless control panels [15], [16], [17]. Haptic startups are increasingly trying to implement more innovative haptic approaches, such as friction modulation, that focus on a more feel-and-navigate approach in automotive applications [18], [19].

A. *Friction Haptic Feedback in Automotive User Interfaces*

In general, haptic feedback shows a positive effect on driving performance, visual load, drivers' awareness and thus driving safety across a multitude of guiding and warning use-cases and interior locations [20], [21]. Most haptic warning and assistance systems are embedded at locations that are in direct and continuous contact with the driver, such as a seat or a steering wheel, and thus need to be categorized as tactile interfaces. Haptic devices are located primarily in the dashboard or middle console. Table I[1] gives a comprehensive overview of the impact of haptic feedback on driving performance and UX in deliberate in-car interaction of direct and remote[2] touch interfaces based on the succinct review in our previous work [8].

To our knowledge, no experimental studies examining electrostatic friction modulation in an appropriate automotive-

[1]The overview is based on the following sources: [22], [23], [24], [25], [26], [27], [28], [29], [30], [3], [31], [32] and [33].

[2] In direct touch, the location of input (control) and output (representation) of Graphical User Interfaces (GUI) coincide [34]. In contrast, remote touch refers to the control of a GUI via an external interface, such as a touchpad.

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related context have been reported yet. Transferability of previous results can be boiled down to the following aspects: (1) technology, (2) scenario.

First, most previous automotive UI studies examined the impact of in-vehicle haptic feedback in the context of a multisensory dual-task setting but mainly employed vibration-based haptic screen devices that actuate the entire UI surface. Research literature cannot attest which feedback modality is the most adequate regarding driving and task performance [23], [29]. We suggest that the overall inconsistent pattern of results varies as a function of task difficulty and methodological aspects. It must be considered that task completion times are often higher in haptic-only conditions due to the nature of serial processing which haptic perception is based upon (e.g., tapping a screen based on visual input is inherently faster than using a rotary encoder). The effectiveness of haptic feedback seems to strongly depend on perceived haptic strength [23] and congruency with other modalities [28]. Additional haptic feedback seems to support drivers in keeping their eyes on the road and thus reduce visual distraction [3], [25], [31]. Differences between different modalities in automotive in-vehicle interaction seem to be mainly experience-based (see Table I). Haptic feedback seems to increase confidence in the current mode of interaction and is more accepted than a mere visual interaction. Yet, most participants tend to favor a fully multisensory (visual + haptic + audio) experience. Vibration-based technologies incorporate an often considerable and undesired actuation noise that might alter the overall haptic impression. Latency, which plays a major role in the effectiveness of haptic feedback in interfaces [35], [36] is much lower for EFM than for electro-mechanical actuators. Kim and Schneider [37] speak of *timbre*, i.e., experiential characteristics inherent to a specific technology, as an important design parameter. Hence, conclusions from previous studies using vibration impulses may be limited for novel surface haptic sensations. Friction haptics seems to underlie highly dynamic characteristics [38] and "breaks" common perceptual habits and expectations for haptic-enabled devices. It cannot be fully understood by simple single-shot measurement [39].

Second, most studies using variable friction displays focused on examining human haptic perception and user interaction settings, such as target acquisition, button replacement, or sliding controls (for an overview, see [13]). Initial design explorations for haptic augmentation of digital user interfaces, such as setting an alarm clock and selecting a text, using ultrasonic friction stimuli are reported in [40] and [41]. Zhang and Harrison [42] described performance enhancements for haptic search tasks incorporating electrostatic friction stimuli. However, most of the studies reported by Basdogan, Giraud, Levesque and Choi [13] have been conducted in a lab context using table-top haptic devices. Research has pinpointed to the importance of context and task requirements for haptic perception [8], so-called "scenario-based" testing [43], and the appropriate evaluation of design [44]. Hence, most previous studies lack context and task information for an ecologically valid evaluation in the automotive context. For example, tactile salience, which is important for identifiable objects in haptic design [45], might vary with different task environments. Pitts, Skrypchuk, Wellings, Attridge, and Williams have discussed the impact of workload on the perceived haptic strength of vibration impulses in a dual-task automotive setting [23]. While electrostatic friction devices may provide convincing haptic feedback in single task settings, it is yet unclear how friction stimuli are perceived when attention is divided. The use of a dual-task setting that sufficiently mimics real-world task demands is essential, which is why we included a primary driving and secondary target-selection task.

In this study, we wanted to examine the application of EFM for "search haptics". With the *Framework of Haptic Processing in Automotive User Interfaces* [8] we provide a four-stage model of in-vehicle haptic interaction. The subsequent stages *Exploration*, *Detection*, *Identification,* and *Usage* pose stage-specific requirements for a successful haptic design. Most of the reported studies (see Table I) have incorporated haptic feedback at the *Usage* level. Even though the secondary task entailed a target-selection task in many cases, haptic feedback has been limited to haptic clicks as confirmation, based mostly on a simple skeumorphic design approach [10]. This might be because vibration-based actuators and the way they are integrated into haptic systems are far more suitable to recreate a convincing button press sensation (user input in *z*-axis) than surface features, such as edges (user input in *x*/*y*-axis). Only a limited number of studies has so far explicitly focused on the *search haptics*-part of the framework, i.e., *Exploration*, *Detection*, *Identification*, for example, by haptically augmenting edges to enable eyes-free "searching" for interactive elements on touchscreens [3], [30]. Tunca, Fleischer, Schmidt, and Tille [29] used an exploration-focused selection task to compare a flat haptic-enabled and passive haptic control panel. EFM relies on active tangential user input. It is more suitable for augmenting interface elements during the *Detection* and *Identification*-level to help "finding" interactive elements. Hence, to measure the effectiveness of the haptic approach in an ecologically valid manner, the secondary task needs to be focused on a feel-and-navigate paradigm to leverage technological characteristics.

III. Method

The study was conducted according to the principles expressed in the Declaration of Helsinki and according to the ethical principles of the German Psychological Society (DGPs) and the Association of German Professional Psychologists (BDP). The general study design (psychophysical testing) was given ethical approval by the local ethics committee of the University of Bamberg.

A. *Participants*

Thirty-two participants took part in the study. They were between 20 and 60 years old (M_{age} =33.2 years, *SD*= 11.4); 12 were female and 20 were male; 28 were right-handed, two left-handed, and two ambidextrous (measured via self-assessment). All participants worked in the broader field of the automotive industries, but were naïve to the aims of the study and had not gone through special training in haptic perception. Ten participants had more extensive experience or previously worked with active haptic devices in various contexts. Thirty participants owned a device with active haptic feedback, mostly smartphones with a linear resonant actuator. Sixteen participants reported they do not drive a vehicle with a built-in

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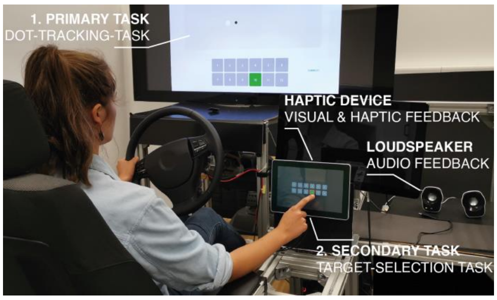

Fig. 1. The study included a dual task setting in a medium-fidelity interior mock-up. The primary screen in front of participants displayed the primary task and the target item. The selection task was performed on the haptic touchscreen device located in a center stack position. Additional speakers were used for audio feedback.

touchscreen. Seven participants stated to use the in-vehicle touchscreen daily, one multiple times a week, six once a week, and two of them only rarely.

B. *Apparatus*

1) *Interior Mockup*

We used a seating bucket consisting of an adjustable car seat, a steering wheel, a primary screen, and a secondary screen connected to a host computer. The apparatus did not include any environmental influences, such as sound or vibrations while driving. The experimental software and Haptic Engine ran on the host computer with a Windows 10 operating system (see Fig. 1). The seating bucket retained the approximate geometrical dimensions of a car interior with a steering wheel, a center console, and the haptic device that mimicked a center-position infotainment display. The primary screen in front of the participants displayed the driving task. The steering wheel was a Logitech Momo Racing Wheel refitted with a steering column to house a standard automotive steering wheel. The force feedback functionality was switched off at all time.

2) *Haptic Device*

The haptic device used in the study was a MimoVue TanvasTouch 10.1-inch Development Kit monitor. It is an off-the-shelf electrostatic friction display based on the principle of electroadhesion, which can be acquired via Tanvas [46]. Spatial resolution of the display is 1280x800 pixels. A single pixel equals 170µm. The haptic effects are created by modulating the friction coefficient of the user's moving finger due to electrostatic attraction by regulating the voltage applied to an additional electrode layer on the device's cover glass. Feedback upon static touch is not possible with this device and will not be discussed further in this study. A more detailed description of the technical stack can be found in [12]. For an extensive explanation and review of the employed actuation principle, we refer the reader to [13], [12] and [47].

3) *Feedback Modalities*

The study implemented a 2×2 design of feedback conditions (factors *haptic/audio* with levels *absent/present*) to assess the effectiveness of the haptic feedback. Haptic or audio feedback was either present or absent. Visual feedback was always

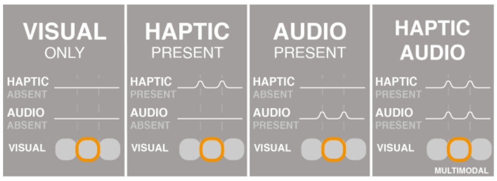

Fig. 2. The study entailed four different feedback conditions with haptic and audio feedback either present or not. Visual feedback in the form of an orange item contour was always present.

present. Feedback was given at transition events when selecting elements in a 2D button matrix (see Fig. 2 and Fig. 4). Element size was 15.3×15.3 mm (90×90 pixel) with an edge width 4.08 mm (24 pixel). The visual feedback consisted of an orange item contour that depicted the selected item in the matrix and was included in all feedback conditions (see Fig. 2 and Fig. 3B). The audio feedback consisted of a "poc"-sound (10ms, like a dull knocking sound) implemented in the touchscreen interaction in current BMW models. The haptic feedback included a two-step approach: (1) white-noise button texture in the search-stage and (2) a low-high-low friction change (1.87-0.34-1.87mm, 4,08mm total width) at transition events when selecting items in the matrix. The white-noise texture enabled participants to blindly "acquire" the start element in each trial. The matrix elements consisted of high-friction areas (see Fig. 3) with low-friction transitions.

The haptic feedback was based on a pre-study with 16 participants in which we compared the effectiveness of different haptic grid configurations. In this pre-study, we identified low friction transitions (width 5,1mm) with high-friction matrix items as optimal. The final iteration of the haptic feedback, which integrated insights from other internal lab-based studies, is shown at the bottom right side of Fig. 3C. We chose the item elements to have a high friction area. The rationale is that the higher friction parts during the exploration movement may already hint towards an interactive area versus the lower friction part on the rest of the screen. A report of the pre-study is included in the supplementary material.

C. *Dual-Task Setting*

This study included an automotive dual-task setting with a primary driving-related task that required constant attention and manual manipulation of the steering wheel as well as a simultaneous secondary target-selection task to mimic an appropriate driving context for haptic evaluation.

1) *Primary Driving Task*

The primary task was shown on a screen directly in front of the participants (see Fig. 3A). Participants were instructed to focus on the primary task and to restrict themselves from looking at the secondary touchscreen – like while driving a car. As an analogue to a typical lane-keeping task, we employed a dot-tracking-paradigm that requires continuous attention and steering, thus providing essential information about deviance from an ideal tracking trajectory. This deviance helps to operationalize error proneness due to a secondary task. We chose to implement this highly controlled paradigm as opposed to a more realistic driving task to reduce the complexity of experimental design and handling as well as to counteract

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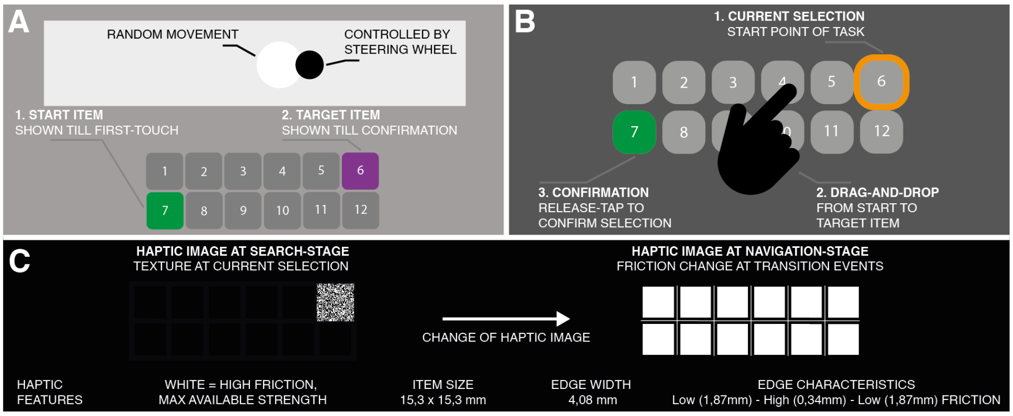

Fig. 3. Depiction of the A) primary screen with the primary driving task and a visual depiction of the 2x6 matric with start and target item to be selected during interaction and B) Secondary haptic screen with the secondary target-selection task. C) Depicts the haptic feedback during the search and navigation task.

vulnerability to systematic strategic and learning effects [48], [49], [23]. The employed paradigm included a white dot, which was moving randomly on a horizontal axis, and a smaller black dot, controlled by turning the steering wheel. The participants' task was to continuously align the black dot. The task's difficulty could be systematically varied by changing the range and speed of the white-dot-movement. We decided to set the task's difficulty to an intermediate level which was evaluated via pre-study expert evaluations. In the post-study questionnaire, participants stated that the task was challenging but still appropriate and immersive. One of the participants' descriptions seems very fitting: "as if you were driving on a curvy countryside road."

2) *Secondary Target-Selection Task*

The secondary task entailed a target-selection task. Participants performed the selection while simultaneously focusing on the primary task. We implemented a tripartite trial procedure of (1) finding the start button, (2) navigating to and (3) confirming the target item (see Fig. 3B) to reflect all the key challenges of operating a car's functions and still enabling participants to fulfill the task similarly to a "blind control" [8]. A 2×6 matrix of elements was presented on the secondary touchscreen device. The 2×6 matrix, with the respective start (green) and target (purple) items, was also displayed on the primary screen in front of the participants (see Fig. 3A).

At the beginning of each trial, only the start element was shown on the secondary screen and augmented by a haptic texture or an audio signal (see Fig. 3C). The start item was randomly located at one of the corners of the item matrix (i.e., item 1, 6, 7, or 12). Participants were able to explore and feel the start button. Upon activation of the start button, the touchscreen changed to a "normal" interaction stage which showed the 2×6 matrix as depicted in Fig. 3B. The target item was purple in the 2×6 matrix in the primary screen in front of the participants. (see Fig. 3A). We did not show the target item on the secondary screen to minimize visual attention and recreate an "intention to control" as natural as possible – in everyday interaction the desired function is not highlighted but defined by a user. Participants had to select the target by dragging the cursor to the target item. This drag-and-drop paradigm ensured that participants really engaged with the haptic and audio feedback and did not just press the target item – as they would potentially do with a regular touchscreen. It also equalized trials across all feedback modalities. The current selection was highlighted by an orange item contour (see Fig. 3B). Confirmation was done by releasing-and-tapping at the desired item. The trials only proceeded upon correct confirmation of the target item. Participants were able to interrupt the selection procedure. Once participants lifted their finger or left the item matrix, the interaction restarted at the search stage with the last-selected item augmented via a haptic texture or sound – similarly to the initial start item. There was no time restriction.

D. *Dependent Variables*

We followed a multimethodological approach for a holistic assessment of UX. Objective measures included response time for performing the primary task, performance on the primary task, and erroneous confirmations. To complement these

TABLE II
POST-BLOCK USER EXPERIENCE QUESTIONNAIRE

Variable	Question
Pleasantness	*How **pleasant** is the feedback?*
Perceived Quality	*How do you rate the **quality** of the feedback?*
Precision	*How **precise** is the feedback for navigation in a grid of elements?*
Annoyance	*How **annoying** is the feedback?*
Fitting	*How **fitting** is the feedback for navigation in a grid of elements?*
Difficulty	*How **difficult** was the selection task using the touchscreen?*
Interference	*How much did the secondary selection task including the feedback **interfere** with the main driving task?*
Visual Distraction	*How much did the secondary selection task **visually distract** from the driving task?*
User Experience	*Does the feedback enhance **user experience**?*

Note: Rating scale ranged from 1-7 with the anchors adjusted to the item, for example: 1 representing *not at all* and 7 *very pleasant*.

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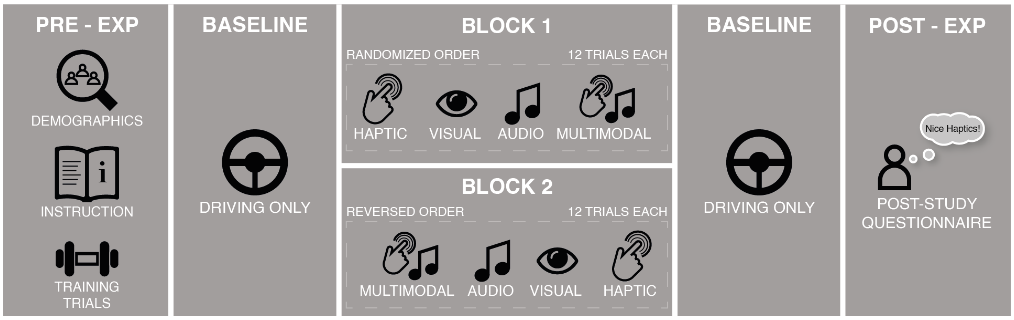

Fig. 4. Each study session consisted of a pre-experimental, two baseline (driving only), two experimental (each including four different feedback conditions with 12 trials each) and a post-experimental block.

objective measures, we included a post-block UX questionnaire and a post-study questionnaire. Table II describes the questionnaire items that were presented after the completion of every feedback block. In the post-study questionnaire, participants were asked (1) to rank the feedback modalities based on their preferred interaction, (2) to rate the perceived strength of the haptic feedback on a scale from 1 (*very weak*) to 7 (*very strong*), and (3) to provide general feedback on the study, the task and how they felt about the different feedback modalities in the form of open questions.

E. *Procedure*

The experiment was conducted in a quiet and specially prepared room. Upon arrival, participants were asked to wash and disinfect their hands. Participants were made aware of their right to withdraw themselves and their data from the study without consequences and without giving any reasons. Written informed consent was then given by each participant. The experimenter introduced participants to the procedure of the study and collected demographic data. Participants were instructed to find a comfortable seating position while the experimenter presented the experimental task, trial procedure, and the post-block experience questionnaire (see section Dependent Variables). Participants were told to imagine sitting in a car while driving and controlling a car's functions but prioritizing the primary dot-tracking task to perform as well as possible. In a pre-study training block, which included haptic feedback, participants familiarized themselves with the study setup and the haptic device. The experimenter did not explicitly introduce participants to the haptic feedback. The goal was to establish an ecologically valid test setting by not favoring a specific kind of feedback modality and preventing the influence of any potentially biasing *a priori* evaluations. The experimental session consisted of an initial "Driving only" block, followed by two experimental blocks and a concluding "Driving only" block. Each of the feedback blocks was presented twice in a randomized and reverse order for every participant. The experimental procedure is depicted in Fig. 4. Each block consisted of twelve trials. The driving-only trials were terminated after twelve seconds. The trials in the feedback blocks proceeded after confirmation of the correct target item. After the experimental session, participants were asked to complete the post-study questionnaire. The session was concluded by clarifying any open questions. The experimenter cleaned all areas of contact prior to the arrival of the next participant. A single session took about 60 minutes.

IV. Results

Error bars in the figures depict one standard error of the mean. Results were analyzed using the statistical software R 4.0.5 [50]. Feedback conditions were described by factors *Haptic* and *Audio* and factor levels *absent* and *present*. Participants performed every feedback condition twice, which is indicated by the *Block*-variables (see Fig. 4). All models included *Haptic:Audio* as an interaction-term. The participants-variable was defined as a random effect in all models. All significance tests were based on an alpha-level of 5%.

TABLE III
Linear Mixed Models for
Task Performance, Response time and Erroneous confirmations

Primary Task Performance					
Fixed.Effects	**Estimate**	***SE***	***df***	***t***	***p***
(Intercept)	0.002443	0.000425	55	5.75	**<0.001**
HapticPres	-0.000080	0.000180	3036	-0.44	0.66
AudioPres	-0.000091	0.000180	3036	-0.50	0.62
Block	0.000020	0.000028	3036	0.71	0.48
HapticPres: AudioPres	-0.000157	0.000255	3036	-0.62	0.54
Response Times					
(Intercept)	5784.79	451.84	39	12.80	**<0.001**
HapticPres	212.65	126.08	3036	1.69	0.09
AudioPres	281.49	126.08	3036	2.23	**0.03**
Block	-261.75	19.45	3036	-13.45	**<0.001**
HapticPres: AudioPres	-393.97	178.30	3036	-2.21	**0.03**
Erroneous Confirmations					
Fixed.Effects	**Estimate**	**SE**		***z***	***p***
(Intercept)	0.888287	0.30909		2.87	**<0.001**
HapticPres	-0.050087	0.07636		-0.66	0.51
AudioPres	-0.074568	0.07685		-0.97	0.33
Block	-0.006513	0.01190		-0.55	0.58
HapticPres: AudioPres	0.074561	0.10901		0.68	0.49

Note: *SE* = Standard Error, bold number indicates $p < 0.05$, Erroneous Confirmations were analyzed using a generalized linear mixed model

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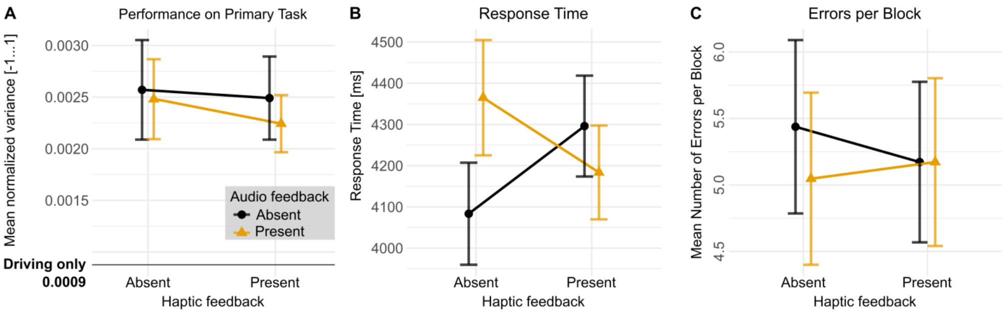

Fig. 5. Line plots for (A) performance primary task, (B) Response Times and (c) erroneous confirmations. Error bars present ± 1 standard error of the mean (SEM).

A. *Objective Variables*

1) *Performance Primary Task*

Performance in the driving task was assessed using the dot-tracking-task. The relative position of both dots was defined by values between -1 and 1. The performance measure was based on the aggregated deviation of both dots. The mean squared deviation for every feedback block was used for the statistical analysis. A linear mixed model with feedback factors *Haptic* and *Audio* and *Block* as predictors were fitted using the *lmer*-function [51]. Table III describes the results from the model. None of the factors yielded a significant result. All feedback blocks differed from the driving-only blocks (Fig. 5).

2) *Response Times*

Response times were measured from the first finger-down event until the correct activation of the indicated target item. Mean response time ranged from 4083ms (*HapticAbsent & AudioAbsent*) to 4365ms (*HapticAbsent & AudioPresent*). A linear mixed model based on response time was fitted using the *lmer*-function. Table III describes the results from the linear-mixed model based on the response times. The block predictor showed a significant result ($\beta = -261.7$, $t\,(3036) = -13.45$, $p < .001$). The negative slope indicates that participants were faster in the second iteration of the feedback blocks (Fig. 4). *AudioPresent* ($\beta = 281.49$, $t\,(3036) = 2.23$, $p = .03$) as well as the interaction term ($\beta = -393.97$, $t\,(3036) = -2.21$, $p = .03$) yielded significant results, meaning *AudioPresent* yielded higher RTs when *Haptic* is *absent*.

3) *Erroneous Confirmations*

Erroneous confirmations represent activations of non-target items in the matrix until confirmation of the correct target. For statistical analysis, we used the aggregated number of erroneous confirmations per block. A generalized linear regression model using *glmer*-function (family parameter set to poisson) with the factors *Haptic*, *Audio* and *Block* as well as an interaction term as predictors was fitted (see Table III). No factor yielded a significant result.

B. *UX-Variables*

Fig. 6 shows mean ratings for all items with relation to experience-based questionnaire that participants filled in after each feedback block. To compare the feedback condition, we fitted a cumulative link mixed model using the *clmm()*-function from the *ordinal* package [52] with factor *Haptic* and *Audio* as well as the interaction *Haptic:Audio* as predictor with each of the UX-variables as a criterium. The results are shown in Table IV. All scales showed two significant main effects (*Haptic* and *Audio* is significant, but not the interaction term) except for *Annoyance* (only *Audio* significant) and *Enhancement,* which showed a significant result for the interaction term. In this case, interpretation of the *Audio* main effect depended on the factor level of the *Haptic* factor ($\beta = -1.45$, $z = -3.11$. $p < 0.01$). The

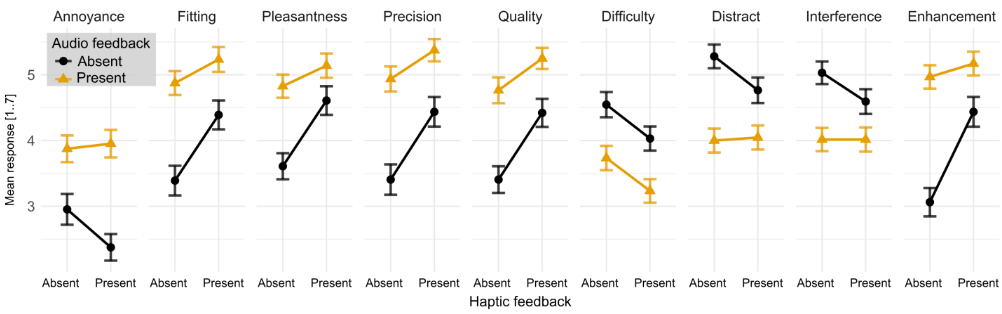

Fig. 6. Mean response values of User Experience variables based on feedback modalities. Error bars represent +-1 standard error of the mean (SEM).

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TABLE IV
CUMULATIVE LINK MIXED MODEL WITH UX-VARIABLES AS CRITERIA

Modality	Estimate	*SE*	*z*	*p-value*
Annoyance				
HapticPresent	-0.65	0.34	-1.92	0.055
AudioPresent	1.36	0.34	4.05	**<0.001**
HapticPresent: AudioPresent	0.73	0.46	1.59	0.111
Fitting				
HapticPresent	1.31	0.35	3.78	**<0.001**
AudioPresent	1.93	0.34	5.59	**<0.001**
HapticPresent: AudioPresent	-0.67	0.46	-1.45	0.148
Pleasantness				
HapticPresent	1.43	0.34	4.17	**<0.001**
AudioPresent	1.61	0.33	4.83	**<0.001**
HapticPresent: AudioPresent	-0.85	0.46	-1.83	0.067
Precision				
HapticPresent	1.40	0.34	4.08	**<0.001**
AudioPresent	2.15	0.35	6.07	**<0.001**
HapticPresent: AudioPresent	-0.83	0.47	-1.77	0.076
Quality				
HapticPresent	1.37	0.34	4.09	**<0.001**
AudioPresent	1.81	0.34	5.37	**<0.001**
HapticPresent: AudioPresent	-0.77	0.46	-1.68	0.094
Difficulty				
HapticPresent	-0.73	0.33	-2.20	**0.028**
AudioPresent	-1.32	0.34	-3.88	**<0.001**
HapticPresent: AudioPresent	-0.04	0.46	-0.09	0.931
Distract				
HapticPresent	-0.79	0.34	-2.30	**0.021**
AudioPresent	-2.10	0.35	-5.98	**<0.001**
HapticPresent: AudioPresent	0.87	0.47	1.87	0.062
Interference				
HapticPresent	-0.70	0.34	-2.06	**0.039**
AudioPresent	-1.81	0.35	-5.18	**<0.001**
HapticPresent: AudioPresent	0.70	0.47	1.50	0.135
Enhancement				
HapticPresent	1.79	0.35	5.13	**<0.001**
AudioPresent	2.40	0.36	6.75	**<0.001**
HapticPresent: AudioPresent	-1.45	0.47	-3.11	**0.002**

Note: SE = Standard Error, bold numbers indicate $p < 0.05$

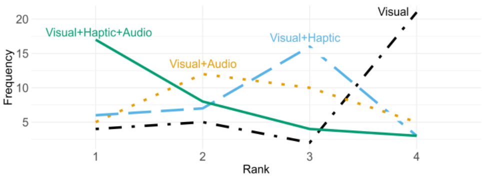

Fig. 7. Frequency data for the modality preference ranking.

Audio-factor only yielded a difference in case haptic was not present.

C. *Post-experimental data*

The post-experimental data included (1) preference ranking of feedback modalities, (2) perceived haptic strength, and (3) qualitative data from the open post-experimental questions. Fig. 7 depicts the frequency of rank assignments for the different feedback modalities. Based on a Kruskal Wallis test, the modalities differed regarding their ranking ($X^2 = 27.43$, $df = 3$, $p < 0.01$). The visual-only condition was least preferred. More than half of the participants preferred the multisensory modality (*Haptic* and *Audio present*). The mean perceived haptic strength was $M_{haptic} = 4.14$ ($SD = 1.57$). Three participants reported they did not consciously feel haptic feedback during the tasks. The verbal responses were categorized using categories that were established in our previous work [38].

V. DISCUSSION

The present research reports an initial evaluation of an electrostatic friction display in an automotive-related context. Results indicate that there were no consistent differences between feedback modalities regarding primary and secondary task performance. Feedback modalities mainly differed on the experience level. In general, any additional feedback was perceived as superior to mere visual feedback. Overall, participants preferred multisensory feedback. The audio feedback seemed to be more beneficial for UX than the electrostatic friction feedback. However, the audio feedback was perceived to be more annoying than haptic feedback. In general, participants perceived the haptic feedback as too weak, which might have influenced the experience evaluations. The following section will discuss these results in greater detail.

A. *Performance and Experience*

The results indicate that feedback modality had no consistent influence on driving and task performance (see Fig. 5).

This finding seems to be counterintuitive at first sight. One explanation could be that the dot-tracking paradigm was not fully suitable to yield significant differences. Despite a highly controlled environment to counteract methodological issues from commonly used approaches, the dot-tracking might have been too abstract. It does lack some characteristics that constitute a typical driving situation, such as anticipatory driving or environmental noise and vibration. Also, the difficulty level of the primary task might have been inappropriate. On the other hand, feedback modalities might not have had an influence on performance as participants may have been too experienced in an automotive multitask setting. In general, this pattern of results fits very well with previously described literature (see Table I). Despite using higher fidelity driving simulations and confirmation-focused tasks, previous studies also did not report a consistent impact of feedback modality on objective measures. The impact of haptic feedback on performance measures may be based on different aspects, such as visual distraction. Gaze behavior operationalized via eyes-off-road time or number and length of fixations and saccades may provide valuable insights on distraction [3], [31], [25].

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A mere performance-based evaluation neglects the holistic nature of user interaction and its implications on UX as differences between feedback modalities seem to be mainly experience-based. Any additional feedback to a visual-only baseline enhanced UX. It made the interaction feel more pleasing, precise, higher quality, less difficult, less distracting, and less interfering. Haptic and audio feedback felt more fitting than mere visual feedback. Table I reports similar findings: haptic interfaces are more accepted, reduce subjective workload and increase user's confidence.

Another intriguing finding was the positive impression of audio feedback compared to the haptic impression. Audio seemed to have a bigger impact on UX than the haptic feedback. The visual-audio condition was ranked higher than the visual-haptic condition. Previous studies describe similar findings [22], [23]. We propose two explanations: Firstly, users may be more accustomed to audio feedback as it is – in contrast to haptic feedback – already widely implemented in consumer devices and in-vehicle touchscreens. Secondly, the haptic feedback seemed to be perceived as too weak to have a similar impact on UX as audio feedback. Three participants reported they did not feel the haptics. A repeated analysis dropping those three participants showed slighty, but not substantially different results. Interestingly, all participants felt the haptics when they were shown a single-task demo application after the study. Averaged perceived haptic strength was 3.8 on a scale from 1 (weak) to 7 (strong). In the post-study questionnaire, about half of the participants wished for stronger haptics. Pitts, Skrypchuk, Wellings, Attridge and Williams [23] also concluded that despite prior validation, the vibration feedback they used was not strong enough to convey stronger feedback than the audio impression. Haptic feedback in this study was based on results from a pre-study (see supplementary material) as well as insight from lab-internal observations. As perceived haptic strength seems to be a crucial aspect for its effectiveness in UX [38], we would like to discuss potential reasons for an overall low perceived strength of the electrostatic impulses.

The implemented haptic device is still in development and may thus be restricted in terms of maximum available haptic strength. While it delivers convincing high-fidelity haptics in single-task table-top settings, perceived intensity deteriorates once a cognitively demanding primary task is introduced. This observation highlights the importance of context information and task demand for design and haptic evaluations [8], [53], [43]. Carbon already stated that *"Design without context liquidates meaning"* [44]. MacLean and Hayward [45], [54] highlight the importance of context on *tactile signal salience*. In single-task settings, participants allocate their attention to haptic impulses felt on display, while in the automotive-relevant setting attention is divided between primary and secondary tasks. As haptic stimuli were involved in a secondary task, they may potentially require a higher tactile salience. The haptic impression might have also been "overshadowed" by the clear and prominent audio signal. Following the notions on multisensory integration the comparatively weak haptic impression might have been hampering its "trustworthiness" and "appropriateness" for the selection task [45], [55], [56]. Overall, development of more capable devices is required to overcome the hurdle of divided attention. Even though haptic saliency was limited in our haptic device it sheds light on some relevant haptic design considerations in the automotive context.

Additionally, EFM is a novel kind of haptic feedback that may have mismatched participant's perceptual habits [44]. They were unfamiliar with the friction sensation, which was often confounded with grease from fingerprints. Also, friction stimuli contradicted some of the participants' expectations towards haptic-enabled touchscreen feedback. Some of the participants expected vibration impulses. All these factors might contribute to a generally weak haptic impression for some participants. In an earlier study [38] we proposed friction stimuli might require familiarization and habituation which goes beyond pure mere-exposure to be fully accepted in UI contexts. Our results indicate that participants required less time for the selections after more training, but the number of erroneous confirmations and performance in the driving task remained on a similar level (indicated by the Block-variable Table III). It seems that with more training participants became faster, but didn't do "better" selections or were less distracted. The drop in response times does not necessarily depend on feedback modality. Designers and practitioners need to be aware that electrostatic friction modulation, as well as haptic feedback via sliding, might be a novel and unfamiliar experience for most users in the upcoming years. Future studies might use familiarization paradigms, such as the *Repeated Evaluation Technique* (RET) [39] that involve a deeper evaluation phase to capture the long-term effects of innovative interfaces.

Association-based insights are hardly considered in perception and interaction-based studies, even though it is essential for product experience as it might affect a product's long-term appreciation [57]. A few participants explicitly reported negatively connoted descriptions including (mild) "electroshock", "sizzle on the finger," or „like a dirty surface" that have already previously been described [38].

Multisensory feedback has been the most preferred type of feedback (see Fig. 7). In demanding contexts, complementary and redundant haptic and audio cues are crucial to support user interaction and reinforce task demands [45] but also to involve the user holistically. This is substantiated by one participant's response ("I like the multisensory feedback. It creates engagement") and has been well documented in previous literature [22], [23] as well as general design guidelines [58], [59], [60]. EFM lacks the by-product actuation noise of vibration-based technologies, which gives designers additional degrees of freedom in sound design. Yet designing a convincing haptic impression becomes more challenging as designers cannot rely on sound to alter the haptic impression. Though the audio feedback was valuable for selecting the correct item, it was perceived as more annoying than haptic and visual feedback, which might negatively impact product experience in the long term. It must be noted that the experimental setting did not include any environmental noises (e.g., engine, traffic, etc.) usually prevalent while driving that might modulate salience and annoyance of the audio feedback.

B. *Limitations*

There are some limitations to the study setup we would like to address. An obvious limitation is linked to perceived haptic strength. The study was performed with a first-generation EFM

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development kit, whose technology is under constant development [46]. Some participants reported difficulties regarding position sensing and haptic strength, which might follow the dependence of surface haptics on the moisture content of the skin [13], [61]. This might have been influenced by participants' dry skin due to frequent hand cleaning and disinfecting during data collection (June 2020). Precision in terms of finger sensing as well as perceived haptic strength might have also been limited by the current hardware and firmware version. Yet, most participants did not have any problems at all. Albeit using a prototype-level device, this initial evaluation poses the opportunity to identify risks and potentials for further technological developments.

Other limitations refer to the studies' methodology. The study setup did not include any measures of visual distraction to control for gaze behavior. The "Visual Distraction"-variable was introduced to capture participants' perceived visual distraction. Previous studies have shown a positive influence on gaze behavior in driving tasks [3], [25], [31].

This study only assessed friction stimuli in a 2D-target-selection task. Studies have shown that friction haptics may also be useful in simpler 1D-target-acquisition tasks, but also more complex interaction use-cases [31], [40], [41].

Some participants pointed to the limited realism of the primary and secondary task as well as hardware setup. The primary goal of this study was to provide an initial evaluation of an up-to-date EFM device using an appropriate driving task with a highly systematic and standardized methodology. The "drag-and-drop"-paradigm used in the selection-task differs from a tap-and-touch-centric approach but ensured that participants felt the transition feedback and could not "skip" the navigation-part of the interaction. Also, additional noise or vibrations while driving might increase realism and should be considered to be included in future studies.

The study included a limited set of UX-variables, that are crucial for an initial UX evaluation. The variables were based on previous studies [22], [24], [23]. We did not include existing UX-questionnaires as this study focused on exploring the impact of the feedback modality rather than the interaction use-case itself. Nevertheless, variables such as pleasantness, annoyance, etc., allow for an initial user-centric evaluation of the friction stimuli. We encourage other researchers to validate our findings using higher-fidelity interface prototypes and testing environments.

C. *Outlook*

Designing enjoyable and efficient interfaces that require little visual attention remains a challenge for automotive UI designers. This study indicates that audio and friction haptics may be an essential piece to the puzzle, yet haptic feedback is no omnipotent remedy to reduce visual distraction and enhance UX. What it means is that simply adding haptic feedback does not make it a good interface. What is still missing is a proper psychologically-driven framework of translating the tangibility of high-quality analog haptic impressions to a digital interaction space. Understanding haptics from a user-centric perspective is crucial as user associations, experiences, expectations, and context underlie the functional assessment of haptic stimuli [53], [62], [44]. For example, while high-frequency textures might be salient, negatively connoted associations potentially deteriorate long-term appreciation. In addition, friction stimuli are still a novel haptic quality that the majority of users has no experience with to fully appreciate its effectiveness.

UI-elements, such as the use of dedicated physical buttons, information hierarchy, element size on screens, and prioritization of voice interfaces potentially have a bigger contribution to eyes-free operation than mere haptic feedback on visual interfaces. While automotive voice interfaces become increasingly versatile from a technological perspective and thus alleviate mental and visual demand, a large German customer survey [7] indicates that users still might have preconceptions towards speech interaction and prefer other - mostly haptic - ways of interaction. We hope that future interaction research and engineering will incorporate a deeper psychological and user-centric approach to accommodate psychological aspects, such as habituation, haptic experience, user associations, expectations, and context instead of following a techno-centric approach. Future research needs a clear focus on actual user needs instead of a techno-centric approach during interior development.

This study showed the overall positive influence of surface haptics for use in an automotive 2-D-target-selection use-case. However, fully software-defined haptics, such as EFM, allows for a much broader application of haptic use cases, such as the haptic augmentation of virtual items via different surface features [63], fully augmented sliders, turn dials and toggles [19], [64].

VI. Conclusion

This study provides an initial evaluation of electrostatic friction modulation in an applied automotive multitask setting and preliminary guidelines based on these findings. Focusing on objective measures neglects a holistic assessment of haptic feedback in user experience contexts. Participants preferred multisensory feedback. Despite using a prototype-level device, we argue that surface haptic feedback benefits user experience design in seamless tangible user interfaces as it allows to restore the tangibility otherwise only known from physical buttons. We encourage future research to further explore the design space of surface haptics applications in automotive.

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References

[1] B. I. Ahmad, P. M. Langdon, S. J. Godsill, R. Hardy, L. Skrypchuk, and R. Donkor, "Touchscreen usability and input performance in vehicles under different road conditions," in *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Nottingham, United Kingdom, 2015, pp. 47–54.

[2] A. L. Eren, G. Burnett, and D. R. Large, "Can in-vehicle touchscreens be operated with zero visual demand? An exploratory driving simulator study.," in *The 4th International Conference on Driver Distraction and Inattention*, Sydney, Australia, 2015.

[3] F. Beruscha, W. Krautter, A. Lahmer, and M. Pauly, "An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens," in *2017 IEEE World Haptics Conference (WHC)*, Munich, Germany, 2017, pp. 201–206.

[4] A. Case, *The Hidden Cost of Touchscreens.* [Online]. Available: https:// medium.com/@caseorganic/why-do-we-keep-building-cars-with-

touchscreens-alt-the-hidden-lives-of-touchscreens-55faf92799bf (accessed: Oct. 23 2020).

[5] R. Ramnath, Kinnear N., Chowdhury, S., and Hyatt T, *Interacting with Android Auto and Apple Interacting with Android Auto and Apple CarPlay when driving: The effect on driver performance*. Crowthorne, 2020. Accessed: Feb. 19 2021. [Online]. Available: https://trl.co.uk/uploads/trl/documents/PPR948-_IAM-RoadSmart---infotainment-sim-study.pdf

[6] J. Li, *Why touchscreens in cars don't work.* [Online]. Available: https://uxdesign.cc/why-touchscreens-dont-work-in-cars-69b6ff3d4355 (accessed: Oct. 22 2020).

[7] mobile.de, *Bedienkonzepte im Auto: Mehr als die Hälfte möchte weiterhin Knöpfe und Regler*, 2020. Accessed: Nov. 24 2020. [Online]. Available: https://newsroom.mobile.de/bedienkonzepte-im-auto-mehr-als-die-haelfte-moechte-weiterhin-knoepfe-und-regler/

[8] S. J. Breitschaft, S. Clarke, and C.-C. Carbon, "A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering," *Frontiers in psychology*, vol. 10, no. 1470, 2019, doi: 10.3389/fpsyg.2019.01470.

[9] P. LoPresti, *Surface Haptics: A Safer Way for Drivers to Operate Smooth-Surface Controls.* [Online]. Available: https://www.electronicdesign.com/markets/automotive/article/21145025/surface-haptics-a-safer-way-for-drivers-to-operate-smoothsurface-controls (accessed: Jan. 27 2021).

[10] F. Aleksandrow, *The Move from Mobile to Your Car – Touch in Today's Automotive Infotainment Systems.* [Online]. Available: https://www.immersion.com/the-move-from-mobile-to-your-car-touch-in-todays-automotive-infotainment-systems/ (accessed: Jul. 20 2020).

[11] C. Moussette, *Simple haptics: Sketching perspectives for the design of haptic interactions*. Umeå: Umeå Institute of Design, Umeå University, 2012.

[12] C. Shultz, *Surface haptics technology enriches touchscreen interactions.* [Online]. Available: https://www.edn.com/surface-haptics-technology-enriches-touchscreen-interactions/

[13] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces," *IEEE Transactions on Haptics*, 2020, doi: 10.1109/TOH.2020.2990712.

[14] M. Lust and R. Schaare, "Bedienoberflächen mit aktivem haptischem Feedback," *ATZ Automobiltech Z*, vol. 118, no. 6, pp. 48–53, 2016, doi: 10.1007/s35148-016-0043-z.

[15] Audi AG, *Die neue Form der Haptik.* [Online]. Available: https://www.audi.com/de/experience-audi/models-and-technology/design/modern-touch.html

[16] C. Kessels, *An in-depth look at the UX of the Porsche Taycan.* [Online]. Available: https://uxdesign.cc/an-in-depth-look-at-the-ux-design-of-the-porsche-taycan-540254d6d996

[17] P. Schäfer, *Neue Mercedes-Benz S-Klasse nutzt zweite Generation des MBUX.* [Online]. Available: https://www.springerprofessional.de/infotainment/ergonomie---hmi/neue-mercedes-benz-s-klasse-nutzt-zweite-generation-des-mbux/18161298

[18] Hap2U, *Haptic Technology.* [Online]. Available: https://www.hap2u.net/haptic-technology/ (accessed: Feb. 14 2021).

[19] Tanvas, *TanvasTouch for Automotive: Feel More than the Road.* [Online]. Available: https://tanvas.co/sample-applications/automotive/ (accessed: Feb. 14 2021).

[20] S. M. Petermeijer, D. A. Abbink, M. Mulder, and J. C. F. de Winter, "The effect of haptic support systems on driver performance: A Literature Survey," *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 467–479, 2015, doi: 10.1109/TOH.2015.2437871.

[21] Y. Gaffary and A. Lécuyer, "The use of haptic and tactile information in the car to improve driving safety: A Review of Current Technologies," *Front. ICT*, vol. 5, p. 445, 2018, doi: 10.3389/fict.2018.00005.

[22] M. J. Pitts, M. A. Williams, T. Wellings, and A. Attridge, "Assessing subjective response to haptic feedback in automotive touchscreens," in *Proceedings of the 1st international Conference on Automotive User interfaces and interactive Vehicular Applications*, 2009, pp. 11–18. Accessed: 2009.

[23] M. J. Pitts, L. Skrypchuk, T. Wellings, A. Attridge, and M. A. Williams, "Evaluating user response to in-car haptic feedback touchscreens using the lane change test," *Advances in Human-Computer Interaction*, vol. 2012, no. 1, pp. 1–13, 2012, doi: 10.1155/2012/598739.

[24] M. J. Pitts, G. E. Burnett, M. A. Williams, and T. Wellings, "Does haptic feedback change the way we view touchscreens in cars?," in *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction*, Beijing, China, 2010, p. 38.

[25] M. J. Pitts, G. Burnett, L. Skrypchuk, T. Wellings, A. Attridge, and M. A. Williams, "Visual–haptic feedback interaction in automotive touchscreens," *Displays*, vol. 33, no. 1, pp. 7–16, 2012, doi: 10.1016/j.displa.2011.09.002.

[26] A. Rydström, C. Grane, and P. Bengtsson, "Driver behaviour during haptic and visual secondary tasks," in *Proceedings of the 1st international Conference on Automotive User interfaces and interactive Vehicular Applications*, 2009, pp. 121–127.

[27] C. Grane and P. Bengtsson, "Haptic addition to a visual menu selection interface controlled by an in-vehicle rotary device," *Advances in Human-Computer Interaction*, vol. 2012, no. 2, pp. 1–12, 2012, doi: 10.1155/2012/787469.

[28] C. Grane and P. Bengtsson, "Driving performance during visual and haptic menu selection with in-vehicle rotary device," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 18, pp. 123–135, 2013, doi: 10.1016/j.trf.2012.12.011.

[29] E. Tunca, R. Fleischer, L. Schmidt, and T. Tille, "Advantages of active haptics on touch surfaces," in *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2016, pp. 137–144.

[30] E. Tunca, I. Zoller, and P. Lotz, "An Investigation into Glance-free Operation of a Touchscreen With and Without Haptic Support in the Driving Simulator," in *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Toronto ON Canada, 2018, pp. 332–340.

[31] J. Mullenbach, M. Blommer, J. E. Colgate, and M. A. Peshkin, "Reducing Driver Distraction with Touchpad Physics," Thesis, Master of Mechanical Engineer, Evanston, IL: Northwestern University, 2013. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/26086/dot_26086_DS1.pdf?

[32] A. B. Weddle and H. Yu, *Confirmation haptics for automotive interfaces: Cadillac CUE User Study.* [Online]. Available: https://www.immersion.com/wp-content/uploads/2015/10/CUE-whitepaper_jun13v1.pdf (accessed: Jan. 9 2019).

[33] H. Richter, R. Ecker, C. Deisler, and A. Butz, "HapTouch and the 2+1 state model," in *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Pittsburgh, Pennsylvania, 2010, pp. 72–79.

[34] H. Ishii, "Tangible bits: Beyond pixels," in *Proceedings of the 2nd international conference on Tangible and embedded interaction - TEI '08*, Bonn, Germany, 2008, p. xv.

[35] A. B. Weddle, H. Yu, and M. Moreno, *UX impacts of haptic latency in automotive interfaces: Literature Review and User Study.* [Online]. Available: https://pdfs.semanticscholar.org/de7c/0c19188642cc925c256608f048163ea5973d.pdf (accessed: Jan. 15 2019).

[36] T. Kaaresoja, "Latency guidelines for touchscreen virtual button feedback," Dissertation, University of Glasgow, Glasgow, 2015.

[37] E. Kim and O. Schneider, "Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Honolulu HI USA, 2020, pp. 1–13.

[38] S. J. Breitschaft and C.-C. Carbon, "An Exploratory Evaluation of Participants' Reactions to Electrostatic Friction Modulation in a UI-Research Context," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.

[39] C.-C. Carbon and H. Leder, "The Repeated Evaluation Technique (RET). A method to capture dynamic effects of innovativeness and attractiveness," *Appl. Cognit. Psychol.*, vol. 19, no. 5, pp. 587–601, 2005, doi: 10.1002/acp.1098.

[40] V. Levesque *et al.,* "Enhancing physicality in touch interaction with programmable friction," in *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, Vancouver, BC, Canada, 2011, p. 2481.

[41] V. Levesque, L. Oram, and K. E. MacLean, "Exploring the design space of programmable friction for scrolling interactions," in *2012 IEEE Haptics Symposium (HAPTICS)*, Vancouver, BC, Canada, 2012, pp. 23–30.

[42] Y. Zhang and C. Harrison, "Quantifying the Targeting Performance Benefit of Electrostatic Haptic Feedback on Touchscreens," in *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces - ITS '15*, Madeira, Portugal, 2015, pp. 43–46.

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[43] M. Jakesch, M. Zachhuber, H. Leder, M. Spingler, and C.-C. Carbon, "Scenario-based touching: On the influence of top-down processes on tactile and visual appreciation," *Res Eng Design*, vol. 22, no. 3, pp. 143–152, 2011, doi: 10.1007/s00163-010-0102-5.

[44] C.-C. Carbon, "Psychology of Design," *Des. Sci.*, vol. 5, p. 339, 2019, doi: 10.1017/dsj.2019.25.

[45] K. E. MacLean and V. Hayward, "Do It Yourself Haptics: Part II [Tutorial]," *IEEE Robot. Automat. Mag.*, vol. 15, no. 1, pp. 104–119, 2008, doi: 10.1109/M-RA.2007.914919.

[46] Tanvas, *TanvasTouch.* [Online]. Available: https://tanvas.co/products/mimovue-with-tanvastouch/ (accessed: Jan. 27 2021).

[47] C. D. Shultz, M. A. Peshkin, and J. E. Colgate, "Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek," in *2015 IEEE World Haptics Conference (WHC)*, Evanston, IL, 2015, pp. 57–62.

[48] C. Gelau, "Zur Frage der Reproduzierbarkeit der Bewertungen von Nebenaufgaben im Fahrzeug mit dem Lane Change Test (LCT)," *Z. Arb. Wiss.*, vol. 67, no. 2, pp. 65–73, 2013, doi: 10.1007/BF03373906.

[49] T. Petzoldt, S. Brüggemann, and J. F. Krems, "Learning effects in the lane change task (LCT)--realistic secondary tasks and transfer of learning," *Applied Ergonomics*, vol. 45, no. 3, pp. 639–646, 2014, doi: 10.1016/j.apergo.2013.09.003.

[50] R Core Team, *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing, 2021. [Online]. Available: https://www.R-project.org/},

[51] A. Kuznetsova, P. B. Brockhoff, and R. H. B. Christensen, "lmerTest Package: Tests in Linear Mixed Effects Models," *J. Stat. Soft.*, vol. 82, no. 13, 2017, doi: 10.18637/jss.v082.i13.

[52] R. H. B. Christensen, *ordinal---Regression Models for Ordinal Data: R package version 2019.12-10.* [Online]. Available: https://cran.r-project.org/package=ordinal

[53] C.-C. Carbon and M. Jakesch, "A model for haptic aesthetic processing and its implications for design," *Proc. IEEE*, vol. 101, no. 9, pp. 2123–2133, 2013, doi: 10.1109/JPROC.2012.2219831.

[54] K. E. MacLean, "Haptic interaction design for everyday interfaces," *Reviews of Human Factors and Ergonomics*, vol. 4, no. 1, pp. 149–194, 2008, doi: 10.1518/155723408X342826.

[55] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, pp. 429–433, 2002, doi: 10.1038/415429a.

[56] R. B. Welch and D. H. Warren, "Immediate perceptual response to intersensory discrepancy," *Psychological Bulletin*, vol. 88, no. 3, pp. 638–667, 1980, doi: 10.1037/0033-2909.88.3.638.

[57] S. J. Breitschaft and C.-C. Carbon, "Function Follows Form: Using the Aesthetic Association Principle to Enhance Haptic Interface Design," *Front. Psychol.*, vol. 12, p. 2619, 2021, doi: 10.3389/fpsyg.2021.646986.

[58] J. L. Gorlewicz *et al.,* "Design Guidelines and Recommendations for Multimodal, Touchscreen-based Graphics," *ACM Trans. Access. Comput.*, vol. 13, no. 3, pp. 1–30, 2020, doi: 10.1145/3403933.

[59] Google Inc., *Android Haptics.* [Online]. Available: https://material.io/design/platform-guidance/android-haptics.html#usage (accessed: Oct. 28 2020).

[60] Apple, *Human Interface Guidelines: Haptics.* [Online]. Available: https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/haptics/ (accessed: Jan. 27 2021).

[61] L. Jones, *Haptics*. Cambridge: MIT Press, 2018. [Online]. Available: https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5493344

[62] S. J. Breitschaft, S. Heijboer, D. Shor, C.-C. Carbon, and E. Tempelman, "Physical Fights Back: Perception Framework for Haptic Practitioners in User Interaction Design," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.

[63] S. J. Breitschaft, A. Pasthukov, and C.-C. Carbon, "Examining Detectability of Virtual Haptic Items rendered on an Electrostatic Friction Display," Poster presented at EuroHaptics 2020, Leiden, The Netherlands, 2020.

[64] Immersion Corporation, *Large Screen Touch Displays.* [Online]. Available: https://www.immersion.com/use_cases/large-touch-screens/ (accessed: Dec. 1 2020).

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Supplemental material for the main article "Where's My Button?"

Stefan Josef Breitschaft, Alexander Pastukhov & Claus-Christian Carbon

I. Introduction

This report describes the method, procedure and results from the pre-study briefly described in Section "Feedback Modality (section III.B.3) of the main article. The main goal of the pre-study was to explore the design space of haptic edges to be used as transition feedback between elements in a button matrix. We aimed to gain insights into which kind of haptic feedback may optimally support interaction. The pre-study employed the same methodological approach, haptic devices, trial procedure, dual-task-setting and dependent variables, which is why we do not describe it in detail in this report (see main article). The last section of this report discusses the rationale of the haptic design of the grid we used in the haptic condition of the main study.

II. Method

The pre-study was conducted according to the principles expressed in the Declaration of Helsinki and according to ethical principles of the German Psychological Society (DGPs) and the Association of German Professional Psychologists (BDP). The general study design (psychophysical testing) was given ethical approval by the local ethics committee of the University of Bamberg.

A. Participants

Twenty participants took part in the study. They were between 19 and 27 years old (M_{age} =22.3 years, SD= 1.8); 16 were female and 4 were male; 18 were right-handed and two left-handed (measured via self-assessment). Participants were naïve to the aims of the study and had not gone through a special training in haptic perception.

B. Apparatus

The pre-study employed the same off-the-shelf MimoVue TanvasTouch 10.1-inch Development Kit monitor as the main study. For additional information on the Tanvas Device we would like to refer to the Methods section of the main study. In contrast to the main study, which employed a seating bucket, the pre-study used a simpler hardware setup. Participants were seated at an office desk. The primary dot-tracking task was displayed on a computer monitor in front of the participants. The primary task was performed using a Logitech G25 Steering Wheel which was attached to the desk in front of the participants. The haptic touchscreen device was positioned on a chair in a position similar to the location of a central information display in vehicles.

C. Dual-Task Setting

The pre-study employed the same dual-task setting as the main-study. The primary task as well as the secondary task share the same working principle and were not changed from the pre-study to the main study. For a detailed description please see the main article (section III Method).

D. Haptic Stimuli

In contrast to the main study, the pre-study only included visual-haptic blocks. We focused on examining the supportiveness of semantically different types of haptic edges instead of focusing on varying singular physical factors, such

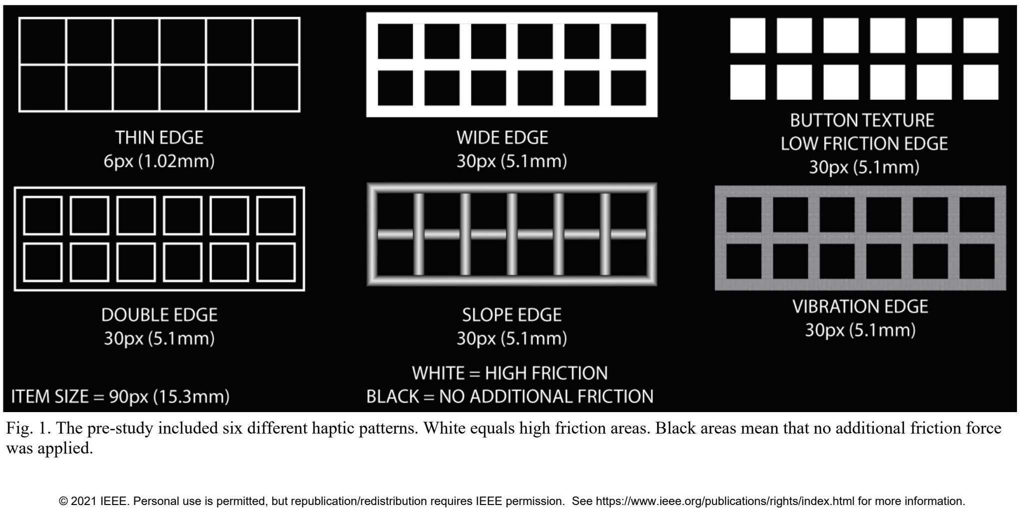

Fig. 1. The pre-study included six different haptic patterns. White equals high friction areas. Black areas mean that no additional friction force was applied.

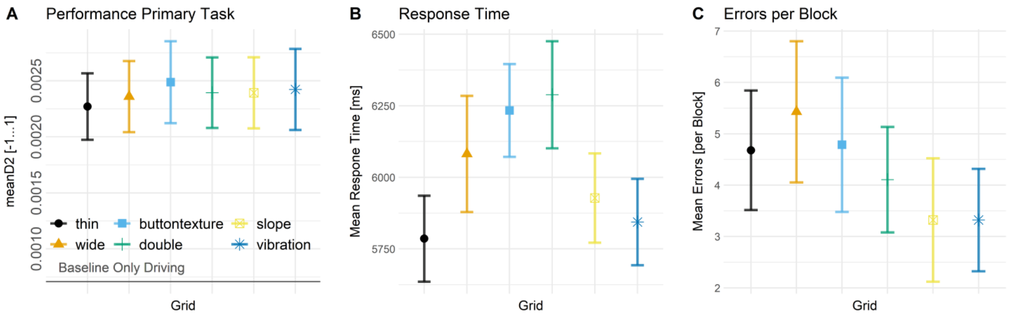

Fig. 2. Line plots for (A) performance primary task, (B) Mean Response Times and (c) erroneous confirmations. Error bars present ± 1 standard error of the mean.

as edge width and amplitude. We compared six different haptic stimuli that mainly differed based the type of haptic feedback pattern upon transitions between matrix items. Fig. 1 depicts the haptic grids we used in the pre-study. White areas depict high friction areas, whereas black areas depict that area where no additional friction force was applied. White equals the maximum available strength provided by the Tanvas unit. Item size of grid elements were 15.3mm (90 px; 1px = 170 µm). Edge width for the *thin*-grid was 1.02mm (6px). Edge width for the *wide*, *vibration*, *double*, *slope* and *button texture*-grid was 5.1mm (30px). The *vibration*-grid consisted of a 1px-checkerboard pattern.

E. Dependent Variables

The pre-study employed the same data collection strategy the main article to explore how different types of haptic stimuli impact user experience (UX) and performance measures. The objective measures include response times, primary task performance and erroneous confirmations. The objective measures were complemented by a post-block UX-questionnaire including the following variables: Pleasantness, Perceived Quality, Precision, Annoyance and Fitting.

F. Procedure

The procedure of the pre-study was similar to the main study. For a detailed description please see the main article. The study was conducted in a quiet and specially prepared room. Upon arrival participants were asked to wash their hands. Participants were made aware of their right to withdraw themselves and their data from the study without consequences and without giving any reasons. Written informed consent was then given by each participant. The experimenter introduced participants to the procedure (dual-task setting, trial procedure, general aim, etc.) of the study. Participants were told to imagine sitting in a car while driving and controlling a car's functions but prioritizing the primary dot-tracking task to perform as good as possible. The experimental session consisted of a training block (8 trials), followed by a driving-only block, twelve haptic blocks and a concluding driving-only block. Participants were not explicitly introduced to the haptic feedback during the training block. The driving only and haptic blocks contained 16 trials each. Trials in the driving blcok were terminated after 12 seconds, trials in the haptic block after correct confirmation of the target item. Each of the haptic blocks (in total six different blocks) were presented twice in randomized and reversed order. The sequence generally followed this pattern: ABCDEF-FEDCBA. After every haptic block the participants were asked to complete the UX-questionnaire. After the experimental session, participants were asked to complete the post-study questionnaire. The session was concluded by clarifying any open questions. The experimenter cleaned all areas of contact prior to the arrival of the next participant. A single session took about 60 minutes.

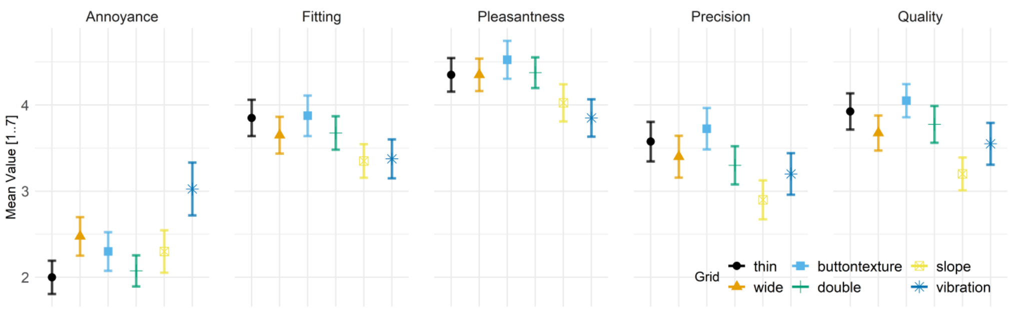

Fig. 3. Mean response values of User Experience variables based on the six different haptic patterns. Error bars represent +-1 standard error of the mean

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TABLE I
LINEAR MIXED MODELS FOR
TASK PERFORMANCE, RESPONSE TIME AND ERRORS

Primary Task Performance					
Fixed.Effects	**Estimate**	***SE***	***df***	***t***	***p***
(Intercept)	0.0029553	0.0003478	29	8.50	**<0.001**
buttontexture	0.0002175	0.0001585	3814	1.37	0.17
double	0.0001244	0.0001585	3814	0.79	0.43
slope	0.0001227	0.0001585	3814	0.77	0.44
vibration	0.0001526	0.0001585	3814	0.96	0.34
wide	0.0000889	0.0001585	3814	0.56	0.57
Block	-0.0000805	0.0000133	3814	-6.08	**<0.001**
Response Times					
(Intercept)	8314.3	553.5	24	15.02	**<0.001**
buttontexture	447.9	195.5	3814	2.29	**0.02**
double	502.9	195.5	3814	2.57	**0.01**
slope	142.0	195.5	3814	0.73	0.47
vibration	58.3	195.5	3814	0.30	0.77
wide	296.0	195.5	3814	1.51	0.13
Block	-297.5	16.3	3814	-18.20	**<0.001**
Erroneous Confirmations					
Fixed.Effects	**Estimate**	***SE***		*z*	***p***
(Intercept)	1.14148	0.28413		4.02	**<0.001**
slope	0.00293	0.14601		0.02	0.98
thin	0.34865	0.13503		2.58	**<0.01**
double	0.20120	0.13894		1.45	0.15
wide	0.49180	0.13107		3.75	**<0.001**
buttontexture	0.35448	0.13446		2.64	**<0.01**
Block	-0.04679	0.01085		-4.31	**<0.001**

Note: SE = Standard Error, bold number indicates $p < 0.05$, Erroneous Confirmations were analyzed using a generalized linear mixed model

TABLE II
CUMULATIVE LINK MIXED MODEL WITH UX-VARIABLES AS CRITERIA

Modality	**Estimate**	***SE***	*z*	***p-value***
Annoyance				
double	-0.34	0.46	-0.74	0.4586
slope	-0.10	0.47	-0.22	0.8272
thin	-0.51	0.46	-1.11	0.2653
vibration	1.13	0.47	2.40	0.0165
wide	0.43	0.44	0,97	0.3343
Fitting				
double	-0.05	0.42	-0.12	0.9043
slope	-0.70	0.41	-1.70	0.0887
thin	0.14	0.41	0.33	0.7409
vibration	-0.65	0.43	-1.52	0.1286
wide	-0.28	0.42	-0.68	0.4941
Pleasantness				
double	-0.22	0.41	-0.53	0.5991
slope	-0.66	0.42	-1.60	0.1100
thin	-0.21	0.41	-0.50	0.6195
vibration	-0.97	0.42	-2.31	**0.0210**
wide	-0.27	0.41	-0.65	0.5161
Precision				
double	-0.51	0.42	-1.21	0.2245
slope	-1.09	0.42	-2.60	**0.0093**
thin	-0.11	0.41	-0.28	0.7825
vibration	-0.63	0.42	-1.49	0.1357
wide	-0.42	0.42	-1.02	0.3087
Quality				
double	-0.34	0.41	-0.83	0.4051
slope	-1.22	0.40	-3.04	**0.0024**
thin	-0.16	0.40	-0.40	0.6873
vibration	-0.58	0.41	-1.41	0.1595
wide	-0.46	0.39	-1.21	0.2429

Note: *SE* = Standard Error, bold number indicates $p < 0.05$,

III. RESULTS

Results from the objective and subjective measures will be given in the following section. Error bars in the figures depict one standard error of the mean. Results were analyzed using the statistical software R 4.0.2.

A. *Objective Variables*

Table I describes the results from the objectives measures: primary task performance, response time and erroneous confirmations.

1) *Performance Primary Task*

Performance in the driving task was assessed using the dot-tracking-task. All haptic conditions were more distracting than the driving-only condition. A linear-mixed model with the *Haptic Grid* and *Block* (first or second repetition of the respective haptic block) as factors was fitted using the *lmer*-function. All haptic blocks differed from the driving-only condition. Table I shows that the type of haptic did not have a significantinfluence on performance. A negative slope for the *Block* parameter indicates a learning process.

2) *Response Time*

A linear-mixed model based on response time was fitted using the *lmer*-function. The results are displayed in Table I. The block predictor shows a significant (β = –297.5, t (3814) = -18.2, $p < .001$) result. The negative slope indicates that participants were faster in the second iteration of the feedback blocks. The *buttontexture* (β = 447.9, t (3814) = 2.3, $p < .05$) and *double* grid (β = 502.9, t (3814) = 2.6, $p < .05$) show a significant result indicating participants were slower in these conditions.

3) *Erroneous Confirmations*

A generalized linear regression model using *glmer*-function (family parameter set to poisson) with the factors *Haptic Grid* and *Block* was fitted (see Table I). The block predictor shows a significant (β = –-0.05, z = -4.31, $p < .001$) result. The *thin* (β = –-0.35, z = 2.58, $p < .01$), *wide* (β = –-0.49, z = 3.75, $p < .01$) and *buttontexture* (β = –-0.05, z = 2.64, $p < .01$) grid show a significant result.

B. *UX-Variables*

Fig 3. shows mean ratings for all items from the UX-questionnaire that participants filled in after each haptic block. A cumulative link mixed model using the *clmm()*-function from the *ordinal* package was used to compare the feedback conditions. Table II shows results from the cumulative linked mixed model.

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IV. Haptic design for the Main Study

Overall, there is no general pattern that indicates a single pattern to support interaction optimally. While the *vibration* and *slope* patterns seem to yield lower response times and errors, they tend to score worse in the UX-ratings. The *buttontexture* grid tends to have the highest UX-ratings. Some of the participants described negative associations ("feels like an electroshock", "dry cloth"). We believe that especially vibrational patterns, such as the *vibration*-grid, may be prone to yield such associations, which may have an impact on long-term product appreciation. Also, participants reported that soft feedback, such as the *slope*-grid caused insecurity and may have impeded user experience. Previous literature (reported in section II of the main article) indicates that the additional value of haptic feedback in interaction settings may mainly be experience-based. Hence, we selected a haptic feedback pattern that scored high in terms of user experience ratings. We choose to base the haptic design of the friction stimuli for the haptic condition in the main study on the *buttontexutre*-grid. The *buttontexture*-grid tended to score the best on the UX-variables, even though none of the differences were found significant. We also chose the *buttontexture*-grid as it may correspond best to participants' expectations towards search haptics in an interaction context. The higher friction force required while sliding on the button itself may indicate that participants are within the matrix of elements, i.e., the interactive are. The low friction areas do not indicate interactivity. Yet, while sliding from one element to another, the low-friction edges within the *buttontexture*-grid allow augmenting feedback upon element transitions.

Finally, we used an iteration of the *buttontexture*-grid in the main study. In observations from other lab-internal studies, we found that haptic strength may be optimized by changing the edge width and dividing the transition event into multiple friction changes to create some vibrant feeling. The haptic grid we used is depicted in Figure 3 of the main article.