

A Psychological Turn on Vehicle Acoustics: About the Perception of Automotive Interior Soundscapes in Electrified Vehicles



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Abstract

In this dissertation, I take a psychological turn on vehicle acoustics by investigating how humans perceive acoustic characteristics in electrified vehicles (EVs). The interior soundscape of an EV is composed of a multitude of acoustic characteristics that shape the customer's overall vehicle experience. Among these acoustic characteristics, my dissertation focuses explicitly on automotive powertrain-related acoustics, such as e-powertrain noise and active sound design. The transition from internal combustion engine vehicles (ICEVs) to EVs introduces novel acoustic profiles that fundamentally reshape the acoustic landscape of modern mobility. This shift not only challenges existing engineering conventions and design paradigms but also our understanding of psychological factors, particularly the expectations, preferences, and perceptual processes of vehicle users. With an emphasis on the cognitive and affective mechanisms that shape human perception, my research explores how individuals experience the interior soundscapes of EVs. A human-centered approach to assessing customer perception of automotive acoustics is inevitable for a holistic product development. Throughout this thesis, I employ a variety of methodological approaches established in perceptual and cognitive science, including state-of-the-art methods such as laboratory listening tests and studies in highly sophisticated acoustic simulator environments. By also introducing novel evaluative techniques that are applied for the first time in automotive acoustics, my work contributes to advancing methodological standards in the field. Key perceptual dimensions addressed in this work include perceived quality, the annoyance and perceptibility of e-powertrain noise, dimensions of preference and innovativeness, and various semantic dimensions conveyed by active sound design concepts in EVs. The findings provide insights into perceptual long-term adaptation effects and individual expectations and preferences regarding the perception of EV acoustics. By integrating conceptual, methodological, and applied perspectives, this thesis encourages future research and the applied field to adopt interdisciplinary approaches in the development of vehicle acoustics. With the enhanced understanding of how humans perceive EV soundscapes, a customer-oriented and holistic product development is achieved. Future research should build upon the proposed approaches and explore multisensory integration to advance the holistic approach beyond the acoustic modality. This work highlights the crucial role of integrating psychological insights into engineering practice: not only does it facilitate a deeper understanding of customer expectations, but its implications also guide and advance acoustic vehicle development towards satisfying, emotionally engaging, and semantically meaningful soundscapes in next-generation vehicles.

Original Contributions to This Thesis

This thesis comprises four published peer-reviewed journal articles that can be read independently. All manuscripts embedded in this dissertation are openly accessible online. The following list shows the contributions included in this work and the authors' contributions according to the *CRedit* taxonomy:

Manuscript #1

Münder, M., & Carbon, C.-C. (2022). A literature review [2000 – 2022] on vehicle acoustics: Investigations on perceptual parameters of interior soundscapes in electrified vehicles. *Frontiers in Mechanical Engineering*, 8, 974464. <https://doi.org/10.3389/fmech.2022.974464>

Münder, M.: Conceptualization, Investigation, Writing – Original Draft, Writing – Review & Editing
Carbon, C.-C.: Conceptualization, Writing – Review & Editing

Manuscript #2

Münder, M., & Carbon, C.-C. (2022). Howl, whirr, and whistle: The perception of electric powertrain noise and its importance for perceived quality in electrified vehicles. *Applied Acoustics*, 185, 108412. <https://doi.org/10.1016/j.apacoust.2021.108412>

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Manuscript #3

Münder, M., Müller, G. J., Raab, M. H., & Carbon, C.-C. (2024). Unfolding dynamics in the perception of interior vehicle acoustics via continuous evaluation procedure (CEP). *Frontiers in Acoustics*, 2, 1423168. <https://doi.org/10.3389/facou.2024.1423168>

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Müller, G. J.: Resources, Writing – Review & Editing
Raab, M., H.: Formal Analysis, Methodology, Software, Visualization, Writing – Review & Editing
Carbon, C.-C.: Conceptualization, Formal Analysis, Methodology, Writing – Review & Editing

Manuscript #4

Münder, M., Vitale, R., & Carbon, C.-C. (2024). Back to the future: Innovativeness in sound design for electrified vehicles. *i-Perception*, 16(0), 1-24. <https://doi.org/10.1177/20416695251323786>

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Vitale, R.: Conceptualization, Methodology, Writing – Review & Editing
Carbon, C.-C.: Conceptualization, Methodology, Project Administration, Resources, Writing – Review & Editing

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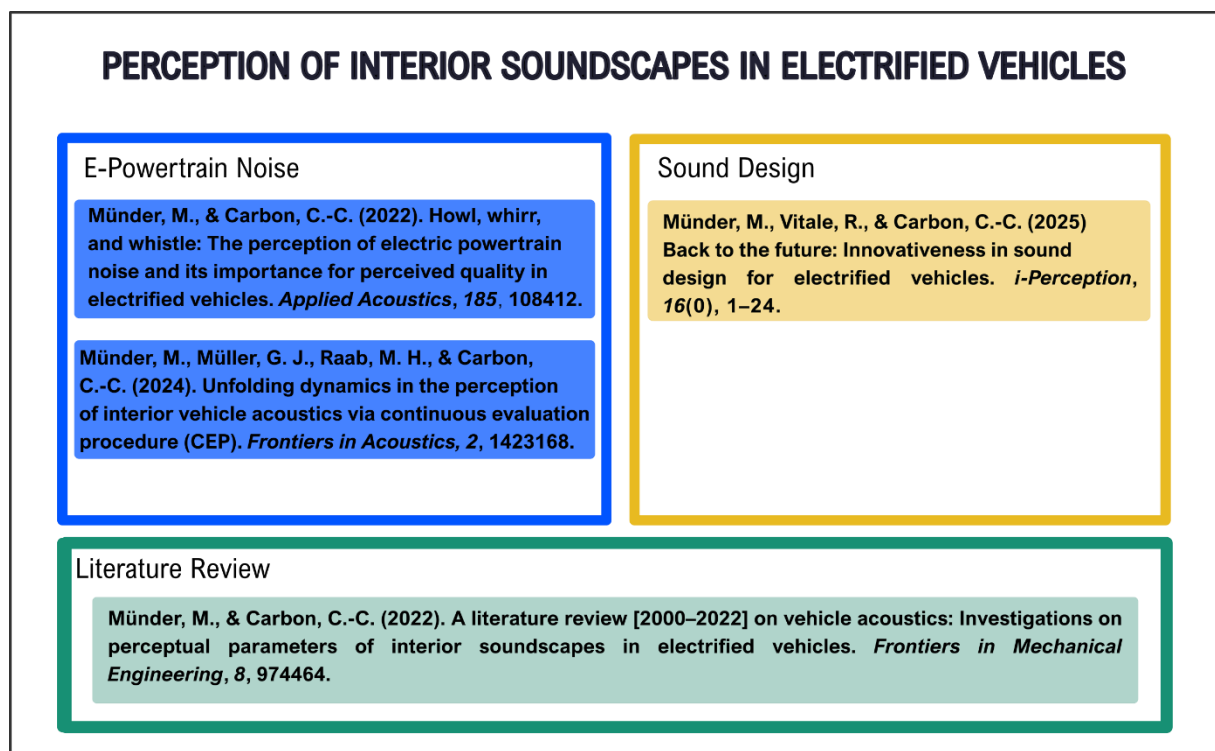
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0 Thesis Structure

Following a brief introduction in section **1 Introduction and Theoretical Background**, I will explain my **1.1 Motivation and Goals** within this thesis. Further, the key subjects of the thesis are addressed in separate sections to offer a general understanding of the topics discussed within the thesis and publications, without claiming to provide an exhaustive elaboration on each subject. After introducing some basics in **1.2 Vehicle Acoustics**, I will elaborate on different aspects of the **1.3 Perception of Interior Vehicle Acoustics**. This theoretical introduction is followed by the four publications from throughout my dissertation project. Each of the thesis contributions is outlined and embedded in a separate section. **Figure 1** illustrates the various contributions and provides an overview of their thematic references to different aspects of EV acoustics and interior soundscapes.

Figure 1



Note. Overview of the contributions embedded in this thesis and their thematic reference.

First, I outline a framework based on our literature review (*Manuscript #1*) in section **2 An Overview: State of Research on Perception of Interior Soundscapes in Electrified Vehicles**. “A literature review [2000 – 2022] on vehicle acoustics: Investigations on perceptual parameters of interior soundscapes in electrified vehicles” (Münder & Carbon, 2022a; *Manuscript #1*) summarizes more than two decades of research on the perception of vehicle acoustics. Then, two studies explicitly focusing on the perception of e-powertrain noise are embedded in section **3 Perception of E-Powertrain Noise**. While in “Howl, whirr, and whistle: The perception of electric powertrain noise and its importance for perceived quality in electrified vehicles” (Münder & Carbon, 2022b; *Manuscript #2*) we apply repeated

evaluation, in “Unfolding dynamics in the perception of vehicle acoustics via Continuous Evaluation Procedure (CEP)” (Münder et al., 2024; *Manuscript #3*) we focus on an even higher temporal resolution and had the participants continuously evaluate their impression of e-powertrain noise. This is followed by a section on **4 Innovativeness in EV Sound Design**, embedding *Manuscript #4* of this cumulative dissertation. In “Back to the future: Innovativeness in sound design for electrified vehicles” (Münder et al., 2025; *Manuscript #4*), we investigate dynamic effects in the perception of novel sound design concepts for EVs. The findings of the published articles are summarized in section **5 Integration of Results and Main Findings**. The implications of the findings are discussed in section **6 Discussion: Result Interpretation, Methodological and Practical Implications for Future Research and the Applied Field**, and section **7 Conclusion** concludes this thesis.

1 Introduction and Theoretical Background

With the increasing electrification in individual automotive transport, the industry is going through a change. Automotive companies and manufacturers that now start or intensify their production of electrified vehicles (EVs) are challenged in various ways (Allman-Ward et al., 2020; Cerrato, 2009; Gavric, 2020; Genuit, 2010). In terms of vehicle acoustics, automotive engineers are specifically challenged with the refinement and design of the acoustic vehicle properties, as the ones of EVs substantially deviate from the ones of internal combustion engine vehicles (ICEVs; see also **1.2.2 Acoustics of Electrified Powertrains** and e.g., Allman-Ward et al., 2020; Blickensdorff et al., 2019; Gavric, 2020; Meek et al., 2012). With this altered acoustic profile, the interior soundscape – i.e., whatever people acoustically perceive in the vehicle – significantly changes in EVs. As the acoustic vehicle properties are of high importance to customer satisfaction (Qatu, 2012; Qatu et al., 2009; Sinambari & Sentpali, 2020; Zeller, 2018), the consideration of respective customer needs plays an integral role within these refinement processes, especially regarding the following aspects:

- How are the EV-specific acoustic characteristics, which are different from those of the familiar and so far dominating ICEV, perceived?
- What kind of acoustic phenomena in EVs are being appreciated or rejected?
- What are the specific acoustic parameters associated with e-mobility, and what do customers expect from the acoustics of an EV?

Of course, an acoustically well-refined driving experience requires high technological expertise. However, open questions regarding customer satisfaction suggest focusing on the individual driver’s perception and evaluation of acoustic impressions. Therefore, insights into human perception of such acoustic criteria are essential to support the determination of efficient technological solutions for the acoustic refinement of EV noise profiles.

1.1 Motivation and Goals

This dissertation shall provide insights for researchers and professionals in the applied field to enhance their understanding of human perception regarding different acoustic characteristics in the context of electrified vehicles (EVs). It draws upon various studies conducted throughout this doctoral project. I am convinced that interdisciplinary collaboration provides valuable insights into complex topics such as the acoustic perception and experience of interior EV soundscapes. Rather than having each discipline focus on its specialty in an isolated form, and therefore only on a part of the overall picture, I advocate for integrating different perspectives from multiple disciplines to gain a comprehensive understanding.

While physical parameters are crucial for refining technological properties of the product's design, perception-related measures reveal how customers experience the resulting acoustics. As a psychologist, the focus throughout my doctoral project was primarily set on the perceptual definition of sound and the conscious *percept*¹ resulting from the experience of the presented interior soundscapes of EVs. Of course, the physical properties of sound should not be neglected, but the special interest of my research lies within the resulting conscious percepts and experience assessed through human evaluation. Therefore, my research integrates human-centered and holistic approaches, using psychological methods not previously applied in the field of vehicle acoustics. By focusing on the driver, who is the ultimate recipient of the various acoustic impressions within the vehicle cabin, we assessed how people perceive the different acoustic characteristics of EVs. To narrow down the multitude of potential noise characteristics from various sources, my research specifically focuses on driving-related acoustics, including e-powertrain noise and active sound design. Rather than isolating specific acoustic features, our study participants evaluated the interior soundscapes of EVs, composed of various acoustic properties within their natural context.

This holistic approach is essential for addressing relevant questions in the applied field and gaining ecologically valid insights. The studies included in this dissertation investigate how people accept specific e-powertrain noise characteristics and their preferences for different sound design concepts. With my research, I hope to guide automotive engineers in refining and designing interior soundscapes of EVs that enhance customer satisfaction.

By introducing novel evaluation methods to the applied field and research community, such as repeated and continuous evaluation techniques, this work seeks to inspire future research in automotive acoustics. Furthermore, my work emphasizes considering individual perception and

¹ A *percept* refers to the mental representation and subjective interpretation of sensory input. It results from perceptual processing and represents the conscious experience of an object. The term is commonly used in perceptual science.

conducting research in realistic and ecologically valid testing settings. I hope to encourage collaboration among researchers from various disciplines and promote innovative approaches to investigating human-centered perception of EV soundscapes.

1.2 Vehicle Acoustics

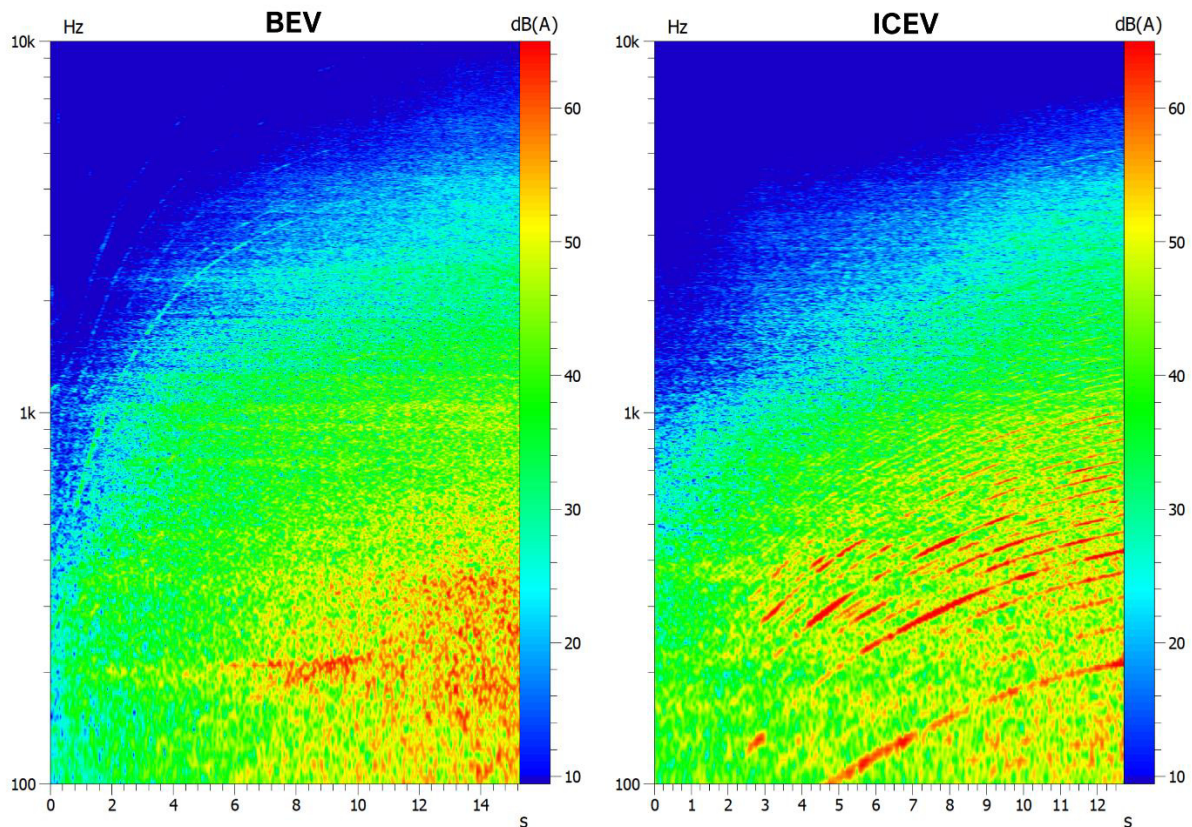
Vehicle acoustics can be described as a sub-discipline of engineering acoustics that finds multiple applications in automotive engineering. The general goal for automotive engineers when designing a vehicle's acoustics can be summarized as reducing noise emergence and emission and/or letting the appearing noise sound in a specific way (Sinambari & Sentpali, 2020). Blickensdorff et al. (2019) describe a stepwise design model for soundscapes in vehicle acoustics: the basis is the avoidance and reduction of disturbing noise components, followed by the perseverance and strengthening of desired noise components, and ultimately the addition of new sound elements under consideration of authenticity. The requirements imposed on the acoustic vehicle design increased over the last decades because of competitive constraints, regulations (Zeller, 2018) as well as the technological progress that seemed to have raised customer standards as the acoustic comfort of a vehicle has become an important purchase reason to buy a car (Sinambari & Sentpali, 2020; Zeller, 2018). To fulfill the high standards for customer satisfaction, the acoustic refinement of the total vehicle already begins with its components (Sinambari & Sentpali, 2020), as each noise source contributes to the overall acoustic appearance of the total product. It is a challenging task demanding careful consideration to find the right balance and orchestrate the multitude of noise sources so that the resulting acoustic appearance of the overall vehicle meets customer expectations.

The shift to e-powertrains causes a significant change in the acoustic profile of a vehicle, which is further elaborated in **1.2.2 Acoustics of Electrified Powertrains**. These changes in the acoustic profile of EVs not only challenge automotive engineers in terms of acoustic refinement but also offer opportunities for novel design approaches (Allman-Ward et al., 2020; Cerrato, 2009; Eisele et al., 2019). Acoustic vehicle characteristics are found to play a vital role in customer satisfaction (Qatu et al., 2009; Schulte-Fortkamp et al., 2007; Sinambari & Sentpali, 2020; Swart & Bekker, 2019; Wagner et al., 2017). Also, acoustic vehicle refinement can be utilized to shape a vehicle's character (Pletschen, 2010; Zeller, 2018). To customer satisfaction, the adequacy of the perceivable noise in the given context and meeting the customers' expectations are crucial. The refinement of specific noise sources must not always aim to eliminate a noise source: customers might even expect certain noise as operational feedback in specific operational use cases (Münder & Carbon, 2022b) or from specific components, as from smaller actuators to adjust the seating position (Sinambari & Sentpali, 2020). Therefore, the generally muted character of EVs is often criticized and stated to lack operational feedback (Blickensdorff et al., 2019; Kleinjohann, 2020). Specific groups, such as car enthusiasts, have

clear expectations about how a vehicle should sound and are emotionally attached to the typical ICEV sound (Krishna, 2021). However, not everyone has yet formed a clear opinion on the most suitable sound for an EV (e.g., Allman-Ward et al., 2020; Petiot et al., 2013). These unclear and diversified expectations might not only originate in a lack of experience with electrified driving but also in a lack of knowledge on the possibilities that arise through an overall quiet vehicle when combined with active sound design. Nevertheless, as vehicle acoustics represent cultural capital and shape human landscapes, they should find explicit consideration within pivotal societal transitions, owing to our safety, comfort, and aesthetic interests (Clendinning, 2018). Mnder and Carbon (2022a) summarize different studies that apply various techniques of sound synthesis to enhance EV acoustics. By the technological potential of active sound design techniques, automotive manufacturers can apply any possible sound to an EV. The industrial strategies, moderated by politics and authorities, influence the success of novel designs and technologies and, therefore, possibly also the demands on sound quality (Fiebig & Schulte-Fortkamp, 2019). Accordingly, an optimized refinement process and attuning a customer-satisfying acoustic driving experience encloses economic potential for automotive companies. This implies not only the need to identify and eliminate disturbing noise sources but also to determine what constitutes a good, customer-satisfying acoustic profile.

In automotive acoustics, Campbell diagrams can be used to visualize how the frequency content and sound pressure level of an acoustic signal vary over time. To illustrate the differences in the noise profiles of conventional and electrified vehicles, I generated two Campbell diagrams shown in **Figure 2**. Both diagrams are based on an ambisonic audio recording of a full acceleration measurement on a BMW test track. The diagram on the left side shows the noise profile of a standard production battery electric vehicle (BEV), and the one on the right side shows the noise profile of a standard production vehicle with an internal combustion engine (ICEV). The x-axis refers to the time dimension of the acceleration process, measured in seconds. The primary y-axis shows the frequency spectrum on a logarithmic scale ranging from 100 Hz to 10 kHz. On the right side of each diagram, the color scale (z-axis) indicates the sound pressure level (SPL) using an A-weighted decibel scale ranging from 10 to 65 dB(A). The SPL has been A-weighted, as it better represents the perceived loudness of the recordings, as human hearing sensitivity to different frequencies is considered by this filter. The color gradient within each diagram reflects the measured SPL associated with the various frequencies. While the ICEV's diagram in **Figure 2** shows distinct and dominant combustion engine orders in the lower frequency ranges below 1 kHz, the BEV's diagram shows more of an undefined, broadband noise carpet within this frequency range. On the contrary, the BEV's diagram shows distinct engine orders in the frequency ranges above the range of 1 kHz, faintly indicated by the traversing lines. Further details about electrified powertrains and EVs are described in section **1.2.2 Acoustics of Electrified Powertrains**.

Figure 2



Note. Campbell diagrams of a standard production BEV and ICEV in a full acceleration scenario. The frequency spectrum is scaled logarithmically; the SPL is A-weighted. Both measurements were recorded according to a standardized measurement protocol; differing performance parameters caused the different lengths of the depicted acceleration processes.

1.2.1 Noise, Vibration, and Harshness (NVH)

In automotive engineering, the term *NVH* (*Noise, Vibration, and Harshness*) encompasses a vehicle's acoustic and vibrational characteristics. Refining NVH characteristics in road vehicles poses a significant challenge to experts from many disciplines due to the multitude of possible noise sources, their interrelatedness, and their speed dependency (Barton & Fieldhouse, 2024). NVH encompasses a wide range of characteristics of air- and structure-borne noise (see, e.g., Barton & Fieldhouse, 2024; Sinambari & Sentpali, 2020; Zeller, 2018), comprising acoustic as well as vibrational signals that lead to aural and/or tactile impressions. Acoustic noise properties, vibration, and harshness are closely associated with the reliability and quality impression a vehicle conveys (Barton & Fieldhouse, 2024; Qatu, 2012). Altogether, their direct sensory impressions make NVH characteristics of immediately perceivable qualia. Because of this tangible nature, the refinement of NVH becomes increasingly important for the overall driving experience of a vehicle. Consequently, NVH refinement is ascribed an increased importance in terms of customer satisfaction in the acoustic vehicle design (Qatu et al., 2009; Schulte-Fortkamp et al., 2007; Sinambari & Sentpali, 2020; Swart & Bekker, 2019; Wagner et al., 2017).

Nevertheless, acoustic engineers have constantly been challenged as NVH development is conflicted with other vehicle design choices, such as efficiency gains and overall weight reduction (Meek et al., 2013). These choices often cause the vehicle's NVH profile to represent a sort of collateral damage (Cerrato, 2009) rather than an active design decision.

The most important noise source contributions to the overall interior noise of a vehicle can be categorized into aerodynamic noise, tire noise, brake noise, and generally powertrain-related noise, such as engine noise, transmission gear noise, and intake and exhaust noise (Barton & Fieldhouse, 2024). With the electrification, the general architecture and components of the powertrain system change and, therefore, also the noise sources. While some contributors, for example, intake and exhaust noise, fall away in EVs due to not having an exhaust pipe, other contributions from the EV's power electronics, such as switching noise (Devillers et al., 2020), are added. As sound quality is often related to powertrain-related NVH criteria (Qatu et al., 2009), the alteration of the powertrain and its components can be expected to cause the most radical change within the NVH profile comparing ICEVs and EVs.

1.2.2 Acoustics of Electrified Powertrains

The increasingly refined NVH characteristics and technological progress in automotive vehicles decreased the noise emissions of vehicles overall throughout the past decades. As the vehicle powertrain is one of the main noise contributors (Barton & Fieldhouse, 2024; Qatu et al., 2009), it dominates a car's NVH profile. Thus, the most radical changes in the acoustic vehicle profile, when comparing EVs with ICEVs, can be expected by the electrification of the powertrain. Automotive engineers are challenged with various novel acoustic characteristics that assemble a unique sound profile in EVs but also confront them with unprecedented design decisions (Eisele et al., 2019; Gavric, 2020; Genuit, 2004, 2010). The so far predominantly ICEV-related broadband noise and NVH phenomena (Gavric, 2020), as (diesel) knocking, booming, rumbling (Genuit et al., 2010; Zeller, 2018), will now increasingly be displaced by e-powertrain related phenomena in higher frequency ranges with tonal components (Gavric, 2020), such as howling, whirring, and whistling (Blickensdorff et al., 2019).

Overall, EVs emit less noise with a lowered sound pressure level (SPL) by up to 20 dB compared to conventional cars (Blickensdorff et al., 2019). Due to the generally muted character, the masking effect of so far prevailing ICE-broadband noise disappears in EVs, and so far unnoticed disturbing noise can become apparent, while at the same time new disturbing noises might emerge (Eisele et al., 2019; Gavric, 2020). Vehicle noise from the outside, such as the low-frequency road and high-frequency wind noise, may now become more noticeable to the driver. Bodden and Belschner (2016) even describe a spectral gap leading to an inharmonic impression of the underlying noise carpet. In our literature review (Münder & Carbon, 2022a) we identified the following three main challenges regarding e-NVH

characteristics and their refinement in the applied field: 1) The naturally muted EVs lead to a lack of masking effects, uncovering previously unnoticed disturbing noise sources while simultaneously diminishing the EV's dynamic character due to their lack of characteristic operational feedback; 2) EVs have a novel NVH profile with high-frequent noise components, which is relatively unfamiliar to most people and can potentially be perceived as annoying, especially when compared to the low-frequency broadband noise of classic ICEVs; 3) The debate on the EV's suitable sound character revolves around whether it should reflect the natural quietness of electrified driving or whether the EV's exceptional performance should be actively enhanced through applied sound design.

Apart from the generally muted noise appearance, the acoustic profile fundamentally deviates from the conventional ICEVs in its NVH properties. The characteristic booming from the operational combustion in ICEVs with their familiar low and mid-frequency engine orders is replaced by the EV-typical noise profile with a tonal character due to mid- and high-frequency orders (Lennström et al., 2011). The typical broadband noise spectrum of an ICEV is dominated by engine orders and harmonics that range below the frequency of 1kHz (Blickensdorff et al., 2019), while noise of electrified powertrains is characterized by tonal components and substantial sound energy in the higher frequencies bands for which the human ear is particularly sensitive (Blickensdorff et al., 2019; Gavric, 2020; Swart et al., 2016). Several studies on e-powertrain noise and its typical high-frequent and tonal acoustic profile, for example, Lennström et al. (2013), Lennström and Nykänen (2015), and Swart et al. (2016), suggest EVs to be perceived as potentially less pleasant and potentially more annoying. Also, the high-frequent characteristic switching noise, known as Pulse Width Modulation (PWM) caused by the e-powertrain's power electronics, which ranges from 250 Hz to 20 kHz, is likely to be perceived as unpleasant, as found by Devillers et al. (2020). Moreover, Meek et al. (2013) report a distinct void within the frequency range of 200 to 1000 Hz in EVs, and Swart et al. (2016) found low roughness values, local SPL-minima in the frequency ranges of 200 to 500 Hz, and EVs to be lacking prominent engine orders. Compared with EVs, these low-to-mid frequency ranges are often found in ICEVs and characterize the familiar broadband noise (Meek et al., 2013; Swart et al., 2016). As these changes in the vehicle noise profiles can result in a less refined vehicle impression and irritating disturbing noise, the NVH refinement in EVs becomes increasingly important to customer satisfaction.

1.2.3 Automotive Sound Design

Electrified powertrains do not only show novel sound profiles but also lead to a generally muted EV driving experience with only a little operational feedback compared to ICEVs. Electrified driving can be described as quiet, smooth, and silent (Kurani et al., 2008). In a study by Gärling (2001), electrified driving was reported to be defined by attributes such as comfort and noiselessness, and 80 % of the sample reported the same amount or even more pleasure when driving electrified compared to driving

an ICEV. On the other hand, EVs frequently get criticized for their increasingly muted soundscape and to lack acoustic feedback that is important to a vehicle's character (Bodden & Belschner, 2014, 2016; Kleinjohann, 2020; Krishna, 2021) – especially, when it comes to sportiness (Swart et al., 2016; Swart & Bekker, 2014). The analysis of social media and online forums by Krishna (2021), for instance, indicates that cars and their NVH properties are experienced and perceived as “soulful” (p. 5) entities and that their owners build emotional connections with their vehicles through sound. Especially passionate car enthusiasts of the conventional combustion engine era criticize electrified driving as a “sterile” (p.5) and “lackluster ‘appliance-like’” (p. 6) driving experience (Krishna, 2021).

As sound enhancement is already used for ICEVs – for example, to highlight specific exhaust pipe sounds or the bubble of a V8 motor to underline a sportier character (Bodden & Belschner, 2014) – it is not far-fetched to apply these measures to the naturally quieter, but highly performant electrified vehicles to add some zest to their acoustic character. In Munder and Carbon (2022a), we identified multiple studies about different sound synthesis approaches and driving sound enhancement strategies for EVs. Through different modification methods, such as adding subharmonics (Gwak et al., 2014b, 2014a) or pitch-shifting (Sontacchi et al., 2015; Yamauchi & Feng, 2014), the impression of sportiness conveyed by a vehicle sound can be influenced. Melman et al. (2021) proved the measure of *Artificial Engine Sound* (AES) compared to other techniques to increase the illusion of sportiness in EVs. Swart et al. (2018) revealed sound enhancement methods, such as high-frequency filtering, low-frequency amplification, pitch transposition, and low-order addition, to attain higher preference scores. While most participants in the study on active sound enhancement of Allman-Ward et al. (2020) preferred different modified sounds, one group within the sample perceived the natural EV interior sound without any modifications to be the most suitable for an EV. Overall, the results of different studies indicate highly diversified individual preferences regarding EV driving sounds and sub-groups with different customer expectations (Celiberti et al., 2024; Genuit & Fiebig, 2014; Lazaro et al., 2022; Maunder & Munday, 2017; Valeri & Pietila, 2020). Modifications in a vehicle's noise and sound profile shape its conveyed impressions and overall character (Kleinjohann, 2020; Pletschen, 2010; Spence & Zampini, 2006; Zeller, 2018), but the debate on the best or most suitable sound design for a specific vehicle seems highly dependent on the target group, vehicle brand and type, and therefore represents a case for individual consideration for each vehicle.

1.3 Perception of Interior Vehicle Acoustics

The following chapter integrates the disciplines of vehicle acoustics and psychology. Therefore, I provide an overview of some basics in acoustics, principles of human auditory perception, and further psychological influencing effects. This section should give the reader a better understanding of the topics discussed in the embedded publications. It is not to be understood as an exhaustive explanation

of the multitude of physical, biological, and cognitive mechanisms and processes necessary for us to hear and interpret acoustic signals.

1.3.1 Physical Parameters of Acoustics and Psychoacoustic Metrics

The physical phenomenon of acoustics can be described as a pressure change in a medium, and in vehicle acoustics, one can generally distinguish air- and structure-borne noise that can result in an audible acoustic event (Sinambari & Sentpali, 2020; Vorländer, 2010; Zeller, 2018). Airborne noise consists of sound waves that travel through the air, whereas structure-borne noise propagates through solid materials, such as vibrations transmitted through the vehicle's body. The audible acoustic stimuli must then be transferred to the receptors within the human hearing organ, where they are transduced to electrical signals that can be cognitively processed (Sinambari & Sentpali, 2020). Due to their physical nature, acoustic properties can be described by physical parameters. For example, the frequency spectrum can be described in Hertz (Hz), the sound's propagation speed can be measured in meter/second (m/s), and the sound pressure level (SPL) in decibel (dB) can be used to describe how loud an acoustic event is (Sinambari & Sentpali, 2020; Zwicker & Fastl, 2010). Physical parameters and units make it possible to describe the physical nature of acoustic events and compare them with one another on an objective level. To interpret the meaning and magnitude of such parameters – in terms of what may be considered, for example, comparatively loud or quiet – a certain degree of expertise is required. Thus, despite fully describing a sound's physical properties, objective parameters might not sufficiently describe what kind of subjective impression it conveys to each recipient.

The discipline of psychoacoustics and its metrics aim to precisely describe this relation between the subjective perception of sound and the physical properties (Fastl, 2002; Sinambari & Sentpali, 2020). These metrics are considered objective and quantifiable parameters and are utilized to indicate the sound quality of automotive acoustics (Genuit & Fiebig, 2011). Some established psychoacoustic parameters are the measures of *loudness* measured in the unit *sones*, *tonality* measured in the unit *mel*, *roughness* measured in *asper*, *sharpness* measured in *acum*, or *fluctuation strength* measured in *vacil* (see e.g., Sinambari & Sentpali, 2020; Zwicker & Fastl, 2010). Psychoacoustic application-oriented indices have been developed within automotive engineering to better describe the subjective impression regarding automotive-specific acoustic phenomena and quantify their physical properties. For instance, the so-called NVH phenomenon *diesel knocking* ("*Dieselnageln*" in German) is a fluctuating noise that impacts the overall perceived quality of a diesel ICEV (Zeller, 2018). Zeller (2018), for instance, reports on the *Combustion Knocking Index* (CKI), the *Engine Annoyance Index* (EAI), and the *Diesel Knocking Index* (DKI), all developed to evaluate and quantitatively describe the impulsiveness of the periodic combustion in the diesel engine that leads to this specific noise. These metrics developed for ICEVs are often insufficient for capturing the novel noise profiles and acoustic

characteristics of EVs. In our literature review, we identified a cluster of $N = 16$ research articles considering psychoacoustic metrics to investigate the subjective perception of EV-related acoustics (Münder & Carbon, 2022a). Psychoacoustic metrics can provide an objective reference point for human perception when properly validated, particularly for simpler impressions, such as which stimulus is perceived as louder. Nonetheless, just as the physical parameters, psychoacoustic metrics also demand a certain degree of expertise to be interpreted correctly and cannot further describe more complex percepts conveyed by the acoustics, such as qualitative or semantic impressions.

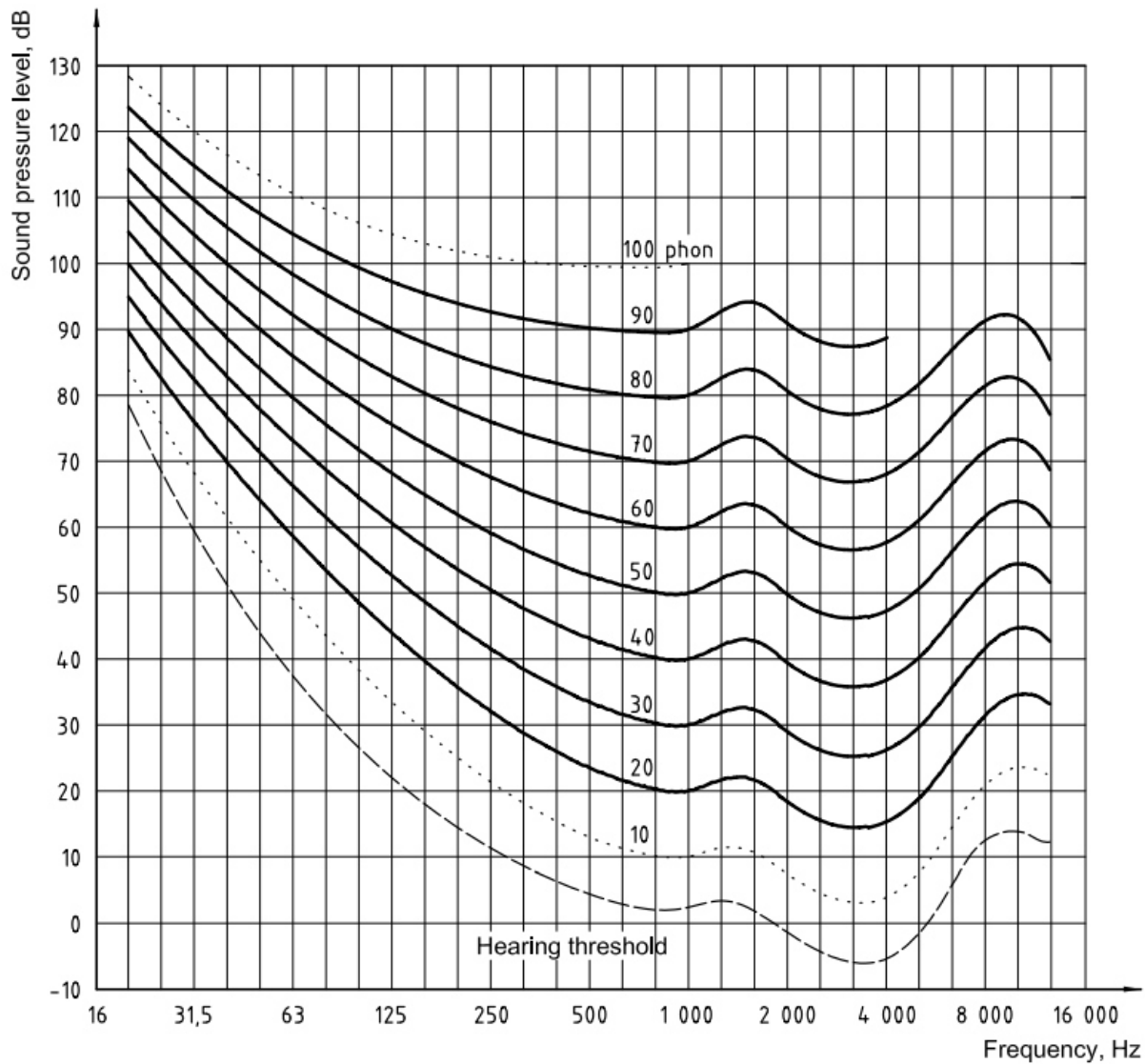
1.3.2 Auditory Perception

Before defining what it means to perceive a sound, one needs to determine what sound is. Depending on one's discipline, the definition of what sound is might vary substantially, as this thought experiment by Goldstein (2010, p. 261) clarifies: "*If a tree falls in the forest and no one is there to hear it, would it be a sound?*". According to a *physical definition* of sound as a pressure change in the air (or another medium), one would affirm the question above, whereas using the *perceptual definition* of sound as the experience of hearing something would lead to a negation of the question (Goldstein, 2010). Without diving further into philosophical discussions, this thought experiment helps one become aware of the differentiation between the physical and perceptual domains and why it is crucial when discussing matters of acoustics. Human evaluative behavior is not solely guided by the physics of acoustic signals but rather by their transduced meaning (Blauert, 2005). While the physical properties of sound should not be neglected, my research primarily focuses on the perceptual definition of sound and the resulting experience from a conscious *percept*.

As the basis of human auditory perception, the individual's hearing ability is an important point to consider. The sensory input in the form of physical sound is the basis for the subsequent physiological, perceptual, and cognitive processes. The transduction of physical sound energy into physiological signals, broken down and encoded on the level of the auditory nerve, is a necessary pre-condition for further perceptual steps when processing this information within the auditory cortex (Hermann et al., 2011). On the lower end, the frequency of 16 to 20 Hz defines the human hearing threshold (Bendixen & Schröger, 2017; Genuit & Sottek, 2010; Schönhammer, 2013; Sinambari & Sentpali, 2020), where the general human hearing ability begins. Our hearing ability reaches a frequency range of up to 16 kHz (Genuit & Sottek, 2010; Zeller, 2018) or even up to 20 kHz, depending on individual factors such as age, with the audible range decreasing at the upper end (Bendixen & Schröger, 2017; Sinambari & Sentpali, 2020). The audible range is limited by the infrasonic range to frequencies lower than the human hearing threshold and the ultrasonic range beyond higher frequencies than 16 kHz (Schönhammer, 2013; Sinambari & Sentpali, 2020; Zeller, 2018). So-called isophone curves or equal loudness contours – defined by the International Organization for Standardization within the ISO

226:2023 (2023) – describe the relation between the frequency and amplitude of a sound (Schönhammer, 2013). These isophone curves indicate the required sound pressure level (SPL; measured in *dB*) of different frequencies (measured in *Hz*) to convey the same loudness impression (measured in *phon*; Genuit & Sottek, 2010). **Figure 3** exemplifies the norm curves in the version of the ISO 226:2003.

Figure 3



Note. Normal equal-loudness-level contours for pure tones under free-field listening conditions according to the International Organization for Standardization as defined in the ISO 226:2003 (2003).

The norm curves further indicate the sensitivity for specific frequency bands of the human hearing apparatus – meaning a comparably low SPL is needed for an acoustic stimulus to become audible or perceived as specifically loud. The isophone curves indicate a generally lower sensitivity in the low-frequency range and an exceptionally high sensitivity in the ranges between 2 to 5 kHz (Genuit & Sottek, 2010; Schönhammer, 2013; Sinambari & Sentpali, 2020), with the highest sensitivity at

approximately 4 kHz (Zeller, 2018). Considering such general and individual factors, it is important to account for variations in different individuals' resulting perceptual evaluation data of the same acoustic stimulus. In the context of vehicle acoustics, these general sensitivities play a crucial role as the low-frequency bands correspond to the ICEV-typical broadband noise, and the generally higher frequency range with its tonal properties corresponds to the characteristics of e-powertrain noise in EVs (Gavric, 2020).

In addition to these physiological factors, the influence of psychological effects is to be considered when assessing the perception of acoustic events and scenes, such as the interior soundscape of a vehicle. The perception of acoustics in the real world is a generally complex task. Nevertheless, not only can the auditory system extract relevant spectro-temporal information or determine the location of a sound from potentially competing signals, but it can also disentangle this complex, combined stream of sensory input (Hermann et al., 2011). This disentanglement of combined and complex sensory streams is possible through auditory grouping and segregation mechanisms that selectively focus on one stream or another (Bregman, 1994). Therefore, the fundamental concept of perception can be described as a conscious sensory experience (Goldstein, 2010) or interpreting and organizing sensory input to produce a meaningful experience of the world, including oneself (De Ridder et al., 2011). From this conscious *percept*, subsequent processes such as recognition or action can be induced, depending on the perceiver's knowledge about the situation (Goldstein, 2010). This knowledge can substantially influence our perception and illustrates the differentiation between two types of perceptual processes: when receptors receive sensory input and this information is transduced to neural processing, a perceptual bottom-up process is followed; when a person's knowledge (i.e., facts, memories, or expectations) is considered, the situation is processed top-down (Goldstein, 2010). These two processing types are not mutually exclusive but often work together in perception (Goldstein, 2010). Therefore, our experience of the physical world is influenced by cognitive and affective processes, as our perception is under constant construction by the alignment of personal predictions and conveyed impressions of given stimuli (Carbon, 2019b).

1.3.3 The Concept of Sound Quality in Vehicle Acoustics

The term *sound quality* is often discussed in the context of vehicle acoustics and customer satisfaction. Within the field of acoustic research and automotive acoustics, one can find manifold definitions for it. For example, different definitions emphasize elements such as the sound's adequacy (Blauert & Jekosch, 1997) or its suitability (Guski, 1997). Genuit (1996) suggests a multi-dimensional approach to define the concept of acoustic quality, composed of physical, psychoacoustical, and psychological factors. The latter include cognitive, affective, and situational aspects (Nykänen, 2008; Zeitler, 2007). While physical characteristics and metrics are relatively easy to analyze, subjective dimensions are

much harder to assess (Genuit et al., 2010). However, they are of the highest interest regarding customer-oriented NVH development as they are immediately perceivable for the driver. The basic physical attributes of an acoustic event define the general sound character according to Fiebig (2012) and can be determined in a laboratory. From this general sound character, he distinguishes sound quality, which represents a perceptual construct influenced by product meaning, interaction, context, and cognition (Fiebig, 2012). Especially during cognitive processes, the adequacy of a sound to its context is vital (Fiebig & Schulte-Fortkamp, 2019). This multitude of definitions for the construct of sound quality illustrates that physical phenomena, such as the acoustic events and their properties, should be differentiated from perceptual constructs, such as the perceived quality of sound. Stylidis et al. (2015) show that the terminology of perceived quality is deficient in a common understanding and is used as a broad rather than a distinct term within the industry and research. However, I prefer using the term *perceived quality* within my research (e.g., Münder et al., 2024; Münder & Carbon, 2022b), as the *percept* of a product – defined by physical properties and sensory input – only emerges through a human perceiver (Carbon, 2019b).

Furthermore, multimodal aspects potentially influence the overall *percept* of a product experience (Carbon, 2019b). In the context of vehicle sound design, Sottek et al. (2005) highlight the importance of multimodal perception, as acoustics are not only linked to hearing but also vibrational and visual impressions. Considering multi-sensory integration of the different sensory processing channels can enrich the product experience (Carbon, 2019b) or improve safety and usability (Schifferstein & Spence, 2008). With the need to understand a customer's perception of overall product quality and to provide a method to quantify subjective evaluations, Stylidis et al. (2015) established a multi-dimensional model of overall perceived quality in the automotive industry. It describes perceived quality in the automotive industry with a dualistic approach connecting the *Value-Based Quality* (VPQ) and the *Technical-Based Quality* (TPQ). The TPQ consists of different perceived qualities, each originating in different modality domains – such as the visual, acoustic, haptic, and olfactory domains – with which the customer perceives the product (Stylidis et al., 2015). The VPQ embodies the total customer experience of product attributes, incorporating the subsets of the TPQ as well as external factors, such as context, brand identity, and customer behavior (Stylidis et al., 2015). As perceived quality is strongly related to the concept of coherence – and therefore the Gestalt (Carbon, 2019b) – it is important to follow integrative approaches when assessing matters of perceived quality.

1.3.4 The Holistic Gestalt and a Psychological Turn on the Perception of Vehicle Acoustics

Following a holistic research approach, the axioms of *Gestalt psychology*, which have a long research tradition, come into play. Depending on the different research schools within the discipline, the experience of the whole is different from the sum of its parts or more than the sum of its parts

(Wagemans et al., 2012, p. 86). This holistic principle plays a key role when evaluating the perception of EVs' interior acoustics. When exposed to such a complex acoustic scene, an individual builds an overall *percept* of the given sensory input. As design represents a holistic entity, only considering its singular parts would kill its Gestalt (Carbon, 2019b) and neglect the inherent complexity of an individual's perception.

When driving a vehicle, various noise sources converge in the driver's cabin, contributing to an interior soundscape. The term *soundscape* is defined in the ISO 12913-1:2014(en) by the International Organization for Standardization (2014) as an "acoustic environment as perceived or experienced and/or understood by a person or people in context". This definition not only focuses on the individual percipient but also emphasizes the complexity of experiencing acoustics. Hence, the interior soundscape of a vehicle can be described as a composition of perceivable disturbing and operational noise, accompanying environmental noise from the surroundings, and actively applied sound enhancement to shape its acoustic character. Additionally, as my research focuses on the driving noise of EVs, the interior vehicle soundscape encompasses transient, non-stationary acoustic scenes rather than impulsive acoustic events of singular nature (e.g., closing the car door or actuating the turn signal lever). Rather than evaluating each of the emerging noise sources and NVH characteristics in an isolated form, it is important to consider the overall composition of the interior soundscape, as each characteristic influences how the acoustic Gestalt of an EV is perceived. Even though vehicle acoustics become increasingly important within vehicle development (Sinambari & Sentpali, 2020), it is important to emphasize that the overall acoustic Gestalt is, again, just a part of the sum of the overall product and sensory input from other domains that contribute to the overall impression as well. This multisensory input we receive through various perceptual domains must be processed. By multisensory integration (Stein & Meredith, 1993), a holistic product experience can be provided (Schifferstein & Spence, 2008), which can then enhance the aesthetic experience as well as foster intuitive product handling (Carbon, 2019b).

Moreover, I would like to elucidate the individual percipient. This thesis aims to investigate the customer perception of the acoustic characteristics in EVs. Therefore, the individual of interest is the customer, who consumes and uses a product (i.e., driving an EV) by employing programs that are deeply rooted in evolution and culturally shaped (Carbon, 2019b). Understanding human perception should be the basis in the quest for an EV driving sound that pleases the customers. Even though physical properties might determine the design, it is our individual construct of how we perceive these objective specifications. What is thought to be the objective reality, defined by physical properties, as a matter of fact is the individual perceived reality (Gregory, 1970). Perception is an active process shaped by general psychological mechanisms and individual psychological factors, such as expectations

and prior knowledge, and represents a person's unique, subjective reality, which simultaneously serves as their only tangible experience of reality (Carbon, 2015b). Examples of such individual factors potentially influencing our perception of (vehicle) acoustics are the individual frame of reference based on former experiences (Genuit & Fiebig, 2014) and our cultural background (Fastl, 2002; Kuwano et al., 1999; Sottek et al., 2005). Therefore, psychological factors must be considered when evaluating product design matters, or, as Carbon (2019b, p. 3) puts it, "the object is dead, long live the subject".

Another fundamental psychological paradigm that can modulate our perception goes back to the work of Gustav Theodor Fechner and his article *The Aesthetic Association Principle* (1866), which was translated to English by Ortlieb et al. (2020). By ordinary examples, Fechner demonstrates how the aesthetic preference is strongly influenced by associative factors, such as the individual learning history, and that direct factors, such as the object properties, play a secondary role (Ortlieb et al., 2020). An object conveys a specific impression, which is then combined with an overall *percept* shaped by its recipient's associations (Ortlieb et al., 2020). Within this thesis, this *object* is represented by an EV's interior soundscape. Building analogies based on associations can help understand and transfer successful designs from familiar products to novel products (Carbon, 2019b). For instance, the qualitative feedback from Mnder and Carbon's (2022b) sample reveals analogies in which e-powertrain noise is compared to "turbines" (p. 8) or public transportation trains ("S-Bahn", "Tram"; both p. 8), which are associated with relatively low perceived acoustic quality. Though Fechner's article primarily focuses on the visual domain, its key findings also apply to other modalities (Ortlieb et al., 2020). Thus, associative factors can also guide and create impressions in the acoustic domain. For example, subtle acoustic information can influence the affective response to a given context and shape how and what we experience and perceive (Fiebig et al., 2020).

Another important factor is the consideration of the stated psychological factors within the evaluation of human perception of e-powertrain noise and EV sound design. Assessing subjective evaluations of complex perceptual constructs – such as perceived sound quality within this thesis – demands an externally valid context (Fiebig & Schulte-Fortkamp, 2019; Guski & Blauert, 2009). Only in this way, externally valid insights on target sound designs can be derived. Without context, which includes both the physical properties of the surrounding environment and psychological representations, the meaning of a design is resolved, as there is no such thing as an absolute good design (Carbon, 2019b). Within automotive acoustics for EVs, this could be exemplified by highly refined e-powertrain noise providing a nearly silent driving experience, which would be adequate and desirable for a luxury car from the premium segment but disappointing when expecting a vigorous supercar. While the preference for one or the other acoustic profile or sound design might be highly interindividual (e.g., Maunder & Munday, 2017; Mnder et al., 2024, 2025; Mnder & Carbon, 2022b; Valeri & Pietila, 2020;

Wagner et al., 2017), some expectations can also be generalized regarding different contexts. In both Mnder and Carbon (2022b) and Mnder et al. (2024), for example, participants reported accepting louder acoustic feedback depending on the acceleration scenario: a higher sound pressure level during full acceleration was not only accepted but also expected, as this condition represents the retrieval of the vehicle's ultimate performance. It is vital to provide as many contextual cues to the questioned sample within an experiment as possible, as otherwise, as demonstrated in the visual and tactile domain by Jakesch et al. (2011), the resulting evaluations might miss the point or even be contradictory. Some methods to assess the subjective sound evaluations within automobiles already incorporate contextual and associative factors, such as the *Associated Imaginations on Sound Perception* (AISP) as applied by Schulte-Fortkamp and Genuit (2005) and the *Explorative Vehicle Evaluation* (EVE) method by Schulte-Fortkamp et al. (2007). These methods represent so-called *Path #1* approaches as they test within ecologically valid contexts (Carbon, 2019a). While such approaches offer low empirical control, following a so-called *Path #2* testing approach enables sufficient accounting for context variables and their influence while maintaining experimental control within a lab-oriented setup (Carbon, 2019a).

Furthermore, time-dependent contextual variables should be considered. Especially by the electrification of automotive vehicles, the acoustic Gestalt of driving sound as we know it from the so far prevailing ICEV noise will be fundamentally changed, resulting in novel kinds of interior soundscapes. Factors such as Zeitgeist, technological progress, and societal changes shape not only the physical design properties but also our mental concept of what we perceive as pleasurable, suitable, and adequate design (Carbon, 2019b). When evaluating dynamic perceptual concepts such as preference, aesthetic appreciation, or innovation, such factors must be considered in experimental designs aiming to identify sustainable designs for the future. Methodological approaches with continuous testing, such as the *Continuous Evaluation Procedure* (CEP; Muth et al., 2015), achieve a higher timely resolution of the evaluations, while repetitive testing, such as the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005) achieves a higher degree of familiarization with the presented material and can therefore reveal dynamic effects.

Genuit (2010) states that the main challenge lies in determining target sounds within the context of alternative drive concepts, which requires integrating interdisciplinary methods and multi-dimensional approaches. This dissertation represents a psychological turn, as described by Carbon (2019b), on developing interior soundscapes in electrified vehicles. With the discipline of psychology as the basis for achieving customer-oriented, sound designs and acoustic profiles, the resulting evidence of my research is intended to facilitate the applied field. In the following chapters, my publications that contribute to this doctoral thesis are incorporated.

2 An Overview: State of Research on Perception of Interior Soundscapes in Electrified Vehicles

The following chapter includes our published literature review *Manuscript #1* (Münder & Carbon, 2022a), which provides a great intro to the field of research on the perception of interior soundscapes in EVs. The manuscript, published in *Frontiers in Mechanical Engineering*, is embedded in its original form and full length in section **2.2. A literature review [2000 – 2022] on vehicle acoustics: Investigations on perceptual parameters of interior soundscapes in electrified vehicles.**

2.1 Introduction to the Literature Review

The motivation for this paper was to summarize the current state of research by subsuming more than two decades of research from the 21st century (years 2000 – 2022) that investigated perceptual parameters of interior soundscapes in electrified vehicles. In Münder and Carbon (2022a), we point out achievements already accomplished, which can serve researchers as a starting point for further investigations. Furthermore, we identify and discuss areas in the field that should be given more attention in future research. Although technical papers are essential for the precise refinement of specific NVH characteristics, our literature review does not elaborate on such contributions. However, it particularly considers perception-related metrics and publications on participant studies related to EV interior noise perception. The total of $N = 53$ retrieved articles are briefly summarized and thematically categorized into specific focus areas: *Cluster A: psychoacoustic metrics* ($n = 16$), *Cluster B: computational prediction models* ($n = 11$), and *Cluster C: subjective assessment and experimental studies* ($n = 26$; Münder & Carbon, 2022a).

2.2 A Literature Review [2000 – 2022] on Vehicle Acoustics: Investigations on Perceptual Parameters of Interior Soundscapes in Electrified Vehicles



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A literature review [2000–2022] on vehicle acoustics: Investigations on perceptual parameters of interior soundscapes in electrified vehicles

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The interior soundscape of a vehicle is an essential asset for experienced comfort and feedback of a car's driver, especially in the premium automotive industry. Here we offer a literature review on the perception of acoustic characteristics of electrified vehicles (EVs) and the impressions and associations they convey to the individual—the driver, the customer, the user. The reduction of the overall sound pressure level (SPL) in EVs offers the opportunity to create exceptional quiet interior soundscapes. At the same time, the reduced SPL challenges NVH (Noise, Vibration, and Harshness) engineers to reduce remaining noises that are no longer masked by operational combustion while creating vehicle-adequate acoustics with pleasingly comfort-assets and operational feedback of the current driving mode. The analyzed body of literature covers research from the 21st century (2000–2022). We aim to comprise the current state of research highlighting specific achievements already made. Furthermore, we show evident gaps that need to be filled and considered in future research.

KEYWORDS

psychoacoustics, NVH, perception, electrified vehicle sound, electric powertrain noise, automotive, sound quality

Introduction

Concomitant with the technological shift to electrified powertrains is a change in the acoustic profile of vehicles which offers new opportunities but also brings new challenges to engineers in the automotive industries (Cerrato, 2009; Genuit, 2010; Meek et al., 2012; Allman-Ward et al., 2020; Gavric, 2020). Among these opportunities are novel configurations of active driving sound for electrified vehicles (EVs) (Bodden & Belschner, 2016; Cerrato, 2009; Fiebig, 2012; Genuit & Fiebig, 2011, 2014) or even the

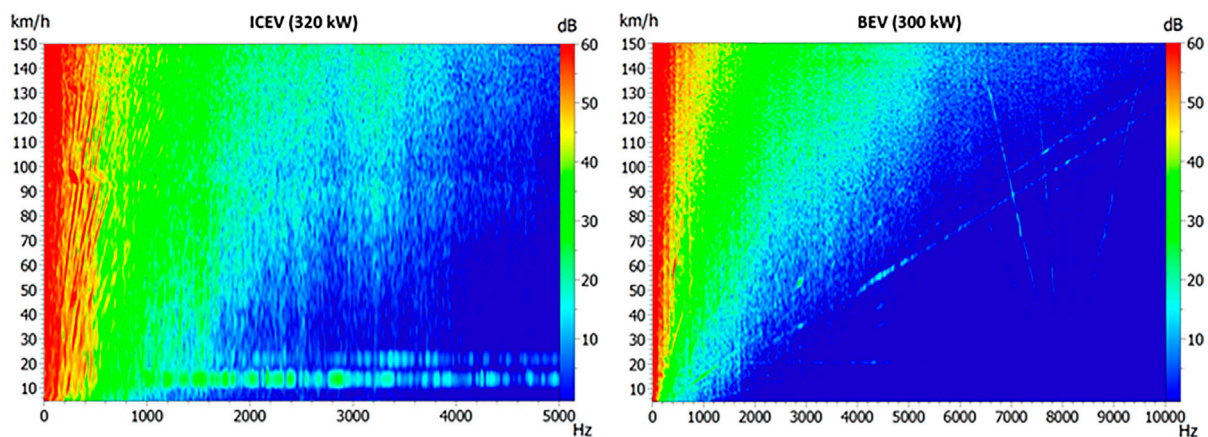


FIGURE 1

Comparison of ICEV and BEV in full acceleration run-up.

Note. Campbell diagrams of an ICEV (320 kW; left side) and a BEV (300 kW; right side) in full acceleration run-up. Please note the different scaling of the x-axes in the diagrams as the frequency ranges depend on the type of powertrain system. The zigzag pattern in the lower frequencies of the ICEV spectrum is caused by gear shifting. These gear shifts are omitted with the electrified system.

innovative shaping of our acoustic environment (Clendinning, 2018). Acoustic characteristics of vehicles are commonly subsumed under the umbrella term NVH (Noise, Vibration, and Harshness), and they are well known to play a crucial role in customer satisfaction (Qatu et al., 2009; Qatu, 2012; Zeller, 2018; Sinambari & Sentpali, 2020). For instance, the sensation of driving in all-electric mode can be described as *quiet*, *smooth*, and *silent* (Kurani et al., 2008) and Gärling (2001) found 80% of their sample reporting experiencing the same amount or even more pleasure driving an EV compared to driving an ICEV (Internal combustion engine vehicle), which was reportedly defined, among other things, by comfort and noiselessness. On the contrary, the analysis of social media and online forums by Krishna (2021) shows that consumers experience cars and their NVH characteristics as “soulful” (p. 5) entities, that they build emotional connections with their vehicles, especially through its sound, which was one of the most significant aspects in the analyzed data. Especially so-called *petrolheads* – a group of passionate car enthusiasts – seem to apprehend electrified driving as “sterile” (p. 5) and a “lackluster ‘appliance-like’ experience” (p. 6) (Krishna, 2021). As the demand for overall ride comfort, a property subjectively experienced through physical variables, increased over the years, the NVH attributes of ambient factors such as noise and dynamic factors such as vibrations play a crucial role in vehicle safety, performance, comfort, and brand image (Ormuz & Muftic, 2004). In terms of EV-NVH three main challenges are the frequently reported: 1) the EV’s silent nature leads to a lack of masking effects and new disturbing noise sources while impairing the dynamic character of the vehicle as they fall short of the accustomed operational feedback; 2) the novel

NVH profile is still relatively unfamiliar to most people and especially high-frequent noise components might be perceived as very annoying; 3) the question of a suitable sound character for EVs, which Otto et al. (1999) described as “a double edged sword” (p.3), since the quietness of an EV can be seen as an unique selling point or vice versa pose the question about the suitable sound character in terms of applying active sound design to emphasize the exquisite vehicle dynamics of EVs (Otto et al., 1999; Cerrato, 2009; Genuit & Fiebig, 2011, 2014; Meek et al., 2012; Allman-Ward et al., 2014; Bodden & Belschner, 2014, 2016; Fiebig & Schulte-Fortkamp, 2019; Allman-Ward et al., 2020; Gavric, 2020; Kleinjohann, 2020; Streicher et al., 2021). Figure 1 compares an ICEV and a BEV (Battery Electric Vehicle) in full acceleration run-up, showing the main differences between conventional and electrified vehicles in their frequency spectra, overall sound pressure level (SPL), engine orders, and operation smoothness.

The EVs’ acoustic characteristics of e-powertrain and applied sound design compose a so-called soundscape, defined by the International Organization for Standardization as the “acoustic environment as perceived or experienced and/or understood by a person or people, in context” (International Organization of Standardization, 2014). Despite the frequently reported and apparent challenges, a considerably smaller amount of research focuses on the interior acoustic experience of electrified driving than on exterior sonification and pedestrian safety in EVs (Melman et al., 2021). Therefore, the focus of this contribution will be on how people perceive the interior soundscape while driving an EV and evaluate the current state of research in this field of acoustic vehicle development and design. A short theoretical introduction of essential changes in

the NVH profiles of EVs and cognitive concepts of perception and aesthetics is followed by an overview of the reviewed literature presented in this paper. We thematically divided the reviewed literature into three different segments: 1) literature discussing objectified measures of human perception in the context of EV-NVH; 2) combining perception-related data with approaches of computational sciences to predict the acoustic quality of EVs; 3) research evaluating human perception of different NVH characteristics of EVs *via* the assessment through participant samples.

Theoretical background

In this section, we provide a brief overview of the changes in the acoustic profile of EVs compared to conventional ICEVs. Furthermore, basic psychological concepts of perception and design, as well as frequently used constructs for customer perception in the field of acoustic engineering and vehicle acoustics, will be apprehended.

Acoustical profile of electrified vehicles

The electrified powertrain concepts lead to a substantially lower SPL (Blickensdorff et al., 2019), allowing hitherto unnoticed disturbing noises from sources such as the external environment, wind, tires, driving-related operation of auxiliaries and power electronics, which so far have been masked by the louder combustion engine, to become apparent (Allman-Ward et al., 2014; Blickensdorff et al., 2019; Eisele et al., 2019; Gavric, 2020). Bodden and Belschner (2014) even describe a spectral gap between the now unmasked high-frequency wind noise and low-frequency road noise leading to an inharmonic noise-background.

However, not only the reduced SPL and thereby unmasked disturbing noises require challenging NVH refinement, but substantial changes in the characteristics of the EVs' NVH profiles themselves also lead to novel challenges in the developmental process of acoustic comfort. The overall SPL seems to be a less critical indicator of sound quality than psychoacoustic parameters (Genuit & Fiebig, 2011), which aim to describe the relationship between physically defined acoustic events and their perceptual dimension in an objective and quantitative manner (Fastl, 2002). As the spectrum of typical e-powertrain noise is characterized by higher frequencies and single tonal components in spectral ranges from 1 – 10 kHz, where human hearing is especially sensitive (Blickensdorff et al., 2019; Gavric, 2020), it is potentially perceived as more annoying and less appealing to customers as psychoacoustic analyses show (Lennström et al., 2013; Lennström & Nykänen, 2015; Swart et al., 2016). Moreover, there is a vital discourse about the quiet nature of EVs and opportunities of possible sound enhancement

strategies in the field (Genuit & Fiebig, 2014; Clendinning, 2018). For instance, some criticize the EV's interior for suffering from a lack of operational feedback (Kleinjohann, 2020) or that its quiet nature might even lead to insecurities about whether the vehicle is ready to use (Knowles et al., 2012). Bodden and Belschner (2014) note that the little operational feedback stands in no proportion to the pronounced dynamic acceleration of EVs. Whereas ICE-typical broadband noise is dominated by its engine orders and harmonics in a frequency range below 1 kHz (Blickensdorff et al., 2019), Swart et al. (2016) found local SPL-minima in the range from 200 to 500 Hz, low roughness values and a lack of prominent orders for commercial EVs, from which they derive the unimpressive and lackluster sound character of natural EV acoustics. With the inherent NVH characteristics only contributing very little to the EV's interior sound quality, Allman-Ward et al. (2014) see it as a requirement for manufacturers to enhance their products through synthetic sound applications if they seek to improve interior sound quality. Through the application of artificial sound design, it is not only possible to re-establish operational driving feedback or to mask disturbing noises in the interior, but also to create a customizable, emotionalizing driving experience (Allman-Ward et al., 2014; Bodden & Belschner, 2016; Streicher et al., 2021). Furthermore, enhancing EVs with artificial sound can help to express specific vehicle characteristics such as brand identity (Sottek et al., 2005; Allman-Ward et al., 2014; Bodden & Belschner, 2016; Kleinjohann, 2020) as well as to sharpen the product's character through distinguishing features for specific vehicle types and segments (Allman-Ward et al., 2020; Streicher et al., 2021). Nevertheless, a clear recommendation for development strategies and conceptual orientation regarding EV sound design cannot yet be concluded, and different directions are conceivable. Altogether, there is a target conflict between the generally preferred quietness in electrically driven vehicles and the demand for an adequate operational feedback (Fiebig & Schulte-Fortkamp, 2019). A rather conservative approach would be to draw analogies to existing experiences with ICE-typical sound and to reference traditional expectations (Bodden & Belschner, 2016). Other strategies like focusing on the perseverance of authentic e-powertrain NVH characteristics and possibly refining it, or creating completely novel yet suitable sound concepts (Genuit, 2012; Genuit & Fiebig, 2014) need to be considered. Kleinjohann (2020) sums up current examples of manufacturers like Volkswagen or BMW, who both cooperate with established composers and music producers to create novel sound concepts for EVs. Cerrato (2009) even presumes a transition phase from less innovative sound concepts, referencing familiar and relatable sounds of the combustion engine, to increasingly innovative concepts daring novel approaches such as, for example, sci-fi analogies. As the association between acoustic feedback of a vehicle and its power and performance parameters have been built over decades,

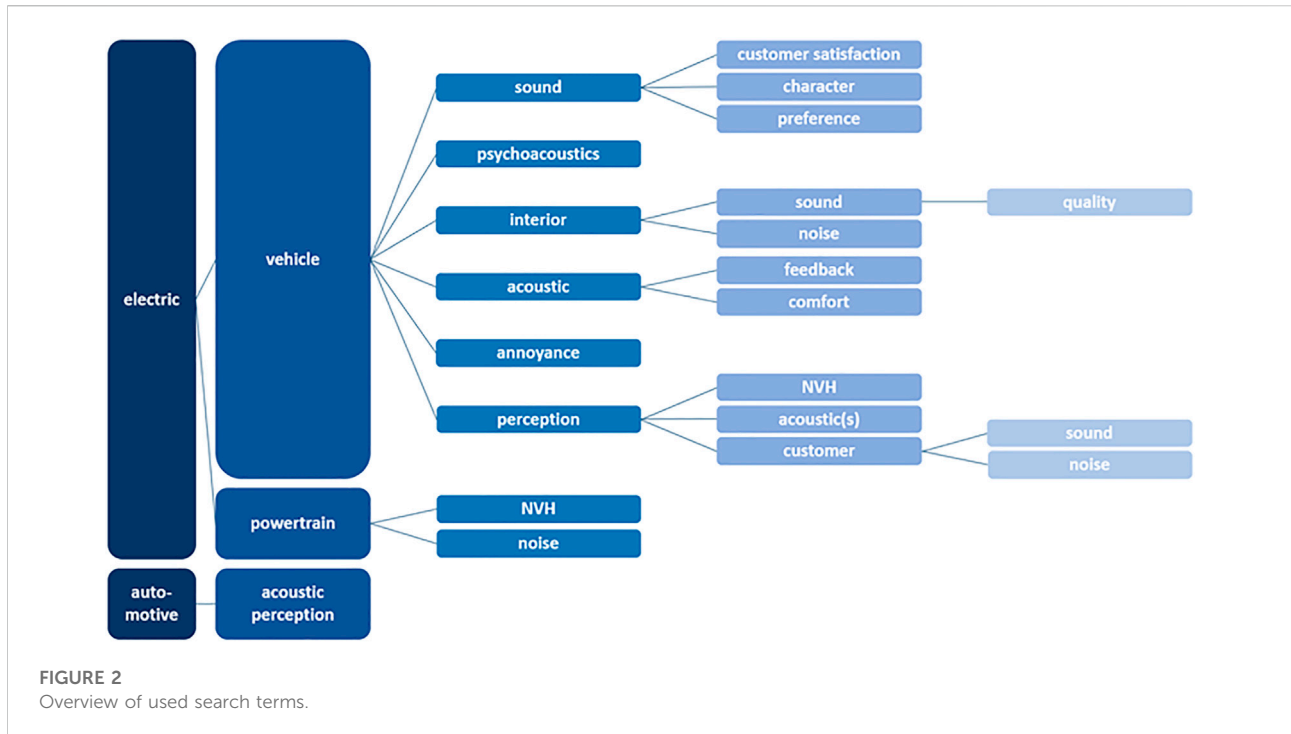
resolving such association patterns will become difficult (Cerrato, 2009; Clendinning, 2018; Genuit & Fiebig, 2011, 2014). However, conservative approaches should be questioned, as the conventional ICEV-soundscape is hard to be naturally transferred onto EVs after all. Distinctive and innovative sound design approaches for EVs now pose the chance to set a novel frame of reference and build new connections between electric power sources and innovative soundscapes.

Subjective perception: cognitive factors and psychological effects

“Subjective” perception (in fact, perception as such, because perception is always a reality-constructing active cognitive act) is a crucial factor in market-relevant features such as comfort or product quality impression overall (Carbon, 2019). The present review focuses on the interior soundscape while driving an EV as it impacts a vehicle’s overall quality impression (Münder & Carbon, 2022). Though subjective dimensions are much harder to assess than physical or technical metrics (Genuit et al., 2010), especially the cognitive processes in subjective evaluation make such approaches even more interesting in terms of customer-oriented NVH development for EVs. NVH characteristics are immediately perceivable qualia shaping a customer’s product experience and therefore contribute to the overall customer satisfaction (Qatu, 2012; Zeller, 2018; Sinambari & Sentpali, 2020) as well as determine target agreements in product development (Blauert, 1986). In acoustic perceptual science, mere physical phenomena – acoustic events – are to be differentiated from perceptual constructs – the perceived quality of sound. Though perceptual constructs are related to specific physical phenomena and sensory information, they only emerge through human perception defined by the International Organization of Standardization (2014). The construct of the sound quality of an acoustic event is defined in manifold ways, such as its adequacy (Blauert & Jekosch, 1997) or suitability (Guski, 1997) of it, or even multi-dimensional definitions such as the suggestion by Genuit (1996) of three influential aspects, namely physical, psychoacoustical and psychological, with the latter including cognitive, affective, and situational factors (Blauert, 1986; Sottek et al., 2005; Zeitler, 2007). Styliadis et al. (2015) established a multi-dimensional model of overall perceived quality with a value-based perceived quality describing the total experience of a customer through its multimodal components and technical perceived qualities, each originating in the visual, acoustic, haptic, and olfactory domains of the assessed product. By accounting for further factors like context, customer behavior, and brand identity, the need to achieve high perceived quality for the given product can be identified (Styliadis et al., 2015). Also, Sottek et al. (2005) highlight the importance of including multimodal perception as the perception of sound is not limited to only

hearing but also linked to vibration or visual perception. These aspects potentially influence the complex interplay of the overall customer experience. Fiebig (2012) distinguishes the general sound character from sound quality: the former is defined by the basic and physical attribute of the acoustic event and determinable in laboratory environments, whereas the latter is to be understood as a complex perceptual construct dependent on its context, product meaning, interaction, and cognition, where especially the sound’s adequacy to its context plays a key role (Fiebig & Schulte-Fortkamp, 2019). Thus, the subjective evaluation of perceptual constructs like sound quality and target sound design must be tested in externally valid context conditions (Genuit, 2010; Fiebig, 2012; Fiebig & Schulte-Fortkamp, 2019).

The mere number of versatile definitions of sound quality illustrates that subjective perception of acoustic events or soundscapes cannot be solely based on their nature. An auditory evaluation leads to an individual impression, strongly influenced by associative principles. For aesthetic theory, this central cognitive principle originates in the Aesthetic Association Principle (AAP) by Fechner (Ortlieb et al., 2020): an object transmits a specific impression by sensation and is then merged into a coherent percept with the individual’s former experiences. Thereby the principle is capable of guiding and creating certain associations in the acoustic domain (Ortlieb et al., 2020) and can be utilized in NVH development and EV sound design. For instance, Fiebig et al. (2020) show that even subtle acoustic information can influence the affective response to a contextual soundscape. Methods for subjective sound evaluation such as the Associated Imaginations on Sound Perceptions method (AISP) (Krebbler et al., 2000), aiming to assess the affective reactions to vehicle interior noise, or the Explorative Vehicle Evaluation (EVE) method (Fiebig & Schulte-Fortkamp, 2019), a practical approach to evaluate a sound concept of a vehicle in its original on-road context, make use of the association principle. Other standard methods to evaluate vehicle sounds and sound quality are, among other things, ranking methods to determine sound preferences, semantic differentials to assess the meaning and suitability of a sound, category scaling, and magnitude estimation to evaluate differences in sound quality (Fastl, 2002). Factors such as cultural background (Fastl, 2002; Sottek et al., 2005) or the individual frame of reference, based on previous experiences (Genuit & Fiebig, 2014), should be considered as they might alternate the associated meaning of a sound. Thus, customer expectations are shaped through previous individual experiences with a product. Sound enhancement can potentially amplify the overall customer driving experience but, at the same time, requires a deepened understanding of what customers actually expect an EV to sound like (Allman-Ward et al., 2020). These expectations are still quite difficult to identify due to scarce internalized experience driving electrified and customers having difficulties in articulating their preferences as they lack



reference points (Genuit, 2012; Genuit & Fiebig, 2014). Fiebig and Schulte-Fortkamp (2019) emphasize that the challenge lies in the evaluation of finding out how the majority assesses sound quality of EVs without any existing frame of reference while accounting for contextual variables of the specific acoustic event.

Methods

We reviewed the pertinent literature according to the following structure: the focal point of the review is research concerned with investigations on the human perception of EV interior soundscape, which results from acoustic NVH phenomena and active vehicle sound design. Investigations with participants and perception-related metrics were of our particular interest. Mere technical papers are of the highest importance for the vehicle's NVH refinement but will not be elaborated on in this review. We included only automotive NVH-related literature published in the years 2000–2022 (effective 28th of February 2022). The used search terms for this contribution are depicted in Figure 2.

In total, we retrieved more than 200 articles from the period between 2000 and 2022 (effective 28th February 2022) that possibly dealt with the acoustic characteristics of EVs and/or their perception. After a thorough review of the articles, we excluded some articles from our list as they did not meet our criteria for investigating the human perception or perception-related metrics of EVs' interior soundscapes and acoustics.

Indicators to exclude articles were, for example, not dealing with the acoustic phenomena in an automotive or EV-specific context, not focusing on the subjective perception of these acoustic criteria, or dealing with the exterior noise and sound of EVs. This left us with 53 articles discussing the intended subject. We subdivided the final list of scientific work into different thematic clusters, which will be introduced in *Results of the research analysis*. At last, we would like to emphasize that this work provides an overview but is not necessarily an exhaustive representation of the interdisciplinary field of research.

Results of the research analysis

We clustered the pertinent literature found with our search focus in three different main categories: A) studies focusing on psychoacoustic measures, which aim to provide an objective measure of subjective human acoustic perception (*Cluster A: psychoacoustic metrics; N = 16*); B) research from the field of computational sciences using subjective and/or objective data to form perception models (*Cluster B: computational prediction models; N = 11*); C) investigations with qualitative assessments and/or experimental study designs following a human-centered approach collecting subjective evaluation data from participants (*Cluster C: subjective assessment and experimental studies; N = 26*).

Cluster A: psychoacoustic metrics

Psychoacoustic metrics are objective and quantifiable parameters developed to describe the relationship between subjective perception and physically defined acoustic events (Fastl, 2002) (see also [Acoustical profile of electrified vehicles](#)). The following section sums up current research on the perception of EV interior soundscape considering such psychoacoustic metrics. We identified two general groups of investigations: articles analyzing EV measurement data and taking objective psychoacoustic measures as sole indicators for subjective perception. On the other side, studies comparing these objective metrics with conducted subjective perception data from participants.

First, we like to look at the research investigating objective psychoacoustic parameters as sole measures for acoustic perception. Fang and Zhang (2014) analyzed the psychoacoustic parameters of loudness and sharpness in e-powertrain noise measurements from a test bench. Though the loudness increased with speed rise and sharpness was found to be unevenly distributed, they concluded the e-powertrain noise to be comfortable in terms of subjective perception (Fang & Zhang, 2014). Sarrazin et al. (2014) also investigated e-powertrain noise, specifically a 12/8 switched reluctance motor (SR), and evaluated parameters such as loudness, tonality, sharpness, and prominence ratio. Main findings show that the torque level had a rather big effect on tonality, loudness, but a smaller effect on sharpness, while the prominence ratio can serve as a detection tool for the various stator mode shapes (Sarrazin et al., 2014). Devillers et al. (2020) investigated on often as unpleasant perceived switching noise caused by the EV's power electronics, also known as Pulse Width Modulation (PWM), which can vary in its switching frequency from 250 Hz to 20 kHz. In their analysis, they considered a couple of psychoacoustic parameters, which are assumed to cause unpleasantness in human perception. This potentially annoying nature of PWM is reflected in their findings of high prominence ratio and tonality values, as well as a strong roughness (Devillers et al., 2020). Moreover, they assume the lack of masking from wind and tire noise at lower driving speeds led to a predominance in the perception of switching noise. Due to its steady character, it lacks informational feedback about driving speed (Devillers et al., 2020). The main conclusion of Devillers et al. (2020) was that switching noise issues are worth considering in an early development stage as it can improve a vehicle's NVH profile while reducing costs. Le Besnerais et al. (2018) also calculated psychoacoustic metrics – in this case, loudness (ISO532B), sharpness, and roughness – for isolated PWM samples at 5 kHz, 6 kHz, 7 kHz, 8 kHz, 9 kHz, and 10 kHz. Data showed that the higher the switching frequency was, the lower values resulted for roughness and loudness, suggesting the switching frequency has an impact on human hearing, though Le Besnerais et al. (2018) suggested further jury tests to determine a threshold level referring to the subjective acceptance for these

metrics. Lennström and Nykänen (2015) specifically investigated the distribution of tonal components in EV noise and analyzed the number of prominent orders, their maximum levels, and frequency separation. Along these lines, they compared the tonality measures tone-to-noise ratio (TNR) and prominence ratio (PR). They recommend using TNR before PR when analyzing EV noise measurements with multiple closely related orders (Lennström & Nykänen, 2015). Stadtfeld (2021) investigated higher transmission input in electrified powertrains leading to pitch noise, generally higher frequencies and noise events even higher than the third mesh harmonic, which is beyond the audible threshold of human hearing. Stadtfeld (2021) cautions against the false conclusion that such frequencies are irrelevant to customer perception as conventional criteria such as frequencies below and above the third mesh harmonic or structure-borne frequencies still apply in further transmission stages of the EV. Specific configurational changes might therefore even facilitate changing previously annoying NVH characteristics to be perceived as a smoother, more unobtrusive noise (Stadtfeld, 2021). As former ICEV-related sound quality targets might not be applicable to the NVH criteria of EVs that are characterized with unusual narrow bands and a higher frequency spectrum, Mosquera-Sánchez et al. (2015) investigated on the complex interrelation between the psychoacoustic metrics of loudness, roughness and, sharpness as well as their cross effects. They concluded loudness as a single parameter to be insufficient and that further metrics need to be complemented to create a sound quality metric, which is suitable to analyze time-frequency patterns – for example, a loudness reduction may lead to an increase in roughness and sharpness – as well as to account for the metric's case dependency for the specific product (Mosquera-Sánchez et al., 2015). In another study, Mosquera-Sánchez et al. (2018) investigated the sound quality specifically of hybrid electric vehicles (HEVs). They provided a framework for sound quality enhancement based on the psychoacoustic metrics of loudness, roughness, sharpness, and tonality. After acoustic measurements from HEVs' passenger compartments were analyzed with the mentioned metrics, enhancement strategies were applied to actively control the sound quality and implement targets in real-time, and finally, the controlled sounds were again analyzed with the objective parameters to verify the applied measures (Mosquera-Sánchez et al., 2018). Qian et al. (2021) developed a sound quality synthesis model for EVs, which considers air- and structure-borne noise sources, as it is based on transfer path analysis (TPA) and transfer path synthesis (TPS). The synthesized and measured interior noise examples were compared in the psychoacoustic metrics of loudness, sharpness, and roughness. As the stimuli only differed by 7% in the analyses, Qian et al. (2021) concluded their model to reflect psychoacoustic physical characteristics of in-vehicle noise and the applied sound quality separation method to be an effective technique for sound design realization offering a

technical basis for the evaluation and development of EV acoustics.

The second group of investigations in this cluster sums up research that analyzed psychoacoustic metrics and compared it with subjective perception data conducted in participant studies. Sarrazin et al. (2012) developed a sound synthesis tool for hybrid and electric vehicles and validated it with data from $N = 29$ NVH experts by letting them compare the synthesized sounds to original recordings in a subjective listening test. Therein participants were asked about the equivalence of the stimuli by evaluating categories of difference and similarity (Sarrazin et al., 2012). Furthermore, they analyzed the objective sound quality and psychoacoustic metrics of Stevens VII loudness, loudness ISO532A and B, fluctuation strength, roughness, pitch, tone-to-noise ratio (TNR), prominence ratio (PR), and sharpness (Sarrazin et al., 2012). As most stimuli were rated as *identical*, *similar*, or *slightly different* in the jury test and good overlaps in the analysis of the objective parameters were found, Sarrazin et al. (2012) concluded their product-specific sound synthesis tool to yield satisfying results. Bassett et al. (2014) investigated the tonal noise of EVs across a wide frequency band, the noise level as well as TNR, Stevens VI loudness, as well as tonality. They compared these metrics to subjective ratings of annoyance and the overall level of high-frequency noise in eight sound stimuli. The highest correlation with the subjective perception data was found for Stevens VI loudness: it considers the loudness of each octave band. It combines these partial loudness shares instead of being dominated by broadband masking noise or the most prominent tone in the signal as in other metrics (Bassett et al., 2014). Moreover, Bassett et al. (2014) found the metrics of PR and TNR to be good indicators to differentiate between tones but do not seem to be good predictors of perceived annoyance, as they did not align with the subjective ratings in their study. Ma et al. (2019) searched for an optimization method for permanent magnet synchronous motors (PMSM) using sensitive critical band (SCB) analysis. As objective parameters, they considered loudness, articulation index, tonality, roughness, fluctuation strength, sharpness, and the A-weighted SPL, which were all different depending on load torque and rotational speed (Ma et al., 2019). In a consequential study for the subjective evaluation of the PMSM noise samples, they had $N = 22$ participants rate the annoyance on a scale from 1 to 20 (the higher the value, the more annoying), representing five levels of annoyance (Ma et al., 2019). Their results show that with the same load torque, the annoyance gradually increased with rotational speed, while at a constant speed, the annoyance rose with load torque. The maximum annoyance was found in the operating condition of 5,800 rpm/100 Nxm (Ma et al., 2019). Through their method, Ma et al. (2019) were able to apply critical band pass filters, which could then be conducive

to improving the sound quality of PMSM. Fang et al. (2015)¹, established an objective evaluation parameter termed sensitive frequency-band energy ratio (SFBER) that correlated highly (0.958) with the subjectively evaluated annoyance, indicating to be of a better fit than other psychoacoustic parameters. The study by Pietila et al. (2019) supports a frequency dependence in the perception of annoyance by tones in the context of EV noise. A frequency-dependent annoyance curve was developed since common psychoacoustic metrics for tonality, such as TNR, hearing model tonality, and PR, focus on the quantification of tonal levels and detect their audibility in the presence of masking but do not intend to represent a function for perceived tonal annoyance (Pietila et al., 2019). To gain a better understanding of customers' preferences in terms of EV tonality, $N = 10$ participants evaluated a total of eight EV drive-away sounds in moderate acceleration and significantly different frequency ranges in a paired comparison task (Pietila et al., 2019). The level of the stimuli got adjusted until perceived as equally annoying, whereby the built annoyance curve of Pietila et al. (2019) showed lower frequencies to be preferable and higher frequencies to be preferable the least, indicating a frequency dependence aspect to tonal annoyance. Doleschal et al. (2021) as well investigated tonal components of e-powertrain noise as they have the potential to diminish perceived pleasantness and, therefore, the acceptance of electrified driving systems. For the experiment, synthesized stimuli were systematically varied in their SPL and number of tonal components and then evaluated by $N = 16$ normal-hearing participants regarding the perceived magnitude of tonal components (MOTC) of the digitally generated sound samples (Doleschal et al., 2021). Doleschal et al. (2021) found the following parameters to have an influence on the perceived MOTC in their study: driving condition, the level of the 24th motor order, the presence of the 48th order, or structural resonances modeled as amplitude modulation. Moreover, psychoacoustic models and their ability to predict changes in perceived MOTC are referenced (Doleschal et al., 2021). Drichel et al. (2021) suggested an efficient prediction model for EV-NVH behavior and investigated the influence of its model fidelity level on the predictive quality of the perceived drivetrain-related airborne noise while considering human perception. The model development itself included the analyses of the psychoacoustic metrics loudness, sharpness, tonality, roughness, and psychoacoustic annoyance, which led Drichel et al. (2021) to the following observations: additional sidebands and friction-related excitations made the stimuli sound less tonal; more broad-band noise led to higher

1 Please note that these findings are conducted from the article's English abstract only, whereas the article of Fang et al. (2015) itself was written in Chinese and not available to us in English language in an authorized version.

roughness; noise components in higher frequency ranges led to higher sharpness scores as the simulation might have underestimated the SPL in these ranges. For the validation of the model $N = 30$ participants were asked to evaluate multiple noise stimuli concerning a reference in regards to their similarity (from 0 = *completely dissimilar* to 100 = *absolutely identical*) in a MUSHRA test (Multi-Stimulus Test with Hidden Reference and Anchor) (Drichel et al., 2021). Table 1 gives an overview of the summarized literature assigned to this cluster and its analyzed parameters: a total of 16 articles, seven of them also including a comparison with subjective data.

Cluster B: computational prediction models

In the following section we sum up research on computational prediction models for different NVH characteristics of EVs. Most articles utilized objective parameters as input variables for their prediction models, some furthermore considered subjective data for validation. All research discussed in this cluster applies techniques and approaches from the fields of computational science and artificial intelligence.

As the NVH profile of EVs and ICEVs differ substantially and subjective jury tests are time-consuming and labor-intensive, many researchers look out for a more efficient way to assess sound perception and thereby predict perceived sound quality. For instance, Mosquera-Sánchez et al. (2014) followed the approach of applying multi-objective algorithms to the sound quality optimization problem. To account for the elementary changes in electrically powered vehicles with more harmonic and tonal components, not only the parameter of loudness was considered, but also roughness, sharpness, and tonality were included in their models (Mosquera-Sánchez et al., 2014). In another study, Mosquera-Sánchez et al. (2016) tested active sound quality control algorithms to improve the sound quality of e-powertrain-induced noises, specifically in HEVs. Again, the sound quality metrics of loudness, roughness, sharpness, and tonality were included in the algorithms, which then reduced the disturbances and therefore were assumed to enhance the overall sound quality of the radiated noises (Mosquera-Sánchez et al., 2016).

The following contributions additionally considered subjective data for the validation of computed models. Fang et al. (2016)², correlated psychoacoustic metrics of loudness, sharpness, roughness,

fluctuation, and articulation index with subjective evaluation ratings of radiated e-powertrain noise. They established a predicting model for the sound quality of e-powertrains based on particle swarm optimization (PSO) and support vector machines (SVM) with higher prediction accuracy than models based on genetic algorithm (GA) methods and grid search methods (Fang et al., 2016). Moreover, their results indicate that subjective sensation could be reflected by sensitive frequency band energy ratio (SFBER) (Fang et al., 2016). Ma et al. (2016) developed an evaluation method for the sound quality of hub permanent magnet synchronous motors (HPMSM) in EVs by applying backpropagation (BP) neural network theory. First, they objectively evaluated the noise of HPMSM *via* (psycho-)acoustic metrics, including loudness, roughness, A-weighted SPL, tonality, sharpness, articulation index, and fluctuation strength, which they took as input variables for the BP neural network (Ma et al., 2016). Then they had $N = 24$ participants evaluate the stimuli subjectively regarding perceived annoyance through the grade evaluation method (GEM) and compared this data with the output of the BP neural network (Ma et al., 2016). In comparison, the evaluation of HPMSM noise by solely an A-weighted SPL appeared to be insufficient, possibly leading to false conclusions, whereas the established BP neural network reflected the physical characteristics of the noise and its influence on the human perception better with an error rate of only 3.97% (Ma et al., 2016). In another investigation, Ma et al., 2017b) again utilized BP neural network theory to develop a method to diagnose abnormal noise in interior permanent magnet synchronous motor (IPMSM) and evaluated its sound quality. The objective evaluation of IPMSM noise included the metrics of sharpness, roughness, loudness, articulation index, tonality, fluctuation strength and A-weighted SPL, which were then compared to the subjective evaluations of $N = 24$ participants that rated relative and absolute annoyance in a listening test by paired comparison method (PCM) and grade evaluation method (GEM) (Ma et al., 2017b). Instead of the A-weighted SPL, Ma et al., 2017b) concluded sharpness to be the most influential factor in perceived annoyance, and their method showed improved detection accuracy for abnormal noise in IPMSM without needing a lot evaluation expertise. Fang and Zhang (2017a) objectively analyzed spectral frequencies, engine orders, and noise sources of e-powertrains and also followed up with a subjective evaluation of sound quality in terms of perceived annoyance. A sample of $N = 21$ participants evaluated measurements of ICEVs and EVs in a listening test, in which the ratings for the ICEV stimuli were found to be more consistent, presumably since these noises were more familiar (Fang & Zhang, 2017a). The psychoacoustic parameters of loudness, sharpness, fluctuation strength, roughness, sensitivity index, and articulation index were then analyzed and correlated with the subjective data, where very strong correlations for the metrics of sensitivity index (0.946) and sharpness (0.838) were found in regards of perceived annoyance (Fang & Zhang, 2017a). Finally, Fang and Zhang (2017a) established a sound quality prediction model through Support Vector Machine (SVM) algorithms, which showed to be effective in predicting the sound quality of e-powertrain noise with a

² Please note that these findings are conducted from the article's English abstract only, whereas the article of Fang et al. (2016) itself was written in Chinese and not available to us in English language in an authorized version.

TABLE 1 Overview of the summarized literature of Cluster A.

| Source | NVH topic | Objective parameters | Subjective evaluation | Conclusions |
|--------------------------------|--|--|--|--|
| Sarrazin et al. (2012) | Sound synthesis tool for EV and HEV | Stevens VII loudness, loudness ISO532A and B, pitch, TNR, roughness, PR, tonality, sharpness | Jury test for equivalence ($N = 29$) | Validation of product-specific sound synthesis tool |
| Bassett et al. (2014) | Tonal high-frequency noise components of EVs | SPL A-weighted, loudness, Stevens VI loudness, articulation index, PR, sharpness, TNR, tonality | Expert sample ($N = N.A.$); acceptance of high-frequency tonal noise (10-point Likert scale) | Highest correlation with subjective ratings: Stevens VI loudness; TNR and PR good indicators to show the difference between tones, but do not align with subjective perception |
| Fang & Zhang, (2014) | Electric powertrain noise | Loudness, sharpness | — | Loudness rising with speed; sharpness unevenly distributed; conclude noise to be perceived as comfortable |
| Sarrazin et al. (2014) | Noise of 12/8 switched reluctance motor | Loudness, tonality, sharpness, PR | — | Large effect of torque level on tonality and loudness, smaller effect on sharpness; PR as detection tool of various stator motor shapes applicable |
| Fang et al. (2015) | EV noise | Sensitive frequency-band energy ratio (SFBER) | Subjective annoyance ($N = NA$) | SFBER higher correlation with annoyance (0.958) than other psychoacoustic metrics, indicating to be a better predictor for SQ |
| Lennström & Nykänen, (2015) | Distribution of tonal components in EV and HEV | Prominent orders (maximum level, frequency separation), TNR, PR | — | TNR recommended before PR in case of multiple closely related orders |
| Mosquera-Sánchez et al. (2015) | Interrelation between psychoacoustic metrics and their cross effects in typical EV noise | Loudness, roughness, sharpness | — | Loudness as single parameter is insufficient to determine sound quality, multi-objective approach needed; sound quality is case and product dependent |
| Le Besnerais et al. (2018) | Electric powertrain noise: isolated samples of pulse width modulation (PWM) at 5, 6, 7, 8, 9 and 10 kHz | Loudness ISO532B, sharpness, roughness | — | Switching frequency with impact on sound perception: the higher the switching frequency, the lower the parameter values for roughness and loudness; recommend further jury tests to determine acceptance levels |
| Mosquera-Sánchez et al. (2018) | HEV interior noise | Loudness, roughness, sharpness, tonality | — | Framework to enhance sound quality in HEV experimentally verified |
| Ma et al. (2019) | Influence of critical bands in permanent magnet synchronous motors (PMSM) on sound quality (perceived annoyance) | loudness, articulation index, tonality, roughness, A-weighted SPL, fluctuation strength, sharpness | Subjective annoyance <i>via</i> rating scale method ($N = 22$) | Present SCB (sensitive critical band) diagnostic method for SQ in PMSM; identified CBs with negative influence on SQ; analyzed different psychoacoustic metrics |
| Pietila et al. (2019) | Tonal frequencies in EV noise | TNR, PR, hearing model tonality (HMT) | Binaural pairwise comparison ($N = 10$) | Development of tonal annoyance weighting curve; show frequency-dependent aspect to tonal annoyance; lower frequencies preferable, higher frequency content as least preferable |
| Devillers et al. (2020) | Pulse Width Modulation (PWM) noise | Tonality, PR, roughness | — | Switching frequency as important developmental consideration as it can reduce costs and improve xEV NVH characteristics |
| Doleschal et al. (2021) | Tonal components in synthesized e-powertrain noise | Tonality measures, perceived magnitude of tonal components (MOTC) | Evaluation <i>via</i> mechanical slider ($N = 16$) | Perceived MOTC significantly influenced by driving condition, level of 24th motor order, presence of 48th motor order, and presence of structural resonances modeled as an amplitude modulation; effect due to amplitude modulation presumably due to increased level of tonal |

(Continued on following page)

TABLE 1 (Continued) Overview of the summarized literature of Cluster A.

| Source | NVH topic | Objective parameters | Subjective evaluation | Conclusions |
|-----------------------|---|--|---|--|
| | | | | component; measures of pure tonality and ECMA-47 standard predict changes in perceived MOTC for level variations in 24th motor order, presence of 48th motor order, modulation frequency and modulation index |
| Drichel et al. (2021) | EV NVH | Loudness, sharpness, roughness, tonality, psychoacoustic annoyance | MUSHRA test for similarity evaluation of reference e-PT noise measurements and noise simulations ($N = 30$) | Suggested prediction model for NVH behavior in EVs found to be efficient after comparison to human perception; additional sidebands and friction related excitations led to less tonality in simulations; additional broad-band noise leads to higher roughness; high-frequency noise components led to higher sharpness as simulation underestimates SPL in higher frequency ranges |
| Qian et al. (2021) | Sound quality prediction model for EVs based on transfer function path techniques considering air- and structure-borne noises | Loudness, sharpness, roughness | — | Separation method over transfer paths as effective technique to realize sound design for EVs; provides technical basis for Sound quality improvement; validation by comparison of synthesized and measured interior noise samples in the objective metrics |
| Stadtfeld, (2021) | High frequencies and pitch noise in eDrives; transmission noise | FFT analyses, harmonic meshes | — | Though some NVH phenomena are non-audible phenomena above and below 3rd mesh harmonic and structure-borne frequencies still need to be considered; configurational changes might even benefit NVH perception |

Note. Sources without information in the column *Sample Size* belong to the first group of *Cluster A* which considers objective psychoacoustic metrics as the sole perception indicator. We do not claim the tabular summary to be complete. For further information on the specifications of parameters and methods, we would like to refer to the respective source articles.

relative error of only 2%. In another study, Fang and Zhang (2017b) had $N = 30$ participants evaluate the noise of PWM-fed electric powertrains in regards to their perceived annoyance, but this time established a prediction model for sound quality *via* a Support Vector Regression (SVR). The objective parameters of loudness, roughness, fluctuation strength, tonality, sensitivity index, and sharpness were analyzed, resulting in the two latter, again, showing the strongest correlations (0.917 and 0.842) with the subjective data (Fang & Zhang, 2017b). Moreover, results showed higher annoyance scores with increasing speed and high frequencies and high harmonic order components were perceived as annoying despite having a lower SPL (Fang & Zhang, 2017b). Qian et al. (2020) established a model for sound quality estimation based on a genetic algorithm-optimized back propagation artificial neural network (GA-BP ANN) and compared it to often used multiple linear regression (MLR) models. They criticize models based on MLR fail to map complex coherences between objective parameters and subjective perception, as well as often lack accuracy, which is why they see it as necessary to establish more accurate nonlinear models (Qian et al., 2020). Qian et al. (2020) had $N = 32$ participants evaluate different binaural EV

measurements in a semi-anechoic chamber, asked to rate the perceived pleasantness of the stimuli on a scale from 1 to 11 *via* the grading method. Objective sound quality parameters such as loudness, sharpness, roughness, fluctuation strength, tonality, articulation index, and A-weighted SPL were evaluated and then correlated with the subjective rating data (Qian et al., 2020). Qian et al. (2020) found the used metrics and the subjective data to be correlated by 0.7 and higher, except for tonality with a much lower correlation coefficient. Overall, the GA-BP ANN model seems to offer advantages in terms of generalization and precision with higher accuracy. It showed a lower average percentage error than the MLR model (5.81 and 8.14%, respectively) for predicting subjective sound quality estimation (Qian et al., 2020). Following a similar approach, Qian and Hou (2021) established a sound quality evaluation model for the interior soundscape of electrified vehicles by utilizing intelligent algorithms and artificial neural network techniques of simulated annealing (SA) and genetic algorithm (GA) to further optimize the backpropagation neural network (BPNN) model. Binaural recordings of EV interior noise from different brands and models were analyzed regarding the objective parameters of

A-weighted SPL, loudness, roughness, sharpness, fluctuation strength, articulation index, impulsiveness, and tonality (Qian & Hou, 2021). Subjective evaluation data was gathered from $N = 36$ participants that evaluated the sound quality of the noise samples played over headphones in random order in a laboratory setting in an anechoic chamber through paired comparison method (PCM) and rating scale method (RSM) (Qian & Hou, 2021). The derived SAGA-BPNN model for sound quality evaluation attained a high prediction accuracy, a low estimation error below 5% for estimated and actual scores, high correlation coefficients, and good generalization ability to forecast the sound quality of EVs (Qian & Hou, 2021). A weighted analysis showed that A-weighted SPL, loudness, sharpness, and roughness were important factors influencing perceived sound quality, sharpness even scoring the highest weighting of 32.62%, presumably due to high-frequency electromagnetic noise in EVs' NVH profiles (Qian & Hou, 2021). Huang et al. (2021) criticized that most investigations in the field have been done on the interior noise of ICEVs with only limited validity for EV acoustics, and though there have been attempts to apply intelligent methods for sound quality prediction, these studies often only considered stationary noise, not applicable to dynamic use cases. Following up on these shortcomings, Huang et al. (2021) applied intelligent prediction methods and based their sound quality prediction model on tacho-tracking psychoacoustic metrics and deep convolutional neural networks (CNN) with adaptable learning rate trees (ALRT). Nonstationary noise of pure electric vehicles (PEVs) was recorded in use cases of normal and rapid acceleration as well as normal braking (Huang et al., 2021). $N = 20$ participants then evaluated these stimuli over high-fidelity headphones with the grade ranking method (scaled from 1 to 7) and tacho-tracking psychoacoustic indices of loudness, roughness, fluctuation strength, sharpness, articulation index, and tonality were analyzed (Huang et al., 2021). In comparison to other conventional methods that aim to quantify the contributions of different prediction metrics, the ALRT-CNN model, which combined subjective and objective data, showed an overperforming effectiveness (Huang et al., 2021). For further optimization, Huang et al. (2021) recommended to focus on the variety of sharpness, roughness, and loudness. For their investigations on the sound quality of power coupling mechanism noise in HEV, Lu et al. (2021) combined the methods of complementary ensemble empirical mode decomposition (CEEMD) and Hilbert transform (HT), as well as relevance vector machines (RVM) to acquire a sound quality prediction model. Psychoacoustic parameters of tonality, fluctuation, loudness, roughness, and sharpness served as input variables for the RVM model (Lu et al., 2021). To proof the model's predictive capability, acoustical signals of the HEV power coupling mechanism under steady- and unsteady state operating conditions were presented in a laboratory environment over loudspeaker array to a sample of $N = 30$ participants that evaluated these stimuli through pairwise comparison in regards of perceived annoyance (Lu et al., 2021). Lu et al. (2021) concluded their CEEMD-HT model to have a higher predictive accuracy than the RVM-psychoacoustics model in terms

of reflecting perceived sound quality and the prediction accuracy for steady operational conditions to be higher than for the unsteady state samples. Huang et al. (2022) focused specifically on tire/road structure-borne (TRS) noise that becomes apparent due to the EV's muted nature and presented a novel method to tackle uncertainty optimization problems with the approach of improved interval analysis method (IIAM). Parameters like suspension shock absorber damping and spring stiffness were identified to contribute to the perceived sound quality of TRS, high correlations with the subjective data were found for loudness, roughness, and articulation index and the IIAM proved to outperform conventional approaches for SQ optimization like genetic algorithm (GA) models in a real-vehicle test (Huang et al., 2022). The described literature is summed up in Table 2.

Cluster C: subjective assessment and experimental studies

In this third cluster, we sum up research that investigated the perception of the EV's interior soundscape following a human-centered approach collecting subjective evaluation data from participants with methods, aside from mere objective metrics, such as qualitative assessments and/or experimental study designs.

Sound quality assessment

Matuszewski and Parizet (2016) examined the validity of commonly used metrics for assessing sound quality in ICEVs in the context of EV interior noise in full-throttle acceleration mode. $N = 19$ participants evaluated recordings regarding perceived unpleasantness using two methods: pairwise comparison (12 stimuli, 66 pairs) and absolute evaluation using a slider bar that indicated five different states of unpleasantness (36 stimuli) (Matuszewski & Parizet, 2016). Matuszewski and Parizet (2016) found the conventional psychoacoustic metrics to be partially applicable as the A-weighted SPL remained an important predictor for perceived unpleasantness. However, metrics like PR should be endorsed due to the mid to high-frequency components in EV noise. Fang et al. (2018) focused the influence of acoustic harmonics in e-powertrain noise on the EV's sound quality, subjective perception, and psychoacoustic measures. Stimuli were recorded in an anechoic chamber with an artificial head and then played back *via* headphones to $N = 30$ participants to be rated in terms of annoyance on a 10-point scale from *very comfortable* to *very annoying* (Fang et al., 2018). Fang et al. (2018) then fed the subject and objective data from a psychoacoustic analysis of the parameters loudness, fluctuation strength, roughness, sharpness, tonality, and sensitiveness into a Support Vector Machine (SVM) algorithm to establish a sound quality prediction model. Fang et al. (2018) found high associations with the subjective perception ratings for

TABLE 2 Overview of the summarized literature of Cluster B.

| Source | Objectives and parameters | Method | Subjective evaluation | Conclusions |
|--------------------------------|--|--|--|--|
| Mosquera-Sánchez et al. (2014) | Multi-objective sound quality optimization of e-PT noise in HEV; loudness, roughness, sharpness, tonality | Multi-objective evolutionary algorithms; SPEA2 (strength Pareto evolutionary algorithm) + NSGA-II (non-dominated sorting genetic algorithm) + SF-cFxLMS (simplified form, complex-filtered-reference, least mean squares) algorithm | — | Active sound quality control model is implemented, accounting for changed sound profile in e-drive mode of HEV with typical harmonic and tonal components |
| Fang et al. (2016) | Sound Quality Prediction of e-powertrain noise; loudness, sharpness, roughness, fluctuation, articulation index | Particle Swarm Optimization (PSO) + Support Vector Machine (SVM) | N.A. | Superior prediction accuracy of PSO-SVM model compared to models built out of a genetic algorithm and grid search methods; subjective data can be reflected with sensitive frequency band energy ratio (SFBER) parameters as the correlation coefficient is 0.946; absolute value and maximum value of the relative error are 2 and 6.7% |
| Ma et al. (2016) | Sound quality evaluation method for EVs with hub permanent synchronous motor (HPMSM); loudness, roughness, sharpness, tonality, articulation index, fluctuation strength, A-weighted SPL | Backpropagation neural network (BP-NN) theory | Listening test ($N = 24$); evaluation of annoyance with grade evaluation method (GEM) | Evaluation of HPMSM noise though only A-weighted SPL appears to be insufficient; established BP neural network models, physical noise characteristics and their influence on human perception better with an error rate of only 3.97% |
| Mosquera-Sánchez et al. (2016) | Active sound quality control of e-PT noise in HEV; loudness, roughness, sharpness, tonality | Multi-objective evolutionary algorithms; SPEA2 (strength Pareto evolutionary algorithm) + NSGA-II (non-dominated sorting genetic algorithm) + NEX-LMS (normalized reference, least mean squares) algorithm + SF-cFxLMS (simplified form, complex-filtered-reference, least mean squares) algorithm | — | Active sound quality control algorithms to enhance the sound quality of HEV by reducing disturbing powertrain-induced noises |
| Fang & Zhang, (2017a) | Sound quality (annoyance) and psychoacoustic metrics in e-PT and ICEV noise | Support Vector Machines (SVM) | Listening test ($N = 21$) in a laboratory; 10-point rating scale | Established effective sound quality prediction model through Support Vector Machine (SVM) method with a relative prediction error of only 2%; highest correlations with subjective data between the parameters of sensitivity index ($r = 0.946$) and sharpness ($r = 0.838$) |
| Fang & Zhang, (2017b) | Sound quality (annoyance) and psychoacoustic metrics in e-PT noise | Support Vector Regression (SVR) | Listening test ($N = 30$) in a laboratory; 10-point rating scale | Sound quality prediction model is established through Support Vector Regression (SVR); highest correlations with subjective data for sensitivity index ($r = 0.917$) and sharpness ($r = 0.842$); higher perceived annoyance with increasing speed; despite lower SPL high frequencies and high harmonic order components perceived as more annoying |
| Ma et al. (2017b) | Sound quality evaluation method for EVs with interior permanent magnet synchronous motor (IPMSM); sharpness, roughness, loudness, articulation index, tonality, fluctuation strength | Backpropagation neural network (BP-NN) theory | Listening test ($N = 24$); absolute and relative annoyance evaluated through paired comparison (PCM) and grade evaluation method (GEM) | Sharpness as most influential factor on subjective annoyance in IPMSM noise instead of A-weighted SPL; improved accuracy of abnormal noise detection in IPMSM noise |

(Continued on following page)

TABLE 2 (Continued) Overview of the summarized literature of Cluster B.

| Source | Objectives and parameters | Method | Subjective evaluation | Conclusions |
|--------------------|---|---|---|--|
| Qian et al. (2020) | Sound quality estimation in EVs; loudness, sharpness, roughness, fluctuation strength, tonality, articulation index, A-weighted SPL | Genetic algorithm-optimized backpropagation artificial network (GA-BP ANN) + comparison to multiple linear regression (MLR) model | Listening test ($N = 32$) in a semi-anechoic chamber; evaluation of pleasantness on an 11-point scale via grade evaluation method (GEM) | Objective metrics correlate with subjective data by $\rho = 0.70$ and higher (except tonality, which has lower coefficient); GA-BP ANN offers advantages regarding generalization + precision: lower average percentage error (5.81% compared to 8.14% of MLR) in sound quality prediction |

Note. We do not claim the tabular summary to be complete. For further information on the specifications of the mentioned parameters and methods, we would like to refer to the respective source articles. N.A. in the column *Subjective Evaluation* means that we had no further information on the reported subjective evaluation; blank fields in this column mean no subjective evaluation was considered.

the parameters of sharpness and sensitivity, which seem to represent the characteristic high-frequency components of EV noise, ranging from the 20th to the 23rd 1/3 octave bands, to which the human hearing apparatus is especially prone. In an experiment, Lennström et al. (2019) specifically aimed to evaluate the coherences between the psychoacoustic metric of tonality and perceived pleasantness of the interior EV soundscape focusing on tonal components between 200 and 900 Hz. Binaural recordings of EV interior cabin noise from test track measurements were presented in varying sound levels to $N = 20$ participants, who were asked to rate the stimuli's pleasantness on an 11-point scale from *very unpleasant* to *very pleasant* (Lennström et al., 2019). Ratings for low-frequency tones (200–400 Hz) turned out to be relatively constant, suggesting to be perceived not as disturbing independent of their sound level, whereas for high-frequency tones (600–900 Hz) the perceived pleasantness varied dependent on the SPL – the louder the tone, the less pleasant (Lennström et al., 2019). Beyond that, the detection rate for 200 Hz stimuli was found to be very low, independent of SPL, and increased in the frequency ranges of the 400 Hz stimuli and 600–900 Hz, respectively (Lennström et al., 2019). Lennström et al. (2019) moreover assumed more sensitive participants to be influenced stronger in their pleasantness rating, as a cluster analysis showed a group of participants to have a higher detectability performance and finding tones in the range of 600–900 Hz to be increasingly unpleasant with rising level, whereas a second group of participants generally rated lower on pleasantness independent of sound level and frequency. The subjective data was then compared to tonality values of different established metrics such as PR, DIN Tonality 45681, ECMA-74 Tonality, and ECMA-74 Tonality modified. Though all metrics demonstrated an accuracy of 80% and higher regarding tone detectability, no metric appeared to predict perceived

pleasantness: the only significant correlation with pleasantness was found for ECMA-74 Tonality ($r = -0.67$). In an analysis excluding the seemingly undetectable 200 Hz stimuli, leaving the frequencies from 400 to 900 Hz, all correlation coefficients increased to 0.70 or higher (Lennström et al., 2019). The findings demonstrate that the discussed metrics could not model the sensation of pleasantness, as they merely aim to model tonality (Lennström et al., 2019).

Focus on specific disturbing NVH sources

Andersson et al. (2016) investigated magnetic noise from electrical machines in rear-wheel drive (RWD) EVs and evaluated the consequences on the perceived sound quality of the resulting noise when using different modulation techniques as well as applying different levels of switching frequency randomization. Six sound files, resulting from the combination of each modulation strategy and randomization level, were evaluated by $N = 18$ participants regarding their sound quality in terms of annoyance through the MUSHRA test method (Andersson et al., 2016). Results show that with space vector modulation, the randomization of the switching frequency did not seem to improve the sound quality (Andersson et al., 2016). For the first three speed segments, the perceived annoyance was higher for discontinuous pulse width modulation (DPWM), but until the field weakens, the randomized switching frequency affected the sound quality positively for DPWM stimuli (Andersson et al., 2016). Moreover, Andersson et al. (2016) found psychoacoustic metrics, such as different loudness metrics, the overall SPL and sharpness to have the greatest impact on perceived annoyance and tonality to be preferred as metric for tonal exposure, since the utilized variation parameters could easily bias PR and TNR. Münder and Carbon (2022) investigated the importance of e-powertrains noise to the perceived quality of EVs overall. Utilizing the

Repeated Evaluation Technique (RET; Carbon and Leder, 2005), $N = 65$ participants evaluated ambisonic 3D measurements of different EVs recorded in four different use case scenarios presented to them in a sophisticated acoustic simulator (Münder & Carbon, 2022). It showed that the more perceivable the e-powertrain noise, the lower the perceived quality overall as a significant negative correlation of $\tau = -0.32$ was found by Münder and Carbon (2022), demonstrating that acoustic characteristics in EVs clearly contribute to the overall perceived quality.

Operational feedback

Yamauchi and Feng (2014) stress the function of vehicle noise to provide feedback about the vehicle's condition and status. The generally quieter soundscape of EVs might complicate accessing information about the vehicles' velocity or acceleration rate for the driver. Mixtures of one-third-octave band noises with controlled frequency shifting were utilized as driving sound stimuli and evaluated their acceleration impression in two subjective experiments – one in a laboratory set-up and one in a driving simulator environment—with the paired comparison method (Yamauchi & Feng, 2014). In the first experiment in the laboratory environment, participants evaluated the acceleration impression to validate the harmonization of the audio and visual impression of the stimuli (Yamauchi & Feng, 2014). The results showed the stimuli with frequency shift to be perceived as having greater acceleration, the 100 Hz component to have a lesser effect on this impression than the higher frequency bands, and a wider frequency shift to have a stronger association with acceleration (Yamauchi & Feng, 2014). The driving action itself, tested for in the second experiment in a driving simulator within an interactive scenario, did not affect the acceleration impression (Yamauchi & Feng, 2014). Küppers (2015) also reports on the dilemma of EVs giving less load feedback due to their natural quietness compared to ICEVs and that it, if it occurs, is often perceived as disturbing or unpleasant due to its high frequencies: the reduction of the disturbing powertrain noise accordingly may lead to a lack of informational and emotional feedback. In the study, synthesized sounds were evaluated in three different environments – a laboratory environment, a driving simulator, and a demonstration vehicle (Küppers, 2015). In a first step, Küppers (2015) validated the synthesized stimuli in the laboratory studio set-up, as participants showed high acceptance for the sound synthesis (27 out of $N = 35$ participants thought positively about the additional sounds). Results from the driving simulator experiment proved the sole wind roll noise to be accepted and perceived as pleasant; although load feedback was wished for in the comments, the genuine e-powertrain noise was rated as the least pleasant and paradoxically perceived as the most artificial sound (Küppers, 2015). Participants evaluated

different sound variants in the vehicle demonstrator: three basic sounds, the sound turned off, and a self-configured sound from within the sample variants they could self-create by adding orthogonal sound parameters (for example, volume, timbre, reaction to throttle pedal) (Küppers, 2015). When participants freely configured the vehicle's sound, only 14% of the sample preferred a switched-off sound, whereas most preferred the sound variants resembling combustion engines (Küppers, 2015). An exploratory study by Lee et al. (2016)³, showed that contextual information and quietness, taken as independent variables, influenced the general user experience of driving an EV. The interior driving sound influenced perceived satisfaction, emotions, and usefulness.

Sound synthesis and enhancement strategies

A couple of studies compared the effect of different sound design concepts for active driving sounds to enhance EVs acoustically. Govindswamy and Eisele (2011) compared the NVH characteristics of an EV with that of its conventional ICE-powered production counterpart and evaluated its perceived pleasantness and dynamic impression through subjective on-road driving tests and a jury test in an audio laboratory set-up. Sounds were objectively analyzed, and synthetically modified, and the applied sounds were then evaluated: a reduction of tonal high-frequency noise shares was found to improve pleasantness and preference ratings (Govindswamy & Eisele, 2011). Though the ICEV was perceived as more dynamic (and less pleasant), the mere addition of ICEV-resembling noise shares to the EV – attempting to improve the dynamic character or to mask unpleasant noise shares with a synthetic admixed sound – worsened the pleasantness and preference ratings, leading to the conclusion to consider sound design needs for each vehicle type individually (Govindswamy & Eisele, 2011). Gwak et al. (2014a) modified sound samples of real EV measurements by adding subharmonics to the existing high-frequency components, which otherwise were perceived as annoying and reduced the dynamic impression of the vehicle. They had $N = 27$ participants evaluate the sound samples regarding preference and on a semantic differential. The proposed sound modification method by Gwak et al. (2014a) proved to be effective in enhancing the perception of the vehicles' interior soundscape: the level, number of tones, and frequency should be chosen carefully and to create a more dynamic sound impression, the tones should be under 600 Hz. Moreover, different customer groups seemed to have different preferences regarding EV sound enhancement strategies (Gwak et al., 2014a). In another study, Gwak et al. (2014b) tested two different sound modification approaches against each other and had

³ Please note that these findings are conducted from the article's English abstract only, whereas the article of Lee et al. (2016) itself was written in Korean and not available to us in English language in an authorized version.

$N = 30$ participants evaluate the specifically modified additive sound samples in regards of their effect on the perceived intensity of acceleration sensation, their sound image (multiple choice of describing adjectives) and their overall preference. Both applied sound modification methods were found to be effective in increasing the sensation of acceleration (Gwak et al., 2014b). While adding subharmonics to the high-frequency components led to a large loudness increment, the adjustment method of time gap improved the acoustic feedback without such significant level increment though attained only low preference ratings (Gwak et al., 2014b). Sontacchi et al. (2015) investigated active sound generation for EVs and down-sized ICEVs to improve their acoustic feedback and their potential effect on driving behavior and experience overall. Though many people preferred quiet vehicles a load-dependent loudness seemed important for the interior sound acceptance, while the as barely sporty described sound of electric engines could be improved regarding their acceleration impression by pitch shifting (Sontacchi et al., 2015). Samples of full-load run-ups were presented to the participants which were asked to identify the most different sound within a stimuli triplet and describe this difference semantically and rate it on an attribute scale (Sontacchi et al., 2015). Sontacchi et al. (2015) concluded that sound descriptions are biased by gender as only male participants named positive energy-related terms, while females focused on versatile descriptors. Additionally, they assumed an increase in amplitude modulation and loudness to elicit impressions of sportiness and acceleration, which could assist drivability and improve the product experience overall (Sontacchi et al., 2015). Sontacchi et al. (2015) advocate the active sound enhancement of EV interior soundscape and a more conservative approach in sound design strategy as they suggested ICEV-resembling sound characteristics and maintaining traditional manufacturer-specific sounds inspired by established experiences. Maunder and Munday (2017) also see an opportunity to enhance dynamics in the driving experience and benefit from positioning a certain brand image in actively controlling the acoustic response inside the EV's cabin while aiming to maintain authenticity. In a survey, Maunder and Munday (2017) conducted information of $N = 30$ participants regarding the perceived acoustic feedback of EVs as well as their agreement with certain statements for each of the stimuli. In general, participants seemed to expect more conventional vehicle sound and rumble noise as it is referenced as powerful or sporty (Maunder & Munday, 2017). In contrast, similarities to typical ICEV noise did not meet their expectations of indicating an environmentally friendly character (Maunder & Munday, 2017). Despite widespread opinions regarding the expectations for EV sound, the authors were able to segment the sample into three distinct groups: the largest group focused on the power aspect and commented on a need for acoustic augmentation in the interior, preferring conventional sound options; secondly, a group recognizing the need for acoustic augmentation but refusing ICEV-resembling sound and appreciating novel approaches; and thirdly, a group of participants preferring the genuine EV interior sound as most suitable, not recognizing a requirement for additional

sound augmentation (Maunder & Munday, 2017). Allman-Ward et al. (2020) developed a pre-set of 18 EV interior sounds, which was evaluated within the project team and of which eight sounds were taken for the final assessment in a jury test. Participants were asked to make a full ranking for preference of the eight stimuli, of which then two final sounds were applied in a real vehicle testing scenario allowing the participants to experience the sounds while driving (Allman-Ward et al., 2020). Though one of the modified sound concepts reached a common preference of 50% among the participants, the most appropriate sound for a sporty EV was the basic interior noise without any additional sound modifications, picked as the best solution by 8% of the sample, indicating the characteristic EV quietness to be appealing for customers as well (Allman-Ward et al., 2020). By comparing subjective perception data and objective metrics, Lanslots et al. (2020) investigated different sound design concepts to emotionalize the acoustic feedback and tackle the oft-cited problem of EVs lacking operational feedback and not doing their great acceleration justice. Designed sound concepts were applied to an EV and then recorded through a binaural headset at the driver's ears positions in defined standard driving conditions of run-ups with an acceleration rate of 13.9 m/s (equivalent to a run-up from 0 to 50 km/h) (Lanslots et al., 2020). Aiming to quantify subjective perception criteria, psychoacoustic sound quality metrics were analyzed and compared across all stimuli, recognizing differences in loudness, sharpness, articulation index, tonality, prominence ratio, but roughness staying relatively the same (Lanslots et al., 2020). Finally, four sound concepts developed through granular synthesis, order-based synthesis, and other modifications, specified in Lanslots et al. (2020), were compared to the baseline sound with paired comparison method by an expert panel ($N = 10$) in a listening test: the sound resembling a V8 motor scored the highest preference, followed by a sound resembling a pickup truck (Lanslots et al., 2020). Although the preference for ICEV-resembling sound concepts might have been influenced by the sample's driving experience (62.5% driving an ICEV, 25% a hybrid and 12.5% an EV), Lanslots et al. (2020) recommended aiming for a balanced proportion of powerful ICEV-resemblance and naturalistic EV sound depending on the load condition. Valeri and Pietila (2020) as well investigated EV sound enhancement as a method to improve NVH-related customer experience by accentuating the natural quiet sound character of EVs, while masking novel and annoying high-frequency components as well as offering feedback on vehicle performance. Differently enhanced sounds were recorded at the driver's ears positions in a full pedal drive-away scenario and subsequently evaluated for preference in a paired comparison task as well as on a semantic differential to describe the experience (Valeri & Pietila, 2020). Valeri and Pietila (2020) found the following results: a reduction of tones (compared to baseline) led to a less sporty, exciting, or futuristic impression while at the same time it promoted a more smooth, natural, luxurious, effortless, pleasant, and harmonious impression; the addition of order harmonics enhanced the impression of sportiness and

excitement while it reduced perceived smoothness, effortlessness, and the harmonious impression; a musical approach of sound enhancement through additional tones with spectral spacing led to a more futuristic, pleasant and harmonious impression, but was perceived as less sporty, exciting and natural. Finally, the results from the paired comparison indicated the diversity of customer preferences and the ability of sound enhancement to impact the product impression, as no sound is preferred overall and only subgroups could be extracted: 25% liked the sound without any modulation significantly better, and 17% preferred the modulation resembling a V8 motor (Valeri & Pietila, 2020). Melman et al. (2021) compared the effects on the perceived sportiness of EVs through measures of Modified Throttle Mapping (MTM) and Artificial Engine Sound (AES) to a baseline condition and a high-performant sports ICEV. The experiment followed a within-participant design, where each of the $N = 32$ participants evaluated the illusion of sportiness in different experimental trials with different road environments and driving tasks, realized in a fixed-base driving simulator with environmental scenery, visualized car interior, and a digitally applied speedometer (Melman et al., 2021). Each test trial was followed up by the assessment of perceived task effort, vehicle impression, and a semantic differential to describe the experience (Melman et al., 2021). AES proved to increase the illusion of sportiness in EVs and improved the speed control compared to baseline, whereas MTM did not significantly change the perception and led to more fluctuating pedal movement (Melman et al., 2021).

Special focus on semantics

Swart and Bekker (2014) investigated the subjective evaluation of EV interior noise and the overall customer satisfaction using a ranking method and a bi-polar semantic differential. Recorded noise samples from an EV's wide-open-throttle acceleration (interior and under-hood noise), two ICEV samples, and an artificially generated sound from a modified EV noise sample were used as stimuli and evaluated by $N = 17$ jurors in a laboratory test setting. The results show that exterior sound samples were generally perceived as louder and less pleasant compared to the interior sound of ICEVs (Swart & Bekker, 2014). Although semantics such as *powerful*, *rumbling*, and *deep* were commonly used to describe the EV sounds, the sporty ICEV sound was still preferred, and the dimensions of *power* and *sportiness* seemed to be expressed stronger (Swart & Bekker, 2014). In another study, Swart et al. (2018) put a particular focus on the sound character by investigating the descriptive dimensions and the overall perceived sound quality of EVs. $N = 31$ participants evaluated EV motor bay recordings and modifications in a listening test regarding overall satisfaction and conveyed semantic values (Swart et al., 2018). The subjective evaluation proceeded in two consequential steps: first, the preference for the stimuli with the differently enhancements was assessed through forced choice comparison ranking

method and in a second step, the most preferred stimuli were evaluated on a bipolar 12-pair semantic differential scale (Swart et al., 2018). Sound enhancement seemed to be generally preferred compared to the standard production sound signature of the measured vehicles, especially enhancement methods such as low-frequency amplification, high-frequency filtering, low order addition, and pitch transposition achieved high scores (Swart et al., 2018). Furthermore, Swart et al. (2018) found the factors *Power*, *Comfort*, and *Deepness*, for the semantic description of the EV sounds and the highest correlations with satisfaction for the semantic attributes *pleasant*, *exciting*, and *comfortable*. In the context of semantic analysis Ma et al., (2017a) used a neural network approach to establish a sound quality prediction model based on the A-weighted SPL and six psychoacoustic parameters (loudness, roughness, fluctuation strength, tonality, sharpness, articulation index). These parameters were compared to semantic evaluation indexes conducted in a subjective listening test. A sample of $N = 20$ participants evaluated the interior noise of EVs on a semantic differential scale with five bipolar pairs (*annoying – pleasing*, *weak – powerful*, *harsh – sweet*, *unobservable – perceptible*, *promiscuous – pure*) (Ma et al., 2017a). Results show that at low speeds, the noise profile was described as *pleasing*, *sweet*, and *pure*, but *weak* and *unobservable*, presumably leading to the perception of a weak dynamic vehicle character and possible lack of vigilance, whereas at higher speeds, the profile was described as *annoying*, *harsh*, *powerful*, *promiscuous*, and *perceptible* compromising on perceived sound quality (Ma et al., 2017a). Swart and Bekker (2019) proposed a new metric to efficiently predict the perceived customer satisfaction regarding EV interior sound signatures and utilized psychoacoustic measures as well as subjective data. Binaural recordings of different EV sound signatures and enhanced, modified versions were subjectively evaluated by $N = 31$ participants in an anechoic chamber via headphones on a 12-pair bipolar semantic differential and a 10-point satisfaction scale (Swart & Bekker, 2019). The semantic analysis showed three main factors of *Comfort*, *Power* and a *Futuristic* factor and semantic descriptors such as *exciting* and *quiet* with weaker associations regarding customer satisfaction, whereas *pleasant*, *comfortable*, and *calm* were found to be highly correlated with perceived satisfaction (Swart & Bekker, 2019). Several significant correlations between objective psychoacoustic metrics and subjective ratings were reported, for example, for sharpness, loudness, and impulsiveness, while for the semantic descriptor *sporty*, no significant associations were found, which Swart and Bekker (2019) ascribed to the lack of a dynamic sound character in EVs. Aiming to bridge the gap between objective and subjective measures and accurately predict the subjective perception of customer satisfaction, Swart and Bekker (2019) followed the approach of single value approximation, including the objective

metrics of sharpness, impulsiveness, and fluctuation strength through multiple linear regression, and established a single value reduction model. The results emphasize the importance of parameter sharpness in EV sound signatures as it predominantly influences customer satisfaction ratings (Swart & Bekker, 2019).

Effects of evaluation context

The testing environment and the given experimental context can have a relevant influence on participants' perception. Depending on the target variable, different evaluation environments might be suitable, and the specific context should carefully be considered before data acquisition. Cocron et al. (2011) questioned $N = 40$ test drivers equipped with EVs in a naturalistic driving study (NDS) for a period of 6 months in the metropolitan area of Berlin about their experience. Though the focus of their investigation on driver's perception primarily focused on possible safety issues due to the reduced noise emissions of EVs, the conducted data shows a high awareness for the lack of driving feedback and the EVs' quietness, as well as expressed concerns regarding pedestrians' and bicyclists' safety in the beginning of the study (Cocron et al., 2011). These concerns decreased after 6 months, and expected substantial problems with the low noise emission level seemed to be obsolete as only a few incidents were reported (Cocron et al., 2011). Active sound design was not favored by the participants after 3 months of driving, but in the final interview, technical solutions, for example, a speed-dependent, the temporary sound was mentioned by a substantial part of the sample (Cocron et al., 2011). Labeye et al. (2016) followed a similar approach and conducted information regarding the driving experience with EVs in a longitudinal study with $N = 36$ participants over 6 months with two measurement time points between (T_0 = beginning and T_1 = after 3 months). Although the EV's quietness was mostly seen as a safety-related topic due to their low recognizability for pedestrians, it was as well stated as an advantage regarding the vehicle experience by the questioned drivers (Labeye et al., 2016). Genuit and Fiebig (2014) followed the Explorative Vehicle Evaluation (EVE) method to interview $N = 10$ participants about their subjective impressions of three different EV sound concepts. Results showed a preference for quiet EVs, especially at low speeds, while at the same time, it was asked for operational acoustic feedback adequately matching the driving situation (Genuit & Fiebig, 2014). Though a slight preference for quiet sound concepts became apparent, the general acceptance of new sound concepts as well as tangible recommendations for EV sound design remain unclear as the participants' comments were quite inconsistent, possibly due to a lack of reference and previous experience driving electrified (Genuit & Fiebig, 2014). Fiebig and Schulte-Fortkamp (2019) also applied the

EVE method to conduct subjective data on spontaneous associations, emotions, feelings, and thoughts regarding the perception of different EV sound concepts from $N = 10$ participants in a realistic driving context. Sound concept variation was achieved by altered parameters of spectral content, total loudness, sound character, loudness gain, modulation, implementation of idle sound, and level load mapping, resulting in three different sound concepts (ICEV oriented, modern/unconventional, inconspicuous/modest) (Fiebig & Schulte-Fortkamp, 2019). Additionally, an individual sound concept, created by the participants themselves, was compared to the original driving noise of the test vehicle (Fiebig & Schulte-Fortkamp, 2019). While more negative than positive comments were reported overall, all sound concepts provoked positive as well as negative feedback, and synthetic sounds provoked more feedback in general (Fiebig & Schulte-Fortkamp, 2019). The results from Fiebig and Schulte-Fortkamp (2019) once again demonstrate the target conflict between the general preference for quiet EVs and the request for a load adequate acoustic operational feedback. Lennström et al. (2011) focused on the influence of the test environment on the sound perception using an 8-pair semantic differential to let participants evaluate different EV driving sounds. They found no significant difference between the testing conditions of laboratory test, vehicle demonstrator, and on-track evaluation regarding perceived sound quality (Lennström et al., 2011). However, a significant effect in the participants' rating consistency showed: participants with an in-car experience (co-driving the EV) prior to the laboratory assessment showed smaller variances in their ratings compared to participants without such an exposition, as typical EV sound might have appeared as unfamiliar at first (Lennström et al., 2011). Another analysis of the preferences towards typical tonal components showed that an increased level of high-frequency tonal components and decreased mid-frequency tonal components ranked high on sharpness, annoyance, powerfulness, and toughness/aggressiveness. In contrast, a modification of the frequency components and vice versa achieved high rankings on overall satisfaction (Lennström et al., 2011). Table 3 summarizes all $N = 26$ articles in this cluster.

Discussion

The pertinent literature of over two decades of research investigating the subjective perception of the interior soundscapes of EVs is summed up and elaborated in the review at hand. Although EVs are only gradually finding their way into our everyday lives, numerous investigations on the perceived quality of their NVH characteristics have already been done. Findings cover a wide range of investigations following

TABLE 3 Overview of the summarized literature of Cluster C.

| Source | Method and test environment | N | Evaluation parameters | Conclusions |
|------------------------------|--|------------------|--|--|
| Cocron et al. (2011) | Naturalistic Driving Study (NDS) in the field at three time points (T0, T1 = 3 months, T2 = 6 months) | 40 | Driving behavior and perception due to EV quietness | Substantial part of the sample mentions a speed-dependent, temporary sound as helpful; encouraging to be more aware of traffic situations due to lack of noise |
| Govindswamy & Eisele, (2011) | On-road driving test and jury test in the laboratory | — | Pleasantness, dynamic impression, preference for synthetic additional driving sound | ICEV sound perceived as more dynamic; admixed noise shares in EV though worsens pleasantness and preference ratings; sound design as product-specific consideration |
| Lennström et al. (2011) | Semantic differential with 7-point scaled bipolar pairs in audio lab, vehicle demonstrator and in-car driving scenario in the field | 22 | Sound perception depending on experimental environment, sharpness, annoyance, toughness/aggressiveness, powerfulness, overall satisfaction | No significant differences between the testing conditions found; higher rating consistency with prior exposure to EV driving sound; high-frequency components increase sharpness, annoyance, powerfulness, toughness/aggressiveness; a decrease of high frequencies and increase of mid-frequency components leads to higher rankings in overall satisfaction |
| Genuit & Fiebig, (2014) | Explorative Vehicle Evaluation (EVE) method in the field | 10 | EV sound concepts, preference | Slight preference for quiet EV sound concepts and request of situational operational feedback; inconsistent opinions regarding new concepts and tangible recommendations |
| Gwak et al. (2014a) | Semantic differential in a listening test in laboratory mock-up vehicle | 27 | Preference modified EV sounds, semantic descriptors | Additional subharmonics prove to be an effective sound modification method to enhance interior soundscape; the number of tones and frequencies should be chosen carefully and below 600 Hz for dynamic impression; customer group dependent preferences |
| Gwak et al. (2014b) | Listening test in a laboratory half-frame demonstrator car with video; multiple choice of describing adjectives for sound image evaluation | 30 | Comparison of sound modification approaches, intensity of acceleration sensation, sound image, overall preference | Both methods are effective in increasing acceleration sensation; additional subharmonics to high-frequency components leads to loudness increment, while adjustment to time gap method improves acoustic feedback without level increment though it reaches less preference |
| Swart & Bekker, (2014) | Jury test in a laboratory; semantic differential and ranking method | 17 | Customer satisfaction with sound for EV, semantic descriptors (e.g., sportiness and powerfulness) | Sporty ICEV sound preferred over EV sound; though semantics of “rumbling,” “powerful,” and “deep” are ascribed to EV sound, less sportiness and powerfulness is perceived |
| Yamauchi & Feng, (2014) | Listening test in laboratory and experiment in driving simulator; paired comparison | 10; 20 | Harmonization of audio and visual stimuli, effect of driving action on acceleration impression | Frequency-shifted stimuli are perceived as having a greater acceleration; higher frequency bands with greater effect; broader frequency shifts perceived as a stronger acceleration; driving task/interaction shows no effect |
| Küppers, (2015) | Listening test in a studio/laboratory and a driving simulator, interactive experiment in a demonstrator vehicle; rating, questionnaire and semantic differential | 35; 30; 40 | Acceptance and preference of synthesized sound concepts and description of sound characteristics | Synthesized sounds were generally accepted; wind roll noise in driving simulator accepted and perceived as pleasant, while load feedback was requested and genuine EV noise was perceived as least pleasant and most artificial; in on-track test in a vehicle demonstrator only 14% chose to switched-off sound, most participants preferred ICEV-resembling sounds |

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TABLE 3 (Continued) Overview of the summarized literature of Cluster C.

| Source | Method and test environment | N | Evaluation parameters | Conclusions |
|-------------------------------|---|----|---|--|
| Sontacchi et al. (2015) | Listening test in a laboratory; rating and verbal description | — | Identification of differences, verbal description of sound samples | Quietness is generally preferred, but load-dependent loudness and increase in amplitude modulation benefits sportiness and acceleration impression, as well as assist drivability as the driver is given operational feedback; sound descriptions seem gender-biased as only male participants use positive and energy-related terms, while females use versatile descriptors |
| Andersson et al. (2016) | Listening test in a laboratory; MUSHRA test method | 18 | Influence of magnetic noise in e-PTs and different modulation techniques/switching frequencies on perceived sound quality (annoyance); psychoacoustic metrics | Space Vector Modulation (SVM) does not improve sound quality; for the first three speed segments, perceived annoyance is higher with discontinuous pulse width modulation (DPWM), but until field weakening region, DPWM affects sound quality positively; loudness metrics, SPL, and sharpness with greatest impact on perceived annoyance; for tonal components tonality metric is to be preferred instead of PR or TNR |
| Labeye et al. (2016) | Longitudinal field study with three time points (T0, T1 = 3 months, T2 = 6 months); questionnaires and travel diaries | 36 | EV driving experience and impact of vehicle quietness on driving behavior | Though quietness is mostly seen as a safety issue, participants perceive it as an advantage, while they also report a higher need for attention for their driving environment as well as altered driving behavior |
| Lee et al. (2016) | Exploratory study in lab-setup with driving simulation and questionnaire with 7-point-Likert scales | 42 | User Experience of interior driving sound in EVs; satisfaction, emotion, usefulness | Contextual information and quietness of EVs influence the general user experience of driving an EV as driving sound influences the driver's emotions and perceived satisfaction and usefulness |
| Matuszewski & Parizet, (2016) | Listening test in a laboratory; pairwise comparison and absolute rating (0–1,000 with a slider) | 19 | Sound quality (unpleasantness); psychoacoustic metrics | Conventional psychoacoustic metrics are partially applicable for EV evaluation; due to mid and high-frequency components metrics like PR should be included; A-weighted SPL remains important predictor for perceived unpleasantness |
| Ma et al. (2017a) | Listening test in a laboratory; semantic differential with bipolar pairs | 20 | Sound quality (annoyance) of EV interior noise, semantic descriptors and psychoacoustic metrics | Noise profile at low speeds is described as pleasing, sweet, and pure but weak and unobservable leading to a weak dynamic impression; higher speeds with increased electromagnetic, wind and tire noise components are described as annoying, harsh, powerful, promiscuous, and perceptible decreasing perceived sound quality |
| Maunder & Munday, (2017) | Survey on individual desktop set-up | 30 | Expectations and semantics regarding EV sound and acoustic feedback | More conventional vehicle sound and rumbling noise, referred to as powerful and sporty, seems to be expected, while typical ICEV sound does not meet the expectation of environmentally friendly EV; segmentation in interest groups: 1) largest group focusing on power aspect, requesting acoustic augmentation in interior and preferring ICEV resemblance, 2) recognizing the need of acoustic feedback but advocate novel sound concepts, 3) preferring genuine EV sound seeing no requirement for sound augmentation |

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TABLE 3 (Continued) Overview of the summarized literature of Cluster C.

| Source | Method and test environment | N | Evaluation parameters | Conclusions |
|-----------------------------------|---|----|--|---|
| Fang et al. (2018) | Listening test in a laboratory; 10-point rating scale | 30 | Perception of acoustic harmonics and effect on sound quality (annoyance) in EV noise and psychoacoustic metrics | Sound quality prediction model is established with Support Vector Machine (SVM) method; high associations between subjective data and metrics of sharpness and sensitivity, which seem to represent high-frequency components in a range for which the human hearing is very sensitive to |
| Swart et al. (2018) | Listening test in a laboratory environment: half-anechoic chamber with jury test members positioned equidistant around ball-speaker; forced-choice comparison, sound ranking, semantic differential with bi-polar pairs | 31 | Sound quality in EVs, semantic description of sound character, overall satisfaction, preference regarding different modification methods in sounds | Sound enhanced stimuli are generally preferred compared to standard production sound signature of the recorded EVs; modification methods of low-frequency amplification, high-frequency filtering, low order addition and pitch transposition improved perceived sound quality; describing factors are "Power," "Comfort," and "Deepness" and highest correlations with satisfaction ratings were found for semantic attributes of "pleasant," "exciting," and "comfortable" |
| Fiebig & Schulte-Fortkamp, (2019) | Explorative Vehicle Evaluation (EVE) method; documentation of comments and semi-structured interview | 10 | Perception of different EV sound concepts | All sound concepts provoke negative and positive feedback; the synthetic sounds provoke more feedback overall and more negative than positive comments; results demonstrate target conflict between general preference for quiet vehicles and wish for load adequate acoustic driving feedback |
| Lennström et al. (2019) | Listening test in a laboratory/sound studio; 11-point rating scale, binary response format | 20 | Perceived pleasantness in EV interior noise focusing on tonal components below 1 kHz and detection of tones; tonality metrics | Detection rate for low frequencies (200 Hz) is very low independent of tone level; increased detection rate for higher frequencies (400–900 Hz) and level-dependent perceived pleasantness (the louder, the less pleasant) in this region; tones in the region of 200–400 Hz were rated rather constant suggesting to be perceived as not disturbing; tonality metrics of PR, DIN Tonality 45681, ECMA-74 Tonality and ECMA-74 Tonality modified show detection accuracy of 80% and higher; only significant correlation between subjective data and ECMA-74 Tonality (-0.67) suggests that metrics merely model tonality but are not capable of modeling sensation of pleasantness |
| Swart & Bekker, (2019) | Listening test in an anechoic chamber over headphones; semantic differential with bipolar pairs, 10-point rating scale; single value approximation to establish new metric | 31 | Customer satisfaction with EV driving sound and semantic description; psychoacoustic metrics | Three main factors in semantic analysis: "Comfort," "Power," and "Futuristic"; "exciting" and "quiet" show weak links to customer satisfaction, whereas "pleasant," "comfortable," and "calm" show high correlations to subjective data; several significant correlations between semantic descriptors and psychoacoustic metrics, but no significant link for the descriptor "sporty"; customer satisfaction model is established through single value reduction model including metrics of sharpness, impulsiveness, and fluctuation strength; sharpness with predominant influence on satisfaction ratings |
| Allman-Ward et al. (2020) | Jury test in a laboratory and real vehicle driving scenario; ranking method and single choice | — | Preference for different EV interior sound concepts | One modified sound concept reached a common preference of almost 50% of the sample; basic interior noise without any modification picked by 8% indicating appeal of quietness as well as active sound enhancement |

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TABLE 3 (Continued) Overview of the summarized literature of Cluster C.

| Source | Method and test environment | N | Evaluation parameters | Conclusions |
|--------------------------|---|----|---|--|
| Lanslots et al. (2020) | Jury test in a laboratory; paired comparison | 10 | Preference for different EV interior sound concepts; psychoacoustic metrics | Sound resembling a V8 motor scored the highest preference, followed by the sound resembling an ICEV pickup truck; sound variants stayed the same in their roughness values, whereas differences in loudness, sharpness, articulation index, tonality, and PR ratio are found |
| Valeri & Pietila, (2020) | Jury test in a laboratory; paired comparison method and semantic differential | — | Preference for different EV driving sound concepts and semantic description | Tone reduction leads to a less sporty, exciting, or futuristic impression; addition of order harmonics enhances the impression of sportiness and excitement while reducing perceived smoothness, effortlessness, and harmony; musical approach leads to more futuristic, pleasant and harmonious impression but is perceived as less sporty, exciting, and natural; great diversity in customer preferences but sound enhancement has impact on overall product impression |
| Melman et al. (2021) | Fixed-base driving simulator experiment, within-participant design; questionnaire and semantic differential | 32 | Perceived sportiness (illusion of sportiness) in EV sounds and effectiveness of different modification methods; perceived driving task effort | Artificial Engine Sound (AES) as a suitable measure to increase perceived sportiness as well as improve driving behavior in terms of speed control; Modified Throttle Mapping (MTM) did not significantly enhance the sportiness illusion and led to fluctuating pedal movement |
| Münder & Carbon, (2022) | Experimental study in fixed-base sound simulator car with 3D ambisonic acoustics; repeated evaluation | 65 | Perceptibility of e-powertrain noise and perceived quality | Perceived e-powertrain noise with strong influence on perceived quality; the relation between perceived e-powertrain noise and quality are load and use case dependent; NVH experts tend to be more critical in their quality assessment; auditory modality contributes to perceived product quality overall |

Note. We do not claim the tabular summary to be complete. For further information on the specifications of parameters and methods, we would like to refer to the respective source articles.

different approaches of assessing qualitative feedback from customer studies, collecting subjective data in experimental studies, analyzing measurements for psychoacoustic metrics, or computing intricate models with conducted perception data to improve the prediction of perceived sound quality and customer satisfaction. Nevertheless, the general question of how the interior soundscape of electrified vehicles should be designed remains unclear. Though the displayed research bears valuable evidence on what might acoustically be preferred or rejected in a customer's point of view, it also becomes evident that not even customers are yet aware of their needs and expectations regarding the composition of interior soundscapes in EVs. The findings so far are volatile due to minimal experience driving electrified and most likely also a lack of knowledge about design possibilities of acoustic enhancement strategies. For now, the general strategy of how to acoustically configure or even stage EVs is left up to each vehicle manufacturer and might possibly look like suggested by

Sinambari and Sentpali (2020): either leaving the natural soundscape as it is with its typical occurring NVH characteristics due to the vehicle's electrification and possibly refining this inherent noise, or adding artificially generated sound to the vehicle amplifying its operational feedback and enhancing specific product features – whether these sound concepts reminisce familiar combustion noise characteristics or embody a completely novel soundscape conveying innovative impressions is yet to be determined. The long-lasting association of vehicle power and noise with increasing acceleration seems to be etched in our minds, but now with the potential of silent EVs is challenged and described by Borg (2014) to be contradicting “a lifetime of experiences and expectations about cars and sound” (p.287), as it has been formed over decades. History, though, reveals contemporary associations between performance parameters of vehicles and their acoustic feedback, as silent automobiles have been appreciated and declared luxurious in the first half of the 20th

century (Krebs, 2016). The now presented opportunity of freely creating novel soundscapes in EVs poses a challenge but at the same time, might help break up such conventions and possibly enrich the variety of how to shape driving experiences through novel soundscapes in the future.

The discussed research in this article highlights the importance of scientifically substantiated approaches to gather subjective data on the perception of the matter. Classic acoustical measures like the overall SPL or analyses of frequency bands will not sufficiently explain variances in customers' perception of the product. Nor will psychoacoustic measures, attempting to objectify subjective perception data, be sufficient on their own if not validated through an adequate data sample of subjective assessments in the targeted application context. Especially context-related and novel evaluation approaches should be endorsed in future research to understand how customers evaluate novel soundscapes for EVs and how they build their expectations towards the respective product. Approaches like the EVE-method (Genuit & Fiebig, 2014; Fiebig & Schulte-Fortkamp, 2019), as well as naturalistic driving studies (Cocron et al., 2011) help to gain externally valid insights on customer behavior and evaluation. To better understand dynamic effects in customer perception, multiple measurement time points are needed to compare the evaluation data over the course of time. This can be done with multiple measurement points through, for example, interviews in externally valid environments (Labeysse et al., 2016), or through approaches such as Repeated Evaluation (Carbon and Leder, 2005) that proved to be effective in controlled laboratory environments to offer a high degree of stimuli evaluation in a pretty short period of time. Moreover, person-related variables such as general driving experience, age, or former experience in driving electrified should be considered to gain customer-group-specific insights on how to target specific sound profiles in EVs.

Conclusion

The reviewed literature in this overview illustrates the uncertainties in customer expectations regarding the configuration and design of EV noise and sound. Human-centered, systematic, and experimental approaches to assess data on the human perception of EV interior soundscapes are needed to counter these yet volatile circumstances and challenges

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in customer needs. Participants need to be offered more extended elaboration with novel sound concepts in externally valid contextual settings, allowing them to explore their preferences and build their expectations. Only this way, we will be able to better understand dynamic effects in perceived quality and preferences regarding novel soundscapes, as well as to collect valid evaluation data on different enhancement strategies to derive design and target guidelines for acoustic automotive development.

Author contributions

MM had the initial idea to summarize the current research achievements on perception of interior soundscapes in electrified vehicles to determine the state-of-the-art in the field. C-CC contributed insights from aesthetic and perception research in automotive contexts and supported in matters of conceptualization and structure. MM and C-CC further worked on the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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3 Perception of E-Powertrain Noise

A special focus within my dissertation is directed towards the perception of the NVH phenomena originating from the electrified powertrain. As described in section **1.2.2 Acoustics of Electrified Powertrains**, powertrain-related noise emissions are one of the main acoustic contributors to a vehicle's interior soundscape. Therefore, it is crucial to the acoustic experience while driving a vehicle. With the technological changes brought about by the electrification of vehicle components, perception-related findings regarding customer satisfaction in vehicle acoustics also need to be revisited. The next chapter includes two of my publications (*Manuscript #2* and *Manuscript #3*), which are primarily dedicated to the perception of e-powertrain noise. In both studies, we asked the participants to evaluate the interior noise of different EVs in different acceleration scenarios. We followed a *Path #2* testing approach (Carbon, 2019a), aiming for high ecological validity while maintaining experimental control.

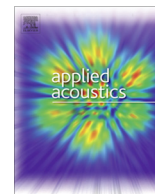
Both studies were conducted in the same highly sophisticated acoustic simulator built from a real vehicle. The vehicle is stationary mounted and equipped with a horizontal six-layer 3D audio system with over 150 loudspeakers, allowing the realistic replay of acoustic recordings through the physical principle of wave field synthesis within the vehicle cabin. Through this, three-dimensional acoustic measurements could be rendered and realistically replayed in the simulator environment. The measurements for both studies were conducted on the same BMW test track, following a standardized measurement protocol and using the same measurement technique. As the recordings were done with a 3D microphone, they contain the transmitted noise, including other noise sources, such as wind or rolling noise, apart from the sole e-powertrain noise, and therefore represent a naturalistic emulation of the overall soundscape within the vehicle's interior. In both studies, the acceleration conditions of slow, comfort, and full acceleration were evaluated (Münder et al., 2024; Münder & Carbon, 2022b), while in Münder and Carbon (2022b), the impression of the recuperation process was additionally asked for. Though the simulator is stationary, the projections of a realistic driving scene onto the windshield and side windows lead to a highly immersive experience within the simulator's cabin. The main difference between the two studies lies in the applied evaluation methods (repeated and continuous evaluation), which were, to our knowledge, both introduced to the field of vehicle acoustics for the first time. Please find the two manuscripts in the following sections: **3.2 Howl, Whirr, and Whistle: The Perception of Electric Powertrain Noise and Its Importance for Perceived Quality in Electrified Vehicles** and **3.4 Unfolding Dynamics in the Perception of Interior Vehicle Acoustics via Continuous Evaluation Procedure (CEP)**.

3.1 Introduction to the Study on Repeated Measures and E-Powertrain Noise

In Mnder and Carbon (2022b; *Manuscript #2*), we examined the interrelation of e-powertrain noise and its perceived quality conveyed by the acoustics of different electrified vehicles. The recordings of different acceleration and deceleration scenarios were evaluated using the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005), which allows for the elaboration of the acoustic stimuli. This allows dynamic aspects to be considered when assessing acoustic impression evaluations. The participants' task was to evaluate how perceivable the e-powertrain noise was to them and how prominently it stood out within the overall soundscape.

In addition to the published findings in our manuscript, our findings contributed to the validation of an internal NVH-analysis tool at the BMW Group, which aims to represent and evaluate the subjective perception of e-powertrain noise. The manuscript, published in *Applied Acoustics*, is embedded in its full length and original form on the following pages.

3.2 Howl, Whirr, and Whistle: The Perception of Electric Powertrain Noise and Its Importance for Perceived Quality in Electrified Vehicles



Howl, whirr, and whistle: The perception of electric powertrain noise and its importance for perceived quality in electrified vehicles

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ABSTRACT

The technical specifications of electrified vehicles (xEVs) will drastically change the way future vehicles might sound compared to conventional vehicles with internal combustion engines (ICEVs). The electrified powertrain is responsible for a profoundly different profile in vibro-acoustical characteristics (NVH: noise, vibration, and harshness) and offers the opportunity to create specific sounds related to certain requirements and endorsing associations for increasing the user experience and aesthetic appreciation. The present study's main aim was to evaluate the perceived emergence of the electric powertrain noise and its implications for perceived quality conveyed by it. Utilizing a sophisticated acoustic simulator presenting ambisonic 3D stimuli from eleven different electrified cars in four different driving scenarios, $N = 65$ participants evaluated the perceptibility of e-powertrain noise and perceived quality of the vehicle's interior soundscape. We revealed the auditory modality as an integral part of assessing the product's quality and gathered qualitative reference points for further investigations.

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1. Introduction

As eco-friendly mobility becomes an increasingly societal objective, technical progress and competitive pressure drive the electrification of vehicles. The progression to alternative powertrains presents manifold challenges to the automobile industries and can be described as non-linear and disruptive development [1]. Due to a radically different acoustical profile of xEVs (generic term subsuming any kind of electrified vehicle) compared to the conventional internal combustion engine vehicles (ICEVs), versatile questions in the development of vehicle acoustics are posed. Facing these changes, acoustic engineers are challenged with reconsidering the optimization process of the differently shaped vibro-acoustical phenomena [2,3], commonly subsumed under the umbrella term NVH (Noise, Vibration, and Harshness). As a main source of various NVH phenomena [4] the vehicle's powertrain holds a key role in the context of acoustical refinement in xEVs.

How we perceive and experience a vehicle is based on multiple variables, which can be differentiated in the degree of their immediate perceptibility. Multisensory information of the product's

characteristics is perceived by our different perception modalities and contribute to the overall, the *holistic* experience [5]. Aside from the visual appearance conveyed to the observer by the vehicle's shape and design, its sound and vibro-acoustical characteristics are the most immediate perceptible features and, therefore, vital components in terms of customer satisfaction [2,4,6,7].

The present contribution mainly focuses on the driver's perception of e-powertrain noise and its implications for the quality impression conveyed by it to better estimate its importance in terms of overall customer satisfaction. To do justice to the experiential side of e-powertrain noise, we pursued a methodological approach which is based on a psychophysics testing framework. We followed a Path #2-testing strategy according to Carbon [8]: We employed a typical car driving context by situating participants in a real car equipped with immersive 3D ambisonic sound capabilities; this leads to ecologically valid testing while preserving the controllability of a lab-based experimental setup.

2. Theoretical background

The resulting implications from powertrain electrification are manifold for both – exterior and interior noise. With the driver's acoustic experience being the focal point of the following contribution, we will be focusing on the interior soundscape. This is done

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by first elaborating on the novel and radically different acoustic xEV profile. Subsequently, psychological constructs like perceived quality and associations and methods of assessing subjective data in listening tests will be considered in a differentiated manner.

2.1. Acoustic profile of the xEV

In the past decades, the acoustic quality of vehicles steadily improved in terms of an overall reduced sound pressure level (SPL) [2]. With the shift from conventional powertrains to electric powertrain concepts, we inherently observe a new, abrupt decrease and change in the overall noise emission. When comparing xEVs with ICEVs, the powertrain configuration has the most extensive implications regarding the resulting noise emission and NVH characteristics, which are often described as howling, whirring, or whistling. The much more muted powertrain concepts can lead to an up to 20 dB lower SPL(A-weighted) in full acceleration mode in xEVs than in comparable ICEVs, according to Blickensdorff et al. [9]. This opens opportunities to creating vehicles in an acoustically novel way, offering extraordinarily pleasing and quiet interior soundscapes with potentially high acoustic comfort. This relative quietness comes at a price as the low absent powertrain noise might even *unmask* various disturbing noises like external noise, wind and tire noise or whining and whistling from auxiliaries and power electronics [3,9,10]. Those sources of noise might have never been perceived as being problematic, disturbing, or irritating in a much louder conventional sound context of ICEVs. Still, now, being unmasked in the xEV's sound profile, the interfering noises possibly need to be reassessed and probably also be optimized in the long run [2].

Not only has the SPL changed but the characteristics of the whole sound profile. Actually, the acoustic profile of xEVs significantly deviates from the one of ICEVs: Instead of the ICE-typical broadband noise spectrum, which is dominated by engine orders and its harmonics in the frequency range below 1 kHz, e-powertrain noise is characterized by higher frequencies and tonal components in the subjectively relevant range from 1 to 10 kHz, for which the human hearing apparatus is particularly sensitive [9,10]. The noise in xEVs is often accompanied by relatively stronger wind and tire noise. Electric powertrains show characteristic switching noise caused by the power electronics, also known as Pulse Width Modulation (PWM), usually varying in the frequency range from 250 Hz to 20 kHz. Research about the discomfort this might induce is still rare, but such switching noise might be perceived as quite unpleasant [11]. As found by psychoacoustic investigations [12–14], the significantly quieter xEVs are potentially more annoying and less acceptable from a customer's viewpoint since their acoustic profile is characterized by higher frequencies and tonal components.

2.2. Perception of e-powertrain noise

Considering the specific acoustic profile of xEVs, which might be perceived as unfamiliar [9] and at times even as unpleasant and annoying [10,12], we focused on the perceptibility of e-powertrain noise and its impact on the overall quality impression conveyed by it. In contrast to physical metrics and technical-objective vehicle characteristics, as for example, performance parameters, we focus on the driver's perception and aesthetic appreciation of the vehicles' soundscape as they are mostly key to market-relevant dimensions such as comfort and overall product quality impression [5]. A soundscape is defined by the International Organization for Standardization in the ISO 12913-1 as an "acoustic environment as perceived or experienced and/or understood by a person or people, in context" [15]. This approach is considerably more challenging to address than merely using

technical measurement on a test bench [16]. Nevertheless, especially specific interferences of noises, which become salient to human ears, but are hard to identify and localize by automatic routines, yet make this approach even more appealing. With NVH phenomena being immediately perceivable qualia, e-powertrain noise contributes to shaping the user's experience and thereby carries a large share of the overall customer satisfaction [2,4,7] and contributes to successful product development [17]. Thus, we want to gain insight into the relation of perceived e-powertrain noise and its associated overall product quality.

When it comes to the term *quality* in the context of acoustics, one can find a wide variety of definitions and approaches to this construct. Sound quality for instance, can be defined as the adequacy [18] or suitability [19] of a sound that is being emitted by a technical object, evolving from a process where multiple quality features are situationally compared to one another [20]. Genuit [21] suggests acoustic quality to be composed of three different influential aspects: 1) the *physical sound* (sound field), 2) *psychoacoustics* (auditory perception), and 3) (further) *psychological aspects* (auditory evaluation). As we focus on the driver's perception of e-powertrain noise and their individual subjective assessment of its conveyed product quality in this study, especially the so-called *psychological aspects*, play a vital role. These psychological aspects include affective, cognitive, and situational factors [17,22]. Altogether they contribute to an overall *percept* rather than just representing a mere sensory perception in the auditory apparatus [15]. According to Styliadis et al. [23], sound quality is a component of *technical perceived quality* (TPQ), which again is a subset of the *value-based perceived quality* (VPQ). The VPQ embodies the total customer experience taking the multimodal components of the TPQ such as visual, haptic, acoustic, and olfactory product attributes into account, as well as external factors [23]. In the realm of this paper, we will prefer the term *perceived quality*, which is conveyed by the acoustic scene, operationalized here by different e-powertrain examples. Related to the construct of sound quality, Genuit et al. [16] further mention the *object-related quality impression*, which emerges from specific product criteria in the sense of the sum of the object's quality itself. Referring to the axiom of Gestalt psychology – *the whole is greater than the sum of its parts* [24] – the quality impression conveyed by the vehicle's acoustic characteristics though is still only one part of a wholesome vehicle experience, serving a single modality. Pioneer perceptual scientist Gustav Theodor Fechner already proposed this Gestalt view in 1866: "the beauty of a whole [...] will [...] not [be] diminished but [...] increased in the way that the whole surpasses the parts" [25, p.7]. Different vehicle characteristics can be perceived via one or more perceptual channels and contribute to the overall constructs, such as vehicle comfort impression [1] or perceived product quality [23]. Eventually, the coherence of the general concept – the total vehicle – is most relevant. Still, to derive the potential for improvement, this general construct needs to be broken apart into the different perception facets and each assessed for themselves [16].

The auditory evaluation results in individual impressions, which are strongly modulated by memory associations – a central principle of cognitive sciences. In aesthetic theory, this idea is originating in Fechner's *Aesthetic Association Principle* (AAP) [25]: the impression of an object conveyed by a sensation – in our case, the acoustical scene conveyed by the vehicle and its e-powertrain – is ultimately linked to the individual's memory and former experience, as they are merged with the current sensation into a coherent percept. Though this principle is widely used in visual perception, Fechner also mentioned the capability of acoustics, regardless of whether it is music, a soundscape, or a distinct acoustic stimulus, to be utilized to create and guide certain associations [25]. For instance, there is strong evidence for

music-to-color associations, which appear to primarily result from a common, mediating emotional association [26–30]. From Fechner's AAP [25] methods like the so-called ASIP (Associated Imaginations on Sound Perceptions) have been derived during the BRITE-Euram EU-Project 96-3727 "OBELICS" (Objective Evaluation of Interior Car Sound) as an approach to systematically analyze affective reactions to interior vehicle sound [31], as well as the EVE-method (Explorative Vehicle Evaluation) as a more practical approach to evaluate target sounds in their original on-road driving context [32]. Moreover, the work of Fiebig et al. [33] depicts recent research on how even subtle acoustic information – defining the contextual soundscape of the given environment – can influence the human affective response.

Another relevant and linked aspect is the consideration of individual factors when assessing subjectively perceived constructs confounded with affective, cognitive, and situational variables. Genuit and colleagues [16] highlighted the relevance of the individual frame of reference when acoustic events are evaluated, due to their comparison with former experiences, and bring on the term of *introspective matching*, which can be based on real experience, assumptions, expectations or also associations. For instance, driving a vehicle has been accompanied by the ICE-typical sound profile for decades for many people and thereby formed their horizon of experience. Customers thereby adapted to certain sound patterns in reference to different operational situations and now expect and associate specific patterns within their situational driving context. In conclusion, perceived quality is not an absolute measure due to its dependency on particular personal and contextual variables. Considering the novel acoustic profile of e-powertrains, with which most people are still quite unfamiliar with, it is essential to find out to what extent e-powertrain noise is related to the individual quality impression when it comes to reassessing this customer-relevant feature.

2.3. Methods to assess subjective measures in NVH development

In the field of vehicle acoustics, perceptual evaluation is pursued by a variety of methodological approaches. Classical approaches are laboratory listening tests, jury testing, semantic differentials, pairwise comparison, or ranking tasks, categorical evaluation, and magnitude estimations [16,34,35]. Strict laboratory and experimental listening tests (so-called Path #3 testing according to Carbon [8]) are predominantly used to assess psychoacoustic measures like loudness, sharpness, tonality, or roughness, but lacks ecological validity as it neglects contextual variables and does not do justice to the complexity of the listener's real-life-percept [16]. On the contrary, real vehicle testing (so-called Path #1 testing according to Carbon [8]) images the contextual variables of the real-life driving scenarios to the full extend and includes the factor of driver-vehicle interaction but lacks the standardization and reproducibility of testing conditions. For instance, approaches like the EVE-method (Explorative Vehicle Evaluation) aim to investigate on affective reactions and noise evaluations of the participants in the original context and thereby, create test surroundings close to reality [32]. Genuit et al. [16] suggested combining approved methods from the field of psychoacoustics with explorative approaches from the field of social sciences to evaluate vehicle acoustics in a standardized, controlled environment, yet taking evaluation relevant context factors into account. Especially when assessing complex constructs, such as the perceived quality of e-powertrain noise in dynamic use case scenarios, the consideration of various context factors is inevitable. As e-powertrain noise is a somewhat novel and uprising phenomenon, studies with subjective evaluations regarding perceived quality and customer satisfaction are relatively rare. For instance, a promising study is the jury testing for xEVs in wide open throttle conducted by Swart and Bek-

ker [36], which provides insights on how the acoustic profiles have an impact on customer satisfaction and comfort evaluation. Here, participants evaluated the stimuli on a desktop computer in an anechoic chamber over headphones.

3. The present study

The main aim of the present study was to evaluate the e-powertrain noise of xEVs in an immersive testing environment regarding its perceptibility through naturalistic driving noise and its conveyed quality impression – this ensures ecological validity while experimental control is preserved (so-called Path #2 testing according to Carbon [8]). Therefore, 3D recordings of eleven different electrified vehicles in four different driving scenarios were evaluated by a sample of sixty-five participants in a sophisticated static acoustic simulator. Instead of assessing single value responses, the methodological evaluation procedure followed the *Repeated Evaluation Technique* (RET) developed by Carbon and colleagues [37–39].

4. Method and experiment

4.1. Participants

The required sample size ($N \geq 55$) was calculated in a *priori* power analysis using G*Power [40] for multiple linear regressions, assuming a medium effect size $f = 0.15$, the error probability of $\alpha = 0.05$ and aiming at a statistical power ($1-\beta$) of 0.80. Participants were recruited and invited via e-mail in the company-internal specialist department for acoustics and vibration as well as in departments for other technical, research-related fields, but also non-technical divisions. There were no restrictions regarding participation in the study except normal hearing ability, which had to be confirmed preliminary to the experimental testing. 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). Participants were informed about their right to withdraw themselves and their data from the study without consequences and without stating reasons. Written informed consent was then given by each participant prior to the experimental testing. Details and rationale of the study were discussed with every participant on the completion of the experiment. The general study design (psychophysiological testing) was given ethical approval by the ethics committee of the University of Bamberg.

4.2. Material and customer-relevant use case scenarios

The driving noises of eleven different xEVs—nine battery electric vehicles (BEVs) and two hybrid electric vehicles (HEVs; operated in electric driving mode only) – were recorded with the 3D ambisonic microphone Ambeo VR Mic from Sennheiser (four channels, first order ambisonic) on a test track of the BMW Group following a standardized measurement protocol. A 3D ambisonic audio format was chosen over binaural format, as to achieve a highly immersive acoustical scene in the sophisticated experimental environment of the used simulator. To achieve a broad frame of reference of available xEV models on the market, we included test vehicles across the whole price segment from different manufacturers. Additionally, to a scenario with full acceleration like in the study of Swart and Bekker [36], further driving scenarios were included: slow acceleration (0.5 m/s^2), comfort acceleration (2.5 m/s^2), and shear/recuperation (rolling out from 100 km/h , i.e., 27.7 m/s , until stop). This was done to follow the so-called

scenario-based testing idea by Jakesch et al. [41] to maximize the external validity of testing. These scenarios reflect situations with various de- and acceleration rates that represent the rich experience bandwidth of customers in real life. The obtained 3D recordings of the eleven vehicles in the four use case scenarios were then rendered to a suitable format for the highly sophisticated acoustic simulator. Utilizing this experimental environment, we were able to present the acoustic stimuli in a highly ecologically valid environment via wave field synthesis while targeting a significant amount of experimental control (see Carbon [8]).

4.3. Apparatus and naturalistic evaluation context

To generate a high degree of ecological validity for the e-powertrain noise evaluations, we aimed for an immersive test environment simulating real-world experience most adequately. Utilizing a highly sophisticated static acoustic simulator built out of a complete vehicle (BMW 5 series belonging to the executive car segment), including physical door opening, full functioning cockpit and complete interior equipment, we were able to provide highly realistic context information. To acoustically emulate a naturalistic driving scenario, our stimuli measurements included general driving noise from typical automotive NVH sources. Therefore, the acoustic scene consisted of different road-, tire-, wind- and powertrain-related NVH sources, which all contribute to the overall SPL to a varying extent, depending on the respective driving situation [4,6]. Utilizing the physical principle of wave field synthesis combined with a six-layer 3D audio system in the simulator, sound recordings from the test track measurements were realistically reproduced in the experimental environment. This technical and experimental setup allowed us to virtually switch between different xEV models without any physical change of test vehicles or the need to reseat the participants. Additionally, it gave us the freedom to randomize the order of trials easily and quickly.

Employing this sophisticated acoustic playback in a physical, real car allowed us to address other modalities which are typically accompanied when experiencing a car’s soundscape. For instance, haptic information was provided as participants were seated on the driver’s seat, accessing the vehicle’s cockpit, including a real steering wheel and pedal set. Additionally, visual information was provided via a speed-accurate video projection of an artificial landscape onto the window surfaces and a speed indicator, referencing the respective speed and acceleration rate. Furthermore, contextual information about the relevant use case scenario before each test block was provided to each participant by the experimenter’s instructions.

4.4. Test block design

The four recorded driving scenarios were represented by four different test blocks. In consultation with a team of specialists from the department of powertrain acoustics, the stimuli for each test

block were selected from the eleven xEV-recordings. The selection criteria were a balanced subset representing the whole bandwidth of xEV models in all segments available on the market and the actual measurement quality to ensure interference-free playback of the stimuli. Resulting from the selection process, the use case scenarios for slow acceleration (SA), comfort acceleration (CA), and shear/recuperation (SR) each consisted of subsets of seven stimuli and the full acceleration (FA) scenario of a subset of six stimuli. The test blocks then were aligned to the order of a storyline of the slow acceleration (SA) followed by comfort and full acceleration (CA and FA) and finally, the shear/recuperation (SR) scenario. By presenting the stimuli of each test block in three randomized sets, participants were urged to deal with the noise examples more thoroughly as they evaluated them repeatedly [38] – this so-called *Repeated Evaluation Technique* (RET) enforces people to elaborate the material, which leads to more ecological valid testing. Additionally, this means that we gain multiple data points from the same person about the same acoustic event which effectively helps to reduce test errors. With the given repetition pattern, each test block consists of 21 stimuli (three repetitions of the seven stimuli in each subset), 18 stimuli (three repetitions of the six stimuli in the subset) in FA, respectively. The playback of the stimuli in each test block followed a randomized order. For better comprehension, Table 1 shows a sequence of stimulus presentations in the slow acceleration (SA) scenario, which exemplifies the procedure in the other use case scenarios as well. Depending on the underlying performance parameters of the specific xEV, each sound sample was presented for 11–25 s. Especially in FA, the examples were shorter as the full performance of the vehicle was retrieved. In the scenario for SR, no time limitation was given as all files were played until the recorded test vehicle came to a complete stop.

4.5. Procedure

The study on e-powertrain noise evaluation was conducted in a single testing session of 45–60 min per participant. Participants were tested individually. At the premises of the test environment, participants gave written consent (see section 4.1 *Participants*) to volunteering in the study. After a brief introduction to the study’s context, the participants received general information about the simulator, but remained naïve to the specific aim of the study and of the presented xEV noise examples and specifics about the repetition of playbacks. The data was obtained via a pre-programmed questionnaire on a tablet equipped with a survey tool. After the introduction by the study lead and assessing some demographic information of the participant, both test person and experimenter sat down in the simulator – the test person on the driver seat, the experimenter on the passenger seat. There was no interference of the experimenter within each test block unless there were task-relevant questions from the participant’s side.

Table 1

An exemplifying order of a stimulus sequence for the slow acceleration (SA) scenario is depicted for better comprehension. In this exemplified order sequence for SA there were seven different stimuli, each representing a different vehicle recording (indicated by the code V_x, alphabetical enumeration from A to G). All seven stimuli were presented in each of the three presentation sets in randomized order. In total, the test block, therefore, consisted of 21 stimuli.

| Set 1 | | Set 2 | | Set 3 | |
|-----------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|
| Presentation Position | Vehicle Recording | Presentation Position | Vehicle Recording | Presentation Position | Vehicle Recording |
| 1 | V_C | 8 | V_E | 15 | V_D |
| 2 | V_E | 9 | V_D | 16 | V_A |
| 3 | V_B | 10 | V_F | 17 | V_F |
| 4 | V_A | 11 | V_A | 18 | V_B |
| 5 | V_F | 12 | V_B | 19 | V_G |
| 6 | V_D | 13 | V_G | 20 | V_C |
| 7 | V_G | 14 | V_C | 21 | V_E |

The stimuli were evaluated on two different dimensions: 1) *Perceived Emergence* and 2) *Overall Quality Impression*. For the first dimension, *Perceived Emergence* of the e-powertrain noise, we were interested in finding out to which extent the e-powertrain noise sticks out of the overall soundscape. This was done by using a scale for subjective evaluations established among the acoustics experts at BMW Group. Participants were instructed to “rate how strongly they perceive that the target signal (typical e-powertrain noise) breaks through the acoustical carpet” via a five-point Likert scale (1 = *inaudible*, 2 = *quiet*, 3 = *discreet*, 4 = *present* and 5 = *dominant*). The second dimension *Overall Quality Impression* aimed at assessing the overall quality impression conveyed by the specific acoustic scene considering the perceived e-powertrain noise. We again employed a five-point Likert scale, this time with the following labels: 1 = *high-quality*, 2 = *rather high-quality*, 3 = *neutral*, 4 = *rather low-quality*, and 5 = *low-quality*, and asked the participants to “rate the overall quality impression conveyed by the holistic acoustic scene considering both, general driving noise and e-powertrain noise”.

The stimuli were presented in a randomized order of the described test block design. Participants were asked for their ratings of the xEV’s e-powertrain noise after each stimulus presentation. Physical response was realized via a tablet computer placed in the central console of the simulator. In general, participants were admonished to answer the task as spontaneously and accurately as possible. Also, they were asked to consider each stimulus independently rather than to rank the examples amongst each other. Immediately after the ratings were submitted, the next stimulus was presented automatically. The experimenter only interfered during the testing if the participant mentioned difficulties in understanding the task. In between test blocks, the participants were given a short listening break. Then the experimenter introduced the subsequent use case scenario. After the last rating was obtained, each participant was asked to provide qualitative feedback about problems with the study procedure, any peculiarities they might have noticed and what they consider indicators for high or rather low quality regarding acoustic characteristics of e-powertrain noise.

5. Results

In the following section, the results of the study are presented. The obtained results were analyzed by using the statistical software R 4.0.3 [42]. After addressing descriptive measures and the data distribution of the ratings, analyses of the relation between the rating dimensions of perceived emergence and perceived quality and their relation to demographic variables and further study parameters are displayed. Finally, an analysis of the qualitative feedback from the participants is presented and set into context.

5.1. Descriptive measures

A total sample size of $N = 65$ participants, of which 48 participants were male (17 female, 0 diverse), 30 participants were from the specialized acoustics and vibrations department (35 of other departments), 37 participants stated their job was related to topics of acoustics and vibrations. With the achieved sample size, the effective test power was 86.7%. The age groups are approximately normally distributed consisting of 6% of the participants being younger than 23 years ($n = 4$), 28% between 24 and 30 years ($n = 18$), 28% between 31 and 38 years ($n = 18$), 23% between 39 and 47 years ($n = 15$), 14% between 48 and 55 years ($n = 9$) and 1% being 56 years and older ($n = 1$).

5.2. Data distribution

The ratings for the perceived emergence and perceived quality of each participant were gathered in the four different use case scenarios for each vehicle. Each stimulus was presented thrice in three consecutive, randomized repetition sets. The mean value for each vehicle in each repetition set was then computed. Fig. 1 shows the rating distribution and mean values (white dots) of the perceived emergence of e-powertrain noise for each vehicle (each indicated by a different color) in each scenario and repetition set.

The employed violin plots give an impression on which distribution the mean values were based on. Some stimuli were

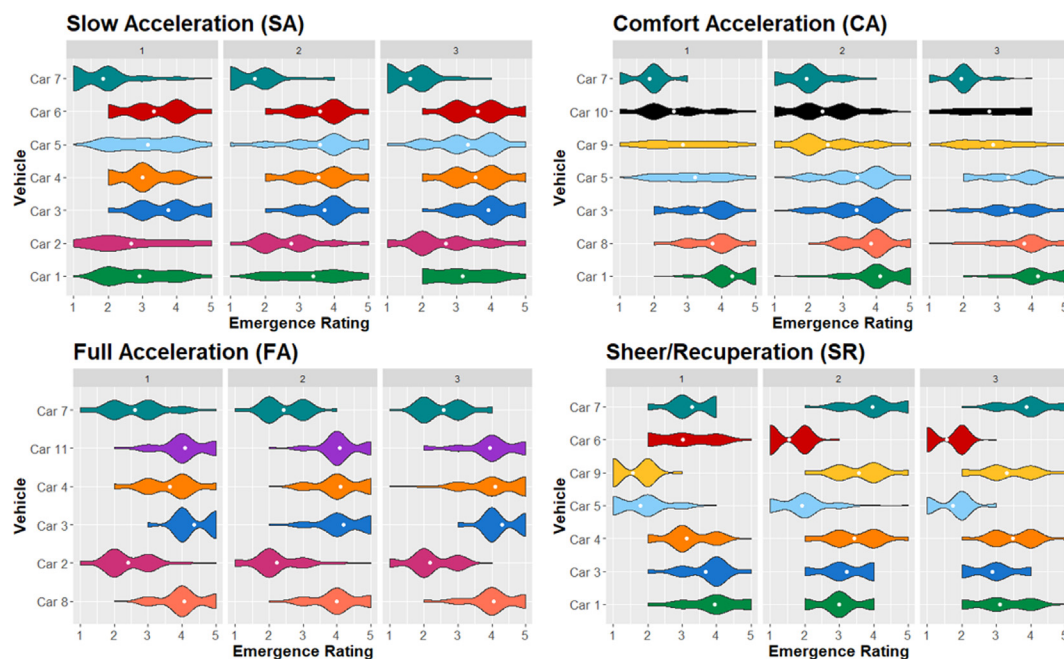


Fig. 1. Rating distribution of perceived emergence in each test block and each presentation set: The emergence rating axis is scaled as follows: 1 = *unhearable*, 2 = *quiet*, 3 = *discreet*, 4 = *present*, 5 = *dominant*; Columns 1, 2 and 3 represent the corresponding presentation number (repetition) of each stimulus.

collectively perceived as either louder (e.g., the graphs for Car 3 in FA) or quieter (e.g., the graphs for Car 7 in CA). Nevertheless, a preliminary view on the data already reveals that the e-powertrain noises could not be assigned to a distinct area on the spectrum universally. One and the same sound example seems to be perceived quite differently amongst the participants since some ratings spread over several rating points. Some stimuli did not show a general trend (e.g., the graphs of Car 9 in CA or the graphs of Car 5 in SA).

The rating distribution (mean represented by a white dot) for the dimension for perceived quality of each vehicle (each indicated by a different color) shows an even wider span overall, indicating an even higher divergence of the participants' perception regarding the qualitative impression e-powertrain noise examples transmits (see Fig. 2). This shows, complex aesthetic evaluation is even more interindividual, and the personally perceived quality of one and the same product can differ tremendously from one person to another. There are only a few exceptions where the violin graphs do not span over the full 5-point-scaled spectrum, e.g., the graphs of the Car 6 in SA.

As we gathered multiple measuring points with the stimulus repetition pattern in each test block, we tested whether the repetition itself affected the ratings. Therefore, we fitted a linear mixed model with the repetition set as a fixed factor and the participant-variable as a random effect using the *lmer*-function [43]. With the given test power, we were not able to detect any significant effects, neither for perceived emergence ($b = 0.02, t(5200) = 1.13, p = 0.26$) nor for perceived quality ($b = -0.01, t(5199) = -0.86, p = 0.39$). The rating patterns do not suggest a general increase of the perceived quality like suggested by the mere exposure effect for liking by Zajonc [44]. It should be noted, though, that liking is not to be compared to perceived quality, and three repetitions might not have been as thorough enough to be qualified as a mere exposure set up [45]. However, such low-frequency presentation effects of mere exposure were rarely documented (e.g., Jakesch and Carbon [46]).

5.3. Relation between emergence and quality perception

For the measures of perceived emergence and perceived quality, we revealed a significant negative correlation of $\tau = -.32, p < 0.001$ (Kendall's Tau for rank-based data) can be found, which can be considered as a moderate relation according to Cohen [47]. Therefore, according to our findings, stronger perceived emergence of e-powertrain noise goes along with lower perceived quality conveyed by the acoustic scene. In Table 2 the correlations between the subjective measures are shown for each use case scenario, all of them being negative. As the correlations vary in the four test blocks, the perceived emergence and the perceived quality seem to be use case scenario dependent. According to the coefficient interpretations after Cohen [47], we find moderate negative correlations between perceived emergence and perceived quality in case of slow and comfort acceleration ($\tau = -.34, p < 0.001$ and $\tau = -.30, p < 0.001$), a small negative correlation in full acceleration ($\tau = -.18, p < 0.001$), and a strong moderate negative correlation in the use case of shear and recuperation ($\tau = -.46, p < 0.001$).

5.4. Relation of perception ratings and demographic variables

For most assessed demographic variables, only non-substantial relations, if even significant, were found (see Table 3). If a partici-

Table 2

Relation of perceived emergence and quality of e-powertrain noise in the four use case scenarios: Interpretation of correlation coefficients according to Cohen [47] as follows: $r \geq .10$ as a small correlation, $r \geq .30$ as a moderate correlation and $r \geq .50$ as a strong correlation. ***= $p < 0.001$.

| Perceived Emergence per Use Case Scenario | Perceived Quality | |
|---|-------------------|------------|
| | <i>r</i> | <i>p</i> |
| Slow Acceleration (SA) | -.34 | < 0.001*** |
| Comfort Acceleration (CA) | -.30 | < 0.001*** |
| Full Acceleration (FA) | -.18 | < 0.001*** |
| Shear/Recuperation (SR) | -.46 | < 0.001*** |

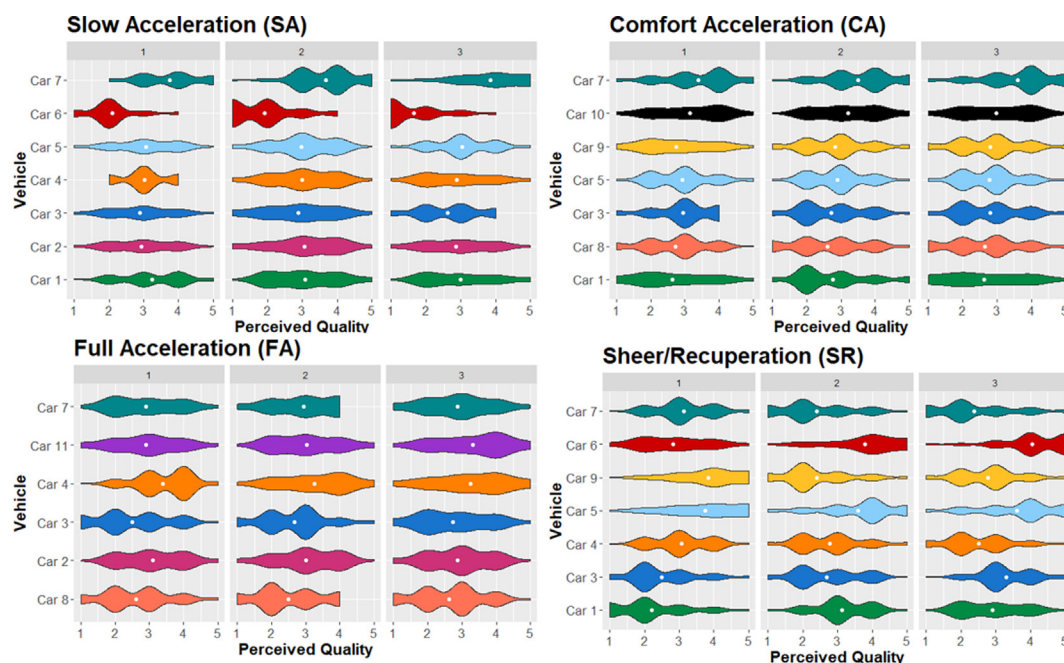


Fig. 2. Rating distribution of perceived quality in each test block and each presentation set: The emergence rating axis is scaled as follows: 1 = low-quality, 2 = rather low-quality, 3 = neutral, 4 = rather high-quality, 5 = high-quality; Columns 1, 2 and 3 represent the corresponding presentation number (repetition) of each stimulus.

Table 3

Influence of demographic variables on perception ratings: Interpretation of correlation coefficients according to Cohen [47] as follows: $r \geq .10$ as a small correlation, $r \geq .30$ as a moderate correlation and $r \geq .50$ as a strong correlation. *n.s.* = not significant. ** = $p < 0.01$. *** = $p < 0.001$. The coding for the different variables goes as follows: for the gender variable: 0 = female and 1 = male; for the age variable: 1 = 23 years and younger, 2 = 24 to 30 years, 3 = 31 to 38 years, 4 = 39 to 47 years, 5 = 48 to 55 years, 6 = 56 years and older; for the department variable: 1 = acoustics/vibrations specialist department, 0 = other; for the professional context variable: 0 = no, 1 = yes; for the variables hearing self-report and hearing report from others: 1 = very bad, 2 = rather bad, 3 = normal, 4 = rather good, 5 = very good.

| Demographic Variable | Perceived Emergence | | Perceived Quality | |
|--------------------------------|---------------------|------------------|-------------------|------------------|
| | <i>r</i> | <i>p</i> | <i>r</i> | <i>p</i> |
| Gender | -.01 | 0.32 <i>n.s.</i> | -.04 | < 0.01** |
| Age | .02 | 0.18 <i>n.s.</i> | -.04 | < 0.001*** |
| Department | .05 | < 0.001*** | -.14 | < 0.001*** |
| Professional context acoustics | .06 | < 0.001*** | -.13 | < 0.001*** |
| Hearing self-report | .04 | < 0.001*** | -.06 | < 0.001*** |
| Hearing report from others | .04 | < 0.01** | -.02 | 0.19 <i>n.s.</i> |

pant confirmed to be either in the acoustics and vibrations department and/or to occupy oneself with such topics in their professional context, they are considered as an expert in our sample. For these variables, *professional context*, and *department*, we found significant small negative correlations in regards of perceived quality ($\tau = -.13$, $p < 0.001$ and $\tau = -.14$, $p < 0.001$). With the *lmer*-function [43] we fitted a linear mixed model with the expert status as fixed factor and the participants as random effects. It shows a significant negative effect of the affiliation to the expert group on the perceived quality ($b = -0.32$, $t(63) = -3.84$, $p < 0.001$), suggesting that experts give lower quality ratings compared to laypersons and therefore can be considered as stricter in their assessment.

5.5. Analysis of the qualitative feedback

After completing the listening tasks, we asked the participants for qualitative feedback on their personal experience in the study. In a follow-up questionnaire, the participants were asked for their remarks on noticeable peculiarities in the study and encouraged to comment on any problems or difficulties they might have had in handling the experimental task. The stated feedback was semantically analyzed, categorized into the dimensions *disturbing factors*, *experiment*, *rating*, *design aspects*, *immersion* and *other* and is summarized in Table 4. Overall, there were no fundamental problems reported, but $N = 50$ participants reported their personal experience in the study.

The feedback gives insight into the related topic and gives indications for future research. Overall, most participants were comforting during fulfilling the experimental task – accordingly, no severe problems with the study task were reported. Difficulties mostly regard the chosen study design, intentionally denying reference points for participants to anchor their assessment. The stated uncertainties reflect the somewhat novel and unfamiliar sound character of xEVs. Sporadically addressed remarks, such as statements in the categories of *immersion* and *other*, can be disregarded as they are not reflecting systematic issues with the study.

The third question referred to what participants perceived as high and low quality regarding the e-powertrain noise. Data of $N = 56$ participants were categorized into feedback regarding the e-powertrain noise’s *composition*, *comparison* with other objects, *motion impression* or *emotional impact* and are shown in Table 5.

Table 4

Qualitative feedback of participants on their personal experience in the study: The statements from the qualitative feedback questionnaire were semantically analyzed, categorized into the respective feedback categories on the left, and summarized. The *N* represents the number of mentions in the corresponding category. Feedback statements were summarized. Pertinent quotes were translated from German by the authors and are denoted by quotation marks.

| Feedback Category | <i>N</i> | Remarks |
|--------------------|----------|---|
| Disturbing Factors | 31 | Wind and tire noise were suspected of having affected the assessment possibly. Differently perceived acceleration rates felt hard to compare. Comparison between different car segments was not possible. Difficulties distinguishing general driving noise from e-powertrain noise – especially in the beginning of testing. Participants noticed partial masking of the e-powertrain noise by environmental noise such as wind and tire noise. |
| Experiment | 26 | Wish for the settling-in phase to gain reference points for rating. Process of “learning while listening” and sorting out if one likes e-powertrain noise or not after a while. Difficulties “perceiving the right noise”. Examples were suspected to be repeatedly presented. It was noticed that sound enhancement or scenarios like idle or constant speed were not included. Number of examples was appropriate. Longer evaluation time was wished for ($n = 1$). “Many audio samples in a row” stated as non-problematic ($n = 1$). |
| Rating | 24 | Difficulties with rating scale and labels: reported to have felt not intuitive or “mixed up”. Uncertainties whether to wish for acoustic operational feedback from the e-powertrain or not. Difficulties of assessing the acoustic event due to its dynamic, transient, and situational character were stated to be leading to indecisiveness about expectations regarding e-powertrain noise. Stimuli were closer to one another or farther apart than expected. The “total acoustic package” was evaluated holistically and “intuitively compared to familiar ICE noise”. |
| Design Aspects | 7 | Different acoustic expectations according to vehicle engine performance mentioned as a relevant factor. Sound harmony matching the respective driving mode mentioned as a relevant factor. |
| Immersion | 7 | Lack of acceleration feedback ($n = 1$). Visual driving simulation perceived as blurred ($n = 1$). Velocity indicator found to be distracting ($n = 1$). First two scenarios were perceived as “unexpectedly loud” ($n = 1$). Video projection and scenery differed in every example. Rear view mirror did not have a picture/visual projection ($n = 1$). |
| Other | 1 | Question if a synthetic “gear switch” will be integrated ($n = 1$). |

It should be noted that the stated feedback gives an insight into how interindividual the participants’ preferences were regarding the soundscape configurations and that the statements need to be seen as individual indications. Causal conclusions for the exact e-powertrain configuration cannot be derived. For the *motion impression* feedback, additionally commented was that different noise characteristics and loudness levels in the different driving scenarios with varying load and acceleration ratios were to be expected and therefore accepted or at times even wished-for as operational feedback.

Table 5

Qualitative feedback on perceived quality of e-powertrain noise: The statements from the qualitative feedback questionnaire were semantically analyzed, summarized, and categorized into the respective feedback categories on the left. Feedback statements were summarized. Pertinent quotes were translated from German by the authors and are denoted by quotation marks.

| Feedback Category | Quality Association | Feedback Statements |
|-------------------|--------------------------|--|
| Composition | High Quality Association | "silent drive". "less noisy" and "less dominant" acoustic environment. E-powertrain noise "blending in with the surrounding environmental noise". E-powertrain "distinctively perceptible from other noise sources". More present as a kind of operational "feedback". As "vibrant", "rich" and "complex" described sounds. A "harmonic composition" of high and low frequencies. "deep frequencies", "bass" and "deep frequency proportions". "high-frequency noise". "linear rising sound". Driving scenario as relevant factor to favored kind of feedback. |
| | Low Quality Association | Lack of operational feedback. "very high tones are disturbing". "narrow bands and high frequencies". "too dominant bass". "prominent frequency shifts". Linear rising noise stated as negative. Negatively perceived tonal and high-frequency acoustic events described as "whining", "howling", "humming", "whirring", "buzzing", "squeaking", "whistling" or "peeping" were mentioned and partially described as even "disturbing". Some mentioned a "modulated howling" or "whining" and defined it as a "disturbing" or irregular, grinding noise". In SR some examples were perceived as having a "downwards sound" and in contrast to the acceleration scenarios described as "sad vs. happy". |
| Comparison | High Quality Association | Associations of low frequencies with "power", as "powerful" or an "almost real engine sound". A "futuristic tone color" and "floating" vehicles. |
| | Low Quality Association | Public transport associations of trains (e.g., "S-Bahn" or "Tram"). A "drowning" e-powertrain. Sounding like the e-powertrain being "tortured". "a rocket close to its impact". Association of "turbines". E-powertrain noise reminding of "games" being "too electric". Comparison to a "barrel organ". For the SR scenario: an "unpleasant richness of sound" as if it was "too high of a load" for the vehicle. |
| Motion Impression | High Quality Association | E-powertrain noise should "suit the load case". Expected and as "feedback of the load request" perceived noise is acceptable. A "soundscape developing according to speed". A "quiet starting noise". |
| | Low Quality Association | "downward sounds" and "modulating amplitudes" with increasing acceleration. |
| Emotional Impact | High Quality Association | "non-audible or low tones are more pleasing". "a rich sound (low to high frequencies) sounds more appealing" and is perceived as of "high quality". |
| | Low Quality Association | "disturbing". "unpleasant". "bad associations". |

6. Discussion

According to the quantitative results and qualitative feedback in this study, the chosen acoustic simulator is suitable to evaluate e-powertrain noise in an ecologically valid environment while maintaining a great amount of experimental control. The used immersive cues for the visual, haptic and auditive context information were found to be helpful by the participants to better put themselves into the relevant use case scenario. Moreover, we were able to show that there is a moderate negative correlation between the intensity of the perceived e-powertrain noise and the overall quality conveyed by it (Kendall's Tau for rank-based data: $\tau = -.32$, $p < 0.001$). This aligns with the model by Styliadis and colleagues [23], that the sound quality, a subset of technical perceived quality contributes to the overall perceived product quality (the value-based perceived quality in the model) and corroborates that NVH attributes, such as e-powertrain noise, play a relevant role in terms of ultimate overall customer satisfaction.

The often positively emphasized quietness of xEVs is, on the other hand, at times criticized for lacking operational feedback

for the driver [9] or even as a loss of subjectively conveyed dynamics and vehicle character [2]. Our results support that customers wish for operational feedback according to the given acceleration scenario and, in the case of full load request, also accept and expect acoustic feedback. Blickensdorff and colleagues [9] defined the most important goals in terms of interior noise design in giving operational feedback, emotional staging, and brand sound design. Further studies need to investigate how to combine these three entities to create a pleasing interior soundscape for xEVs and how guidelines for this design task look like.

However, we would also like to elaborate on the limitations of our study. As we investigated an entirely novel vehicle sound profile, the physical environment of the chosen simulator might have been somewhat outdated. The utilized acoustic simulator built out of a former BMW 5 series, at times also available as a plug-in hybrid vehicle, does not necessarily resemble the design specifics of very recent, highly innovative electric vehicles. Generally, it should be noted that most electric cars on today's market are still based on conventional car models, so this critical point might mainly be relevant for highly innovative xEV concepts. Still, such

a misfitting of visual and acoustic characteristics might bias the experience of the soundscape. Future studies could update the interior or use virtual reality instead.

Another aspect coming up short in the chosen environment is the driver interaction. An action, like e.g., pressing the pedal to accelerate the vehicle, is accompanied by certain expectations regarding the acoustic feedback. Interaction in the test environment could create a link between the participant's action and their expectation regarding the operational feedback and could therefore emulate even more realistic use case scenarios. Including more contextual cues will assist immersion and, thus, a more complete multisensory experience, while maintaining reproducible experimental conditions. To provide experimental settings, which are also economically feasible, further studies should investigate how much immersion is really needed for gaining an optimum of ecological validity.

Also, further investigations using an alternative set of semantic labels when testing perceived emergence should be considered. As assumed beforehand and further approved by qualitative feedback from participants in the study, the here employed semantic labels (*unhearable, quiet, discreet, present, dominant*) are mixing up different dimensions of perception which renders suboptimal for valid testing.

Furthermore, we would like to mention the different length of some stimuli due to the inherent nature of utilized measurements from different test vehicles with different performance parameters. Especially the stimuli in the shear/recuperation scenario varied strongly in their length (13–47 s) due to the different recuperation rates of the xEVs. As derived from our data, there seems to be a very heterogeneous bag of opinions concerning how strongly the e-powertrain noise is perceived, as well as what kind of noise is perceived as of high quality in the recuperation scenario.

Since participants were left in the dark regarding the given product class and further specifications of the presented vehicle, the subjectively perceived quality is especially dependent on each individual's frame of reference and expectation horizon. It is therefore not possible to derive any insights in terms of specific product placement. The finding of the slightly stricter quality assessment of the expert group in our study might be a good example of this individual reference frame, as experts have broader experience with the palette of available products. Moreover, it is their job requirement to compare in-house products critically against the products of competitors. Due to its novelty character, the dynamics in evaluating e-powertrain noise and the expectations to it are difficult to assess. The more experience people gain, the more elaborative their assessment of the presented examples will be. The qualitative feedback from our participants supports this, as they often stated to have felt very indecisive about their rating or to be surprised by how close, or in some cases, how wide apart, the acoustic examples were.

The frequently noted difficulties in differentiating the e-powertrain noise from driving noise or singling it out of the sound carpet in the given evaluation tasks support the axiom of Gestalt psychology [24]. With the inclusion of the naturalistic driving noise, which partially masked the e-powertrain noise, we aimed to obtain holistic scenario evaluations, which therefore are applicable to the external world and real-life customer scenarios.

Finally, it needs to be highlighted that the qualitative data obtained about the associations of high or low perceived quality represent individual preferences. The presented comments therefore can be seen as explorative reference points of what people might associate with different e-powertrain noise conveying a certain level of product quality. Nevertheless, further investigations on the semantics and associations expressed by the soundscapes of xEVs need to be made.

7. Conclusion

The findings of this study support e-powertrain noise to be a customer-relevant attribute, as it conveys information about the product that contributes to the product's overall quality impression of individuals. As this study shows, the subjective perception of an xEVs' soundscape can differ greatly among different individuals, even if the presented stimulus is the same. These differences are even more prominent in more complex perceptual domains such as perceived quality. Our data also shows that despite the overall positively emphasized the quiet sound character of xEVs, customers accept or at times even expect and wish for operational feedback in certain situations as e.g., in the full acceleration scenario. Further investigation on the exact configuration of the e-powertrain noise in terms of its profile is needed to understand what kind represents a favorable combination of characteristic NVH phenomena, leading to a pleasing, customer-oriented in-cabin ambient soundscape for xEVs.

CRediT authorship contribution statement

Mara Münder: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Claus-Christian Carbon:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mrs. Mara Münder, MSc is currently enrolled in the PhD-program of the BMW Group and Bamberg Graduate School of Affective and Cognitive Sciences (BaGrACS). Professor Claus-Christian Carbon, PhD is founder and board chairman of the Bamberg Graduate School of Affective and Cognitive Sciences (BaGrACS) and the Research Group EPAEG (Ergonomics, Psychological Aesthetics, Gestalt). He acts as PhD supervisor for Mara Münder but receives no money for this duty from BMW – he is fully independent regarding his supervision and advises given to Mara Münder.

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3.3 Introduction to the Study on Continuous Measures and E-Powertrain Noise

Since a vehicle acceleration process is transient, it can be better understood as an acoustic scene rather than a stationary acoustic event. Therefore, we conducted another study evaluating the perceived quality of e-powertrain noise and considered the dynamic character of the acoustic stimuli within the applied evaluation method. Again, we focused on EV acceleration processes but aimed for a higher temporal resolution within the participants' assessments. In Munder et al. (2024), we applied the *Continuous Evaluation Procedure* (CEP) by Muth et al. (2015). Applying this method, the participants continuously reported their impressions of the acoustic scene by indicating it via an adjustable lever integrated into the simulator vehicle's middle console.

Participants evaluated different vehicle acceleration processes in terms of the perceived quality and annoyance that the acoustic scenes conveyed. With the high temporal resolution of this method, we revealed dynamic changes in the subjective perception of e-powertrain noise. This allows acoustic engineers to pinpoint critical noise characteristics and acoustic events, as well as their specific timing and influence on the customer's perception. The manuscript, published in *Frontiers in Acoustics*, is embedded on the following pages in its full length and original form.

3.4 Unfolding Dynamics in the Perception of Vehicle Acoustics via Continuous Evaluation Procedure (CEP)



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Unfolding dynamics in the perception of interior vehicle acoustics via continuous evaluation procedure (CEP)

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The evaluation of a soundscape is a challenging task as the object of study is not a stationary event of sensation but rather a dynamic and complex scene stretching over a specific period. To do justice to the time dimension in such acoustic scenes, we utilized the *Continuous Evaluation Procedure* (CEP). Extending common standard instruments asking participants for a singular integral at the end of the sound experience (e.g., on a rating scale), the participants in this study were enabled to continuously evaluate the evolving acoustic scene of accelerating electrified vehicles (EVs) using CEP. With the increasing electrification of powertrains in the automotive industry, acoustic engineers face the challenge of defining innovative sounds using the availabilities of now low-noise emission platforms of EVs that deviate in their noise profiles from familiar but technologically outdated internal combustion engine vehicles (ICEVs), which have defined the general sound schemes for more than a century. To capture dynamic aspects in the quality perception of powertrain noise in EVs, we asked 37 participants to evaluate acoustic recordings of different vehicles in varying acceleration modes in a high-quality three-dimensional (3D) acoustic simulator. Thereby, we revealed much more detailed and time-dependent quality aspects, which do not come forth in an integral singular measure (ISM) where all impressions experienced during the ongoing acoustic scene are blended together. We, therefore, propagate the systematic application of the CEP method when it comes to the qualitative evaluation of transient acoustic scenes. CEP opens the great opportunity to unfold, detect, and analyze dynamic effects in soundscapes and noise profiles, but of any kind of acoustic signal.

KEYWORDS

perceived quality, dynamic evaluation, automotive, acoustic perception, association, e-powertrain, electrified vehicle

1 Introduction

Evaluating acoustic scenes, soundscapes and noise profiles poses a great challenge regarding a research study's design. Compared to stationary stimuli (or constant noise), where properties remain stable over time or the acoustic event is of very brief nature, a soundscape is composed of varying or multiple acoustic properties. Such acoustic stimuli derived from dynamic or environmental scenes, which are per definition of non-stationary sensory quality, show temporal expansion as their acoustic properties develop over time. For example, a piece of

music can start off slow and quiet, contain repetitive, monotonous, or disruptive elements, climax in one part of its composition and might fade out slowly or end abruptly. Due to the complex, dynamic and probably even interactive qualities, such acoustic scenes cannot be described adequately by a singular value, as for example, by rating on a Likert scale. Especially for novel soundscapes to which we have only had a few exposures so far, our rating might turn out more volatile as compared to familiar concepts. In the context of automotive acoustics, a vehicle's acceleration process can be considered as an acoustic scene, which makes its evaluation a challenging task. Unlike relatively stationary sounds, for example, the click of a button, powertrain noise is a non-stationary sensory event of complex nature unfolding across the acceleration process. The rising and load-dependent sound pressure level in a conventional vehicle's acceleration process is familiar and accepted (see for example, Krishna, 2021 or Clendinning, 2018). Moreover, the noise profiles, naturally generated through the technical conditions of the combustion engine, formed our expectations regarding how a vehicle's acceleration should sound. Over decades, it strengthened the association between a load-dependent, growling engine noise and the assumed vehicle's power and is now hard to resolve in the customers' minds (Cerrato, 2009; Borg, 2014; Clendinning, 2018). With the increasing electrification of powertrain systems in the industry, the question among acoustic engineers arises as to what constitutes a high-quality yet pleasing and sportive acoustic profile for electrified vehicles (EVs). Münder and Carbon (2022) found a significant negative correlation ($\tau = -32$, $p < 0.001$) between the perceptibility and qualitative impression of e-powertrain noise. As some participants claimed difficulties in evaluating the transient acoustic scenes—different acceleration scenarios (Münder and Carbon, 2022)—we employed a more sophisticated measurement technique in the present study. This time, we provided a tool that is easy to use and where participants can continuously assess the quality of a dynamically evolving stimulus. With single-value ratings, for example, on a Likert scale, noise characteristics, such as frequency peaks at the beginning or end of the scene, are blended into the rated integral. This potentially leads to specific distinctive properties overwriting the rest or parts of the unfolding signal's impression. The ratings of different stimuli lose their distinctiveness and do not allow causal interpretation of the specific, time-dependent factors that might have influenced the resulting evaluation. Yet, designers must understand those temporal and causal dynamics that might result in an overall appreciation. By applying the *Continuous Evaluation Procedure* (CEP) of Muth et al. (2015) we take a closer look at the dynamic effects while participants experience the involvement of e-powertrain noises. In the present study, we will focus on the evaluation dimensions of *Perceived Quality* and *Perceived Annoyance* in e-powertrain noise from EVs in typical acceleration scenarios.

2 Theoretical background

2.1 E-powertrain noise

The various (vibro-)acoustic characteristics of vehicles can be subsumed under Noise, Vibration and Harshness (NVH). Compared to vehicles with internal combustion engines (ICEVs, i.e., internal combustion engine vehicles), electrified vehicles (EVs) show a radically different NVH profile (Zeller, 2018; Eisele et al., 2019). For EVs, the vehicle's powertrain system, as a main NVH phenomena

contributor (Qatu, 2012), plays an integral part in the developmental process of vehicle acoustics. Not only do EVs have a significantly lower overall sound pressure level (SPL) (Zeller, 2018; Blickensdorff et al., 2019), but the noise spectrum also deviates drastically from the familiar ICEV broadband noise and ranges in higher frequencies, with tonal components for which the human ear is particularly sensitive (Blickensdorff et al., 2019; Gavric, 2020). Additionally, there are several studies investigating e-powertrain noise and its high-frequent and tonal acoustic profile, suggesting EVs to be perceived as more annoying and less pleasant potentially (Lennström et al., 2013; Lennström and Nykänen, 2015; Swart et al., 2016; Devillers et al., 2020).

2.2 Concept of quality in acoustics

In the field of acoustics, there are various definitions regarding sound quality. Only a few definitions address the subjective component of quality perception: aside from the mere physical signal, there needs to be a recipient that perceives and evaluates the sound. The definition of Genuit (1996) considers 1) the *physical sound* (sound field), as well as 2) *psychoacoustics* (auditory perception), and 3) *psychological aspects* (auditory evaluation) as influential factors that compose sound quality. From a perceptual science perspective, the third factor—the auditory evaluation—plays a vital role, as it comprises more than the simple physical sound signal and the biological mechanisms of the human hearing apparatus, such as situational, cognitive, and affective factors (Blauert, 1986; Zeitler, 2007). Styliadis et al. (2015) emphasized the importance of perceived quality for the automotive industry and defined it as a set of *value-based perceived quality* (VPQ) and *technical perceived quality* (TPQ). The VPQ thereby includes external factors, customer behavior, branding and core values of the product. In contrast, the TPQ holds physical properties of the given object in different modalities that, among other things, define sound quality as a part of the TPQ (Styliadis et al., 2015). As the mentioned definitions refer to aspects of the overall auditory experience by a recipient, we prefer the term *perceived quality* to sound quality. The term *perceived quality* builds onto a holistic concept, while *sound quality* is often confounded with the mere physical properties of an acoustic event, ignoring the psychological aspects mentioned above. Genuit (2010), moreover, describes different product properties, such as acoustic characteristics that contribute to an overall object-related quality impression. This means the qualitative impression conveyed by acoustic characteristics of a vehicle—in this study, the e-powertrain noise in an acceleration scenario—only depicts parts of an overall experience. Though acoustic properties such as emitted e-powertrain noise are only one of the manifold factors contributing to the overall product experience, their influence is not to be underrated when considering the holistic vehicle experience. Further aspects to be considered in subjective evaluation of acoustic scenes, such as e-powertrain noise from vehicle run-ups, are the customer's expectations according to the represented driving scenario: in full acceleration scenarios, for example, a louder vehicle feedback is expected (Münder and Carbon, 2022).

2.3 Dynamic effects in perception

Building a bridge to visual perception science, Muth et al. (2015) revealed dynamic effects when employing *Continuous Evaluation*

Procedure (CEP) in the domain of art perception. Applying the *CEP* facilitates assessing a stream of experience with a high temporal resolution across the whole time slice rather than demanding an instant single assessment (Muth et al., 2015). Muth and Carbon (2013) and van de Cruys and Wagemans (2011) report dynamic effects in regards to pleasurableness or liking found in transitioning from a state of uncertainty to a state of understanding the visual percept as coherent—so to say, a Gestalt. As many factors can influence someone's evaluation, such as the context (Jakesch et al., 2011), repeated exposure to certain objects or entities (Zajonc, 1968; Bornstein, 1989), or the fluency of perception (Albrecht and Carbon, 2014), it is worth to consider different evaluation methods to gain a profound understanding of how a product is perceived. Therefore, especially in evaluating transient stimuli, it is worthwhile to consider methods with higher temporal resolution to investigate how a product is perceived and experienced, in addition to one-time singular assessments. Moreover, time-dependent effects such as primacy and recency must be considered, as they can color the subjective impression.

3 Method and experiment

The aim of the present study was to shed light on the evaluation process of non-stationary e-powertrain noise scenes itself and capture dynamic effects. Particularly, we wanted to orient to the study of Münder and Carbon (2022), who investigated e-powertrain noise with the *Repeated Evaluation Technique (RET)* (Carbon and Leder, 2005), but in a more granular way. We followed a so-called *Path #2* testing approach (Carbon, 2019): *Path#2* means a lab-oriented but ecologically high valid test setting. We realized this by utilizing a sophisticated static acoustic simulator, creating an immersive testing environment to ensure ecological validity while maintaining experimental control. The evaluation process was based on the methodological evaluation approach of the *Continuous Evaluation Procedure (CEP)* developed by Muth et al. (2015).

3.1 Participants

In an *a priori* power analysis for repeated measures ANOVA through G*Power (Faul et al., 2007), we calculated the required sample size to be $N \geq 34$ participants, aiming at an error probability of $\alpha = 0.05$ and statistical power ($1 - \beta$) of 0.80, assuming a medium effect size. The required sample size was reached, as a final sample of thirty-seven participants ($N = 37$) took part in this study. The sample was recruited via electronic platforms (mostly email) across different departments of the BMW Group, including the specialist department for acoustics and vibrations. Participation was not compensated and not restricted other than having normal hearing ability. The conduction of the study followed the principles of the Declaration of Helsinki, as well as the ethical principles of the Association of German Professional Psychologists (BDP) and the German Psychological Society (DGPs). Participants had the right to abort the study at any time without giving reasons and to withdraw their data without any consequences. Prior to the experimental testing, the purpose of the study was disclosed to each participant and written consent had to be given to take part in the study. The average age was $M = 35.1$ years ($SD = 11.28$; $min = 20$; $max = 60$ years); 86% of the participants ($n = 32$) were male. Overall, 59% ($n =$

22) of the sample work in the specialist department of acoustics and vibrations, with 16% ($n = 6$) even specifically working on matters of e-powertrain noise. For their hearing ability, self-reported on a five-point Likert scale (a value of 1 representing *very bad hearing* and a value of 5 = *very good hearing*), normal hearing among the participants can be assumed ($M = 3.49$, $SD = 0.69$, $min = 2$, $max = 5$).

3.2 Stimuli

Prior to the testing, we recorded the driving noise of eleven different EVs from various manufacturers on a BMW Group test track with 3D ambisonics recording equipment (Ambeo VR Mic array from Sennheiser with four channels and first-order ambisonics qualities) that is known to create immersive hearing experiences (see Sadia and Carbon, 2023). The microphone array was placed between the two car seats in each vehicle's front row in a standardized vertical position, comparable to where the ears of car passengers would be. Among the vehicles, there were nine battery electric vehicles (BEVs) and two hybrid electric vehicles (HEVs; operated in electric driving mode only) from different manufacturers spreading across the whole price segment. The recording procedure followed a standardized measurement protocol for three different driving scenarios and was performed by trained professionals: a slow acceleration (0.5 m/s^2), a comfortable acceleration (2.5 m/s^2), and full acceleration (maximum performance of the respective vehicle; acceleration from 0 to 100 km/h (i.e., 0–28 m/s) ranged from 4.9 s to 10.5 s among the tested EVs in this scenario). While the measurements were conducted, no other driving activities were performed on adjoining test tracks and all measurements were performed on the same test track section which had smooth asphalt. The gathered 3D audio data was then rendered to a suitable format to be replayed in the acoustic simulator. Due to various factors, such as distinctive bird chattering or disturbing noise from loose objects in the vehicles that we found on some of the recordings, not all eleven vehicles were presented in every acceleration scenario. Recordings with such distinctive disturbing noises were excluded from the stimulus set as they could possibly distract the focus from the sole driving noise and the actual evaluation task. In the end, we selected six stimuli for each acceleration scenario with ensured high recording quality.

3.3 Testing environment and apparatus

By utilizing a sophisticated static acoustic simulator, we were able to realistically reproduce the 3D recordings of the driving scenarios. This was realized through the method of wave field synthesis combined with a six-layer 3D audio system of over 150 loudspeakers in the experimental environment, thus maintaining a high degree of ecological validity. Moreover, the set-up provides realistic context information as the simulator is built out of a complete vehicle, physically seating the participant in the driver's seat of a vehicle cabin. Visuals of a generic roadside environment were projected onto the side windows and the windshield of the simulator to further enhance the immersive impression. To capture a continuous stream of the participant's experience, we applied the *Continuous Evaluation Procedure (CEP)*; see Muth et al., 2015) by substituting the simulator vehicle's gear shift in the middle console with a slider bar (100 mm movement range, raw value output range from 74 to 1023; the



FIGURE 1

The implemented slider bar with labels in the middle console of the simulator vehicle and print-out of the seven-point Likert scale for the integral singular measure (ISM) evaluation on the dashboard (left picture). Demonstration of the continuous evaluation procedure (CEP) on the slider bar while active simulation of acceleration process (right picture) © by the authors. The person in the picture consented to be photographed and displayed in this manuscript.

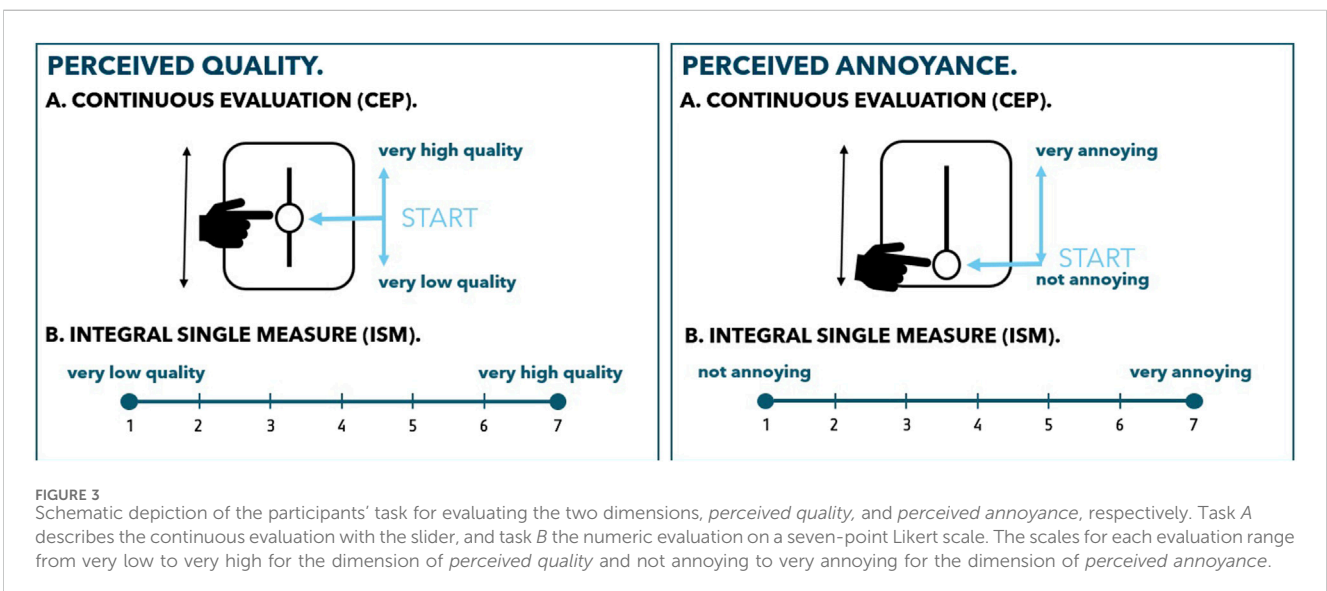
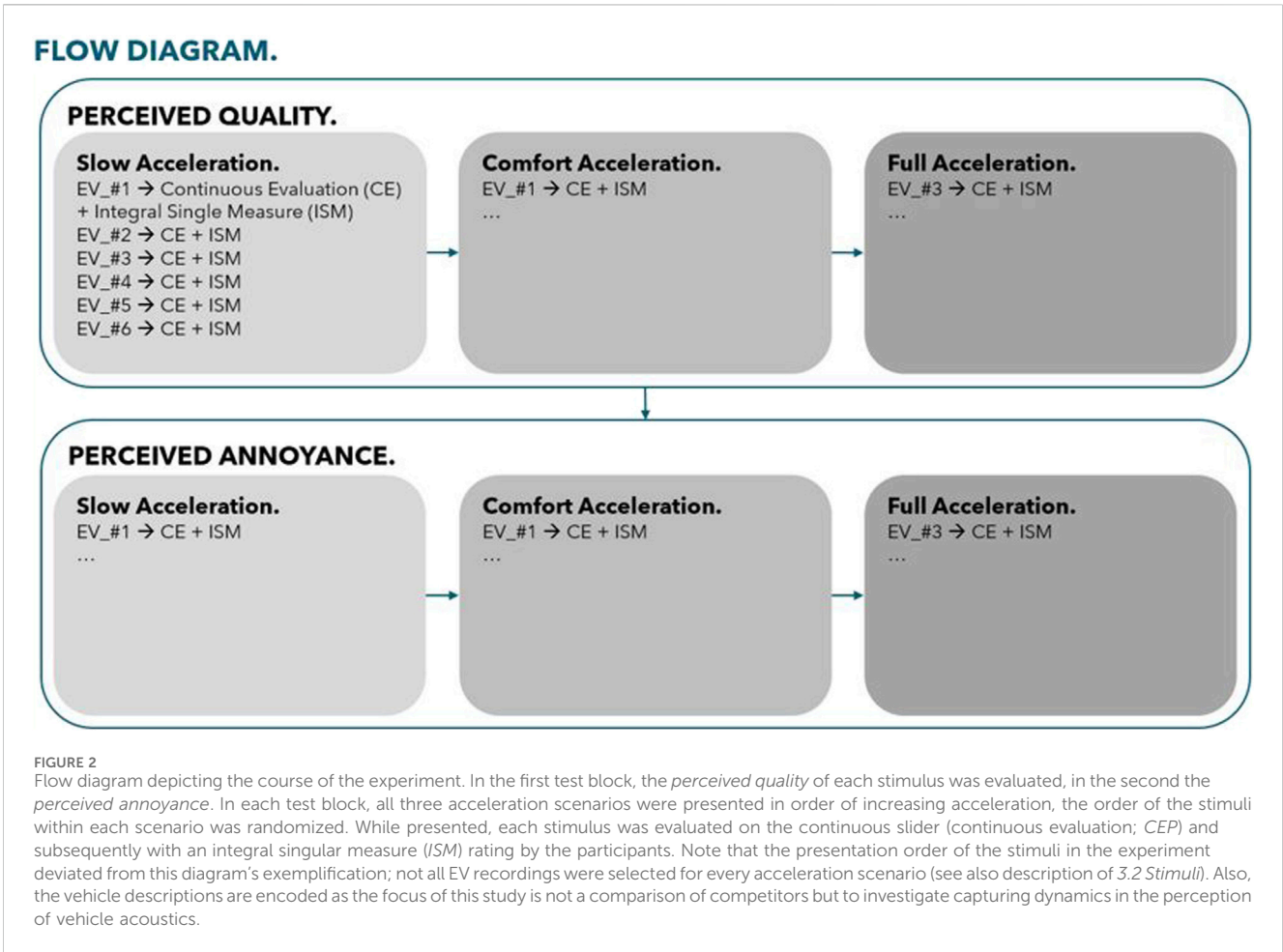
current value was constantly processed by an ATMEGA processor and sent, using an FTDI serial-to-USB interface; for the specific implementation in the simulator, see. Figure 1). This way, participants were able to continuously adjust their evaluation over time in an ergonomic way while experiencing the transient acoustic scene of an EV acceleration process. For signal processing, we implemented a Raspberry Pi and Python script.

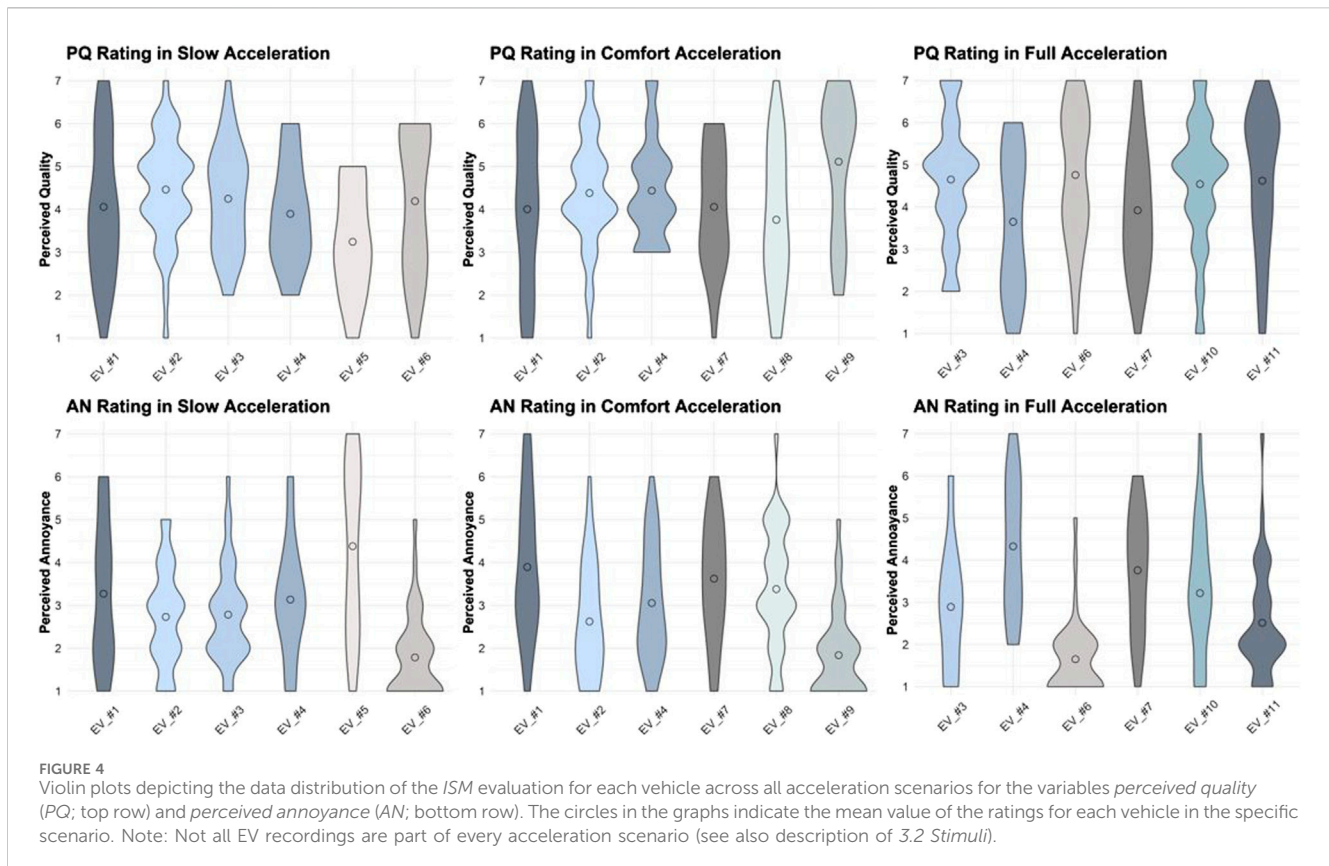
3.4 Procedure

After a short introduction about the study's general purpose and the simulator, the participants were instructed how to execute the evaluation task. The experiment was conducted as a single testing session per participant. While the participant was seated in the driver's seat of the simulator, the experimenter was in the control room. We ensured mediate interaction with the experimenter by providing an audio connection, but this kind of interaction was held to a bare minimum about task-related matters only. To follow the principles of scenario-based testing (Jakesch et al., 2011) and ensure external validity, each scenario was introduced to the participants before the following scenario. A total of six different stimuli in each acceleration scenario was presented in a randomized order. Each stimulus was played for a maximum of 25 s or limited by its natural length due to the respective acceleration scenario. For example, in the full acceleration scenario, most vehicles reached their maximum velocity before the 25 second end mark. In the first test block, participants evaluated the presented stimuli regarding their *perceived quality* impression. After all of the three acceleration scenarios had been evaluated, a second test block followed with

the task to evaluate the stimuli in each acceleration scenario again, but now regarding their *perceived annoyance*. Each stimulus was continuously evaluated via the slider bar (CEP) while ongoing presentation of the stimulus and subsequently rated on a seven-point Likert scale (integral singular measure; ISM) before proceeding with the next stimulus. Thereby, we not only gathered continuous evaluation data, but also ISM data. This helps us to qualify further the continuous signal captured through the CEP method with the conventional integral measure of overall evaluation of such dynamic stimuli. For a better understanding, we provide the course of the experimental procedure in Figure 2.

While a stimulus was presented, the participant's task was continuously adjusting the slider according to their momentary experience. We did not specify any levels, e.g., on a discrete scale, so participants were fully free in using the slider range. Only the starting position of the slider, the minima and maxima for each dimension were defined: for the dimension of *perceived quality* the starting position for the slider was in the middle, representing an average quality impression and leaving space for higher (pulling the slider up) and lower (pulling the slider down) quality impressions. To evaluate the dimension of perceived annoyance, the participants were instructed to start at the lowest lever position possible representing a (totally) non-annoying state and leaving space to the top to indicate more annoying events over time. The exact labeling of the minima and maxima of the scales, as well as the two evaluation tasks for each stimulus, are schematically depicted in Figure 3. After each stimulus presentation, the participant was asked to return the lever to the starting position to prepare the slider bar for the following stimulus evaluation.





4 Analysis and results

4.1 Integral singular measure

The distribution of the integral singular measure (*ISM*) ratings for each EV in each acceleration scenario is shown through the violin plots in Figure 4.

The graphs show that for most stimuli, the whole span of the rating scale was used, indicating a great interindividuality in the impression of *perceived quality*. For a few of the stimuli, though, the ratings do not span over the whole scale, indicating that the sample agrees more with one another on the quality impression conveyed by these stimuli: for example, in the dimension of *perceived quality* in the scenarios of *slow acceleration* (SA) the stimuli of EV_#4¹ and EV_#5, and in *comfort acceleration* (CA) the stimulus of EV_#4. In the dimension of *perceived annoyance*, the ratings span across the whole scale for less of the stimuli, indicating a bit more consensus among the sample in this dimension. This especially applies to the stimulus of EV_#2 and EV_#6 in the scenario of *slow acceleration* (SA), in the CA scenario for stimulus EV_#9, and in the *full acceleration* (FA) for the stimulus of EV_#6. The corresponding statistic values for the *ISM* ratings can be found in Table 1. In the SA

scenario, EV_#2 scored the highest rating in terms of *perceived quality* and EV_#5 in terms of *perceived annoyance*, while also being the stimulus perceived as the least qualitative impression. For the CA scenario, EV_#9 scored the highest on the qualitative impression and lowest on *perceived annoyance*. In contrast, EV_#1 was rated the most annoying in this use case. In the FA scenario, EV_#6 was rated the highest on *perceived quality* and lowest on *perceived annoyance*. In contrast, EV_#4 is rated the highest on *perceived annoyance* while scoring the lowest on *perceived quality*.

With the gathered *ISM* ratings, we fitted a linear mixed model for the two key dimensions with the vehicle type as a fixed factor and the participant variable as a random effect for each of the acceleration scenarios, using the *lmer*-function (Kuznetsova et al., 2017). In the SA scenario EV_#5 was of significantly lower *perceived quality* ($b = -0.81$, $t(180) = -2.83$, $p = 0.0051^{**}$), while at the same time it was perceived as significantly more annoying ($b = 1.11$, $t(180) = 3.72$, $p = 0.0003^{***}$) compared to the other vehicles. In the CA scenario EV_#9 was perceived as of significantly higher quality ($b = 1.11$, $t(180) = 3.83$, $p < 0.001^{***}$), while also being perceived as significantly less annoying ($b = -2.05$, $t(180) = -7.32$, $p < 0.001^{***}$). In the FA scenario, similar effects can be found. Detailed results are summarized in Table 2.

4.2 Continuous evaluation

For an initial visual inspection of the continuous evaluation data, we plotted the slider evaluations from all participants for

¹ The vehicle descriptions are anonymized and encoded as we are focusing on comparing different evaluation methods to capture dynamic effects in the perception of vehicle acoustics in this study rather than providing a comparison of different competitors in the field.

TABLE 1 ISM ratings for Perceived Quality and Perceived Annoyance in the different acceleration scenarios.

| Stimulus | Perceived quality | | | | | | | | |
|----------|------------------------|------|-----------------|---------------------------|------|-----------------|------------------------|------|-----------------|
| | Slow acceleration (SA) | | | Comfort acceleration (CA) | | | Full acceleration (FA) | | |
| | M | SD | Range [min/max] | M | SD | Range [min/max] | M | SD | Range [min/max] |
| EV_#1 | 4.05 | 1.63 | [1; 7] | 4.00 | 1.78 | [1; 7] | - | - | - |
| EV_#2 | 4.46 | 1.24 | [1; 7] | 4.38 | 1.32 | [1; 7] | - | - | - |
| EV_#3 | 4.24 | 1.21 | [2; 7] | - | - | - | 4.65 | 1.48 | [2; 7] |
| EV_#4 | 3.89 | 1.22 | [2; 6] | 4.43 | 1.19 | [3; 7] | 3.65 | 1.67 | [1; 6] |
| EV_#5 | 3.24 | 1.26 | [1; 5] | - | - | - | - | - | - |
| EV_#6 | 4.19 | 1.61 | [1; 6] | - | - | - | 4.76 | 1.61 | [1; 7] |
| EV_#7 | - | - | - | 4.05 | 1.37 | [1; 6] | 3.92 | 1.52 | [1; 7] |
| EV_#8 | - | - | - | 3.76 | 1.64 | [1; 7] | - | - | - |
| EV_#9 | - | - | - | 5.11 | 1.63 | [2; 7] | - | - | - |
| EV_#10 | - | - | - | - | - | - | 4.54 | 1.52 | [1; 7] |
| EV_#11 | - | - | - | - | - | - | 4.62 | 1.66 | [1; 7] |

| Stimulus | Perceived Annoyance | | | | | | | | |
|----------|------------------------|------|-----------------|---------------------------|------|-----------------|------------------------|------|-----------------|
| | Slow Acceleration (SA) | | | Comfort Acceleration (CA) | | | Full Acceleration (FA) | | |
| | M | SD | Range [min/max] | M | SD | Range (min/max) | M | SD | Range [min/max] |
| EV_#1 | 3.27 | 1.64 | [1; 6] | 3.89 | 1.65 | [1; 7] | - | - | - |
| EV_#2 | 2.73 | 1.17 | [1; 5] | 2.62 | 1.32 | [1; 6] | - | - | - |
| EV_#3 | 2.78 | 1.13 | [1; 6] | - | - | - | 2.89 | 1.45 | [1; 6] |
| EV_#4 | 3.14 | 1.36 | [1; 6] | 3.05 | 1.33 | [1; 6] | 4.32 | 1.58 | [2; 7] |
| EV_#5 | 4.38 | 1.98 | [1; 7] | - | - | - | - | - | - |
| EV_#6 | 1.78 | 0.98 | [1; 5] | - | - | - | 1.65 | 0.89 | [1; 5] |
| EV_#7 | - | - | - | 3.62 | 1.40 | [1; 7] | 3.76 | 1.44 | [1; 6] |
| EV_#8 | - | - | - | 3.38 | 1.40 | [1; 7] | - | - | - |
| EV_#9 | - | - | - | 1.84 | 1.01 | [1; 5] | - | - | - |
| EV_#10 | - | - | - | - | - | - | 3.22 | 1.53 | [1; 7] |
| EV_#11 | - | - | - | - | - | - | 2.51 | 1.30 | [1; 7] |

Statistical values for the ISM ratings on a seven-point Likert scale for the dimensions of *perceived quality* and *perceived annoyance*. Note that not every vehicle was part of every stimulus set for each acceleration scenario (indicated by the blanks). The three best-rated stimuli—high scores on *perceived quality* and low scores on *perceived annoyance*—per acceleration scenario in each dimension are highlighted in boldface.

each stimulus per acceleration scenario. We plotted one graph for each dimension—one for the dimension of *perceived quality* (Figure 5) and one for *perceived annoyance* (Figure 6). Both graphs represent the continuous evaluation over the course of the slow acceleration scenario of EV_#5. The overall trend in the *perceived quality* evaluation of EV_#5 (Figure 5)—indicated by the dashed red regression line—shows a downward trend, meaning the qualitative impression of the emitted e-powertrain noise by EV_#5 decreases over the course of time. The overall mean of the continuous evaluations (thick pink-blue line) indicates that something around the 13 second

mark adversely affects the qualitative acoustic impression as the overall trend dips for a couple of seconds until it seems to recover towards the end of the stimulus presentation. The different individual evaluation streams show a high variance, partially or in some cases, even indicating completely opposing impressions.

The overall trend in the *perceived annoyance* evaluation of EV_#5 (Figure 6)—indicated by the dashed red regression line—shows an upward trend, meaning the *perceived annoyance* of the emitted e-powertrain noise by EV_#5 increases over time. While the overall mean of the continuous

TABLE 2 Comparison of Perceived Quality and Perceived Annoyance in the different acceleration scenarios.

| Stimulus | Slow acceleration (SA) | | | | | | | | | |
|----------|---------------------------|------------|--------------|-------------------|------------|---------------------|------------|--------------|------------------|------------|
| | Perceived Quality | | | | | Perceived Annoyance | | | | |
| | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | |
| EV_#1 | 4.05 | 180 | 17.94 | < 0.001 | *** | 3.27 | 180 | 14.03 | <0.001 | *** |
| EV_#2 | 0.41 | 180 | 1.42 | 0.1584 | | -0.54 | 180 | -1.82 | 0.0712 | |
| EV_#3 | 0.19 | 180 | 0.66 | 0.5095 | | -0.49 | 180 | -1.63 | 0.1041 | |
| EV_#4 | -0.16 | 180 | -0.57 | 0.5717 | | -0.14 | 180 | -0.45 | 0.6506 | |
| EV_#5 | -0.81 | 180 | -2.83 | 0.0051 | ** | 1.11 | 180 | 3.72 | <0.001 | *** |
| EV_#6 | 0.14 | 180 | 0.47 | 0.6374 | | -1.49 | 180 | -4.99 | <0.001 | *** |
| Stimulus | Comfort Acceleration (CA) | | | | | | | | | |
| | Perceived Quality | | | | | Perceived Annoyance | | | | |
| | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | |
| EV_#1 | 4.00 | 180 | 16.19 | < 0.001 | *** | 3.89 | 180 | 17.34 | <0.001 | *** |
| EV_#2 | 0.38 | 180 | 1.15 | 0.2506 | | -1.27 | 180 | -4.53 | <0.001 | *** |
| EV_#4 | 0.43 | 180 | 1.32 | 0.1894 | | -0.84 | 180 | -2.98 | 0.0032 | ** |
| EV_#7 | 0.05 | 180 | 0.16 | 0.8694 | | -0.27 | 180 | -0.96 | 0.3370 | |
| EV_#8 | -0.24 | 180 | -0.74 | 0.4597 | | -0.51 | 180 | -1.83 | 0.0690 | |
| EV_#9 | 1.11 | 180 | 3.38 | < 0.001 | *** | -2.05 | 180 | -7.32 | <0.001 | *** |
| Stimulus | Full Acceleration (FA) | | | | | | | | | |
| | Perceived Quality | | | | | Perceived Annoyance | | | | |
| | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | | <i>b</i> | <i>df</i> | <i>t</i> | <i>p</i> | |
| EV_#3 | 1.00 | 180 | 2.96 | 0.0035 | ** | -1.43 | 180 | -4.98 | <0.001 | *** |
| EV_#4 | 3.65 | 180 | 14.08 | < 0.001 | *** | 4.32 | 180 | 18.99 | <0.001 | *** |
| EV_#6 | 1.11 | 180 | 3.28 | 0.0012 | ** | -2.68 | 180 | -9.29 | <0.001 | *** |
| EV_#7 | 0.27 | 180 | 0.80 | 0.4243 | | -0.57 | 180 | -1.97 | 0.0502 | |
| EV_#10 | 0.89 | 180 | 2.64 | 0.0090 | ** | -1.11 | 180 | -3.85 | <0.001 | *** |
| EV_#11 | 0.97 | 180 | 2.88 | 0.0044 | ** | -1.81 | 180 | -6.29 | <0.001 | *** |

Statistical values comparing the stimuli in the specific acceleration scenarios. Significant results are indicated by boldface type. Note that not all EV recordings are part of every acceleration scenario (see description of 3.2 Stimuli). Significance levels: ** = $p < 0.01$, *** = $p < 0.001$.

evaluations for the *perceived annoyance* dimension rapidly increases around the 13 second mark, the overall mean for the *perceived quality* (Figure 5) falls off and consecutively dips. Though the *perceived annoyance* seems to increase after a few seconds, at this point, something seems to be remarkably annoying in the acoustic profile in the slow acceleration of EV_#5 as almost all levers were pulled up.

As a next step, we looked at the gradients, that is, the numerical differentiations, for each vehicle and acceleration condition (Figure 7). Those plots highlight changes in the *perceived quality* and *perceived annoyance*, making the dynamics even more salient. For the vehicle-condition combinations that were

perceived as least annoying in the ISM ratings (EV_#06 for SA, EV_#09 for CA and EV_#06 for FA), the graphs are relatively flat but reveal subtle dynamics throughout the acceleration process and occasional peaks, where the participants seemed to have noticed something. For the vehicle-condition combinations that were rated as most annoying in the ISM ratings (EV_#05 for SA, EV_#01 for CA and EV_#04 for FA), the utilized CEP measure reveals the unfolding dynamics. Instead of a relatively flat graph with subtle dynamics as in the least annoying stimuli, the graphs for the most annoying stimuli show a broader range and more fluctuations. EV_#05 in the SA scenario (please compare to Figure 6) shows fluctuations starting after 3 seconds, with a

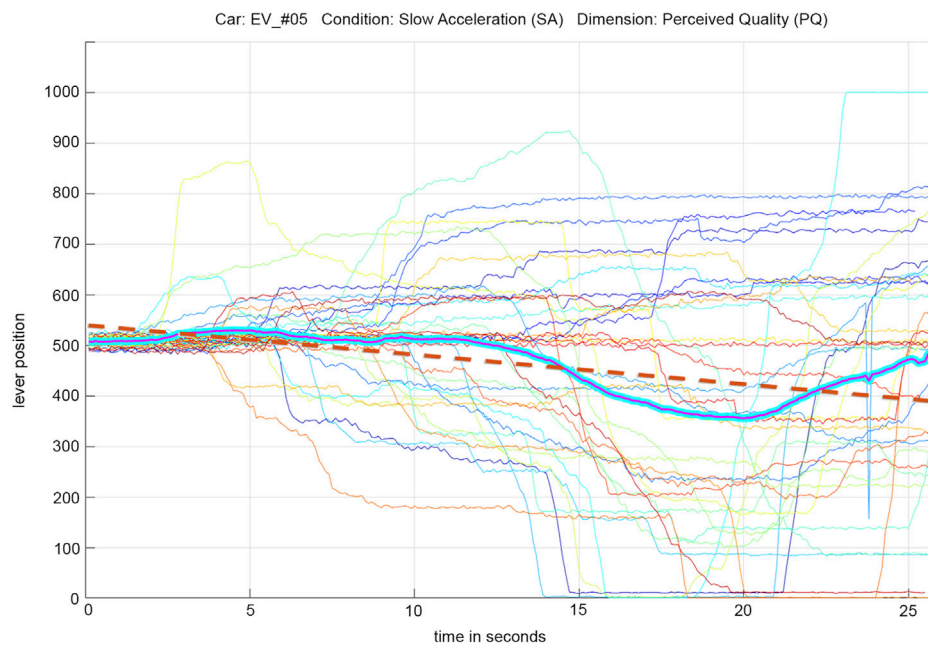


FIGURE 5 Exemplary visualization of the continuous evaluation streams regarding the variable *perceived quality* (starting position of the slider in the middle) for EV_#5 in the slow acceleration (SA) scenario. Each colored thin line represents the evaluation stream of a single participant, and the thick pink-blue line indicates the overall mean over time. A regression line (dashed red line) depicts the overall trend of the sample's evaluation.

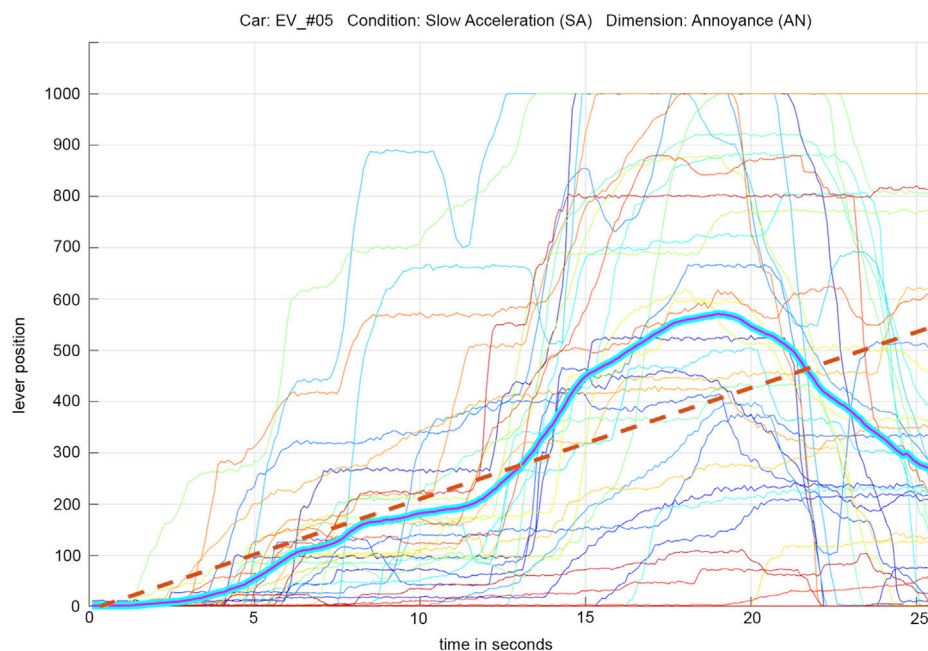


FIGURE 6 Exemplary visualization of the continuous evaluation streams regarding the variable *perceived annoyance* (starting position of the slider at the bottom) for EV_#5 in the slow acceleration (SA) scenario. Each colored thin line represents the evaluation stream of a single participant, and the thick pink-blue line indicates the overall mean over time. A regression line (dashed red line) depicts the overall trend of the sample's evaluation.

very distinct, steep slope starting at the 11-s mark, and the most distinct peaks around the 14 second mark. In contrast, EV_#01 in the CA scenario starts to be very annoying rapidly and soon after

launch but does not cause any more disturbances after the five second mark. A similar pattern is visible for EV_#01 in the full acceleration condition.

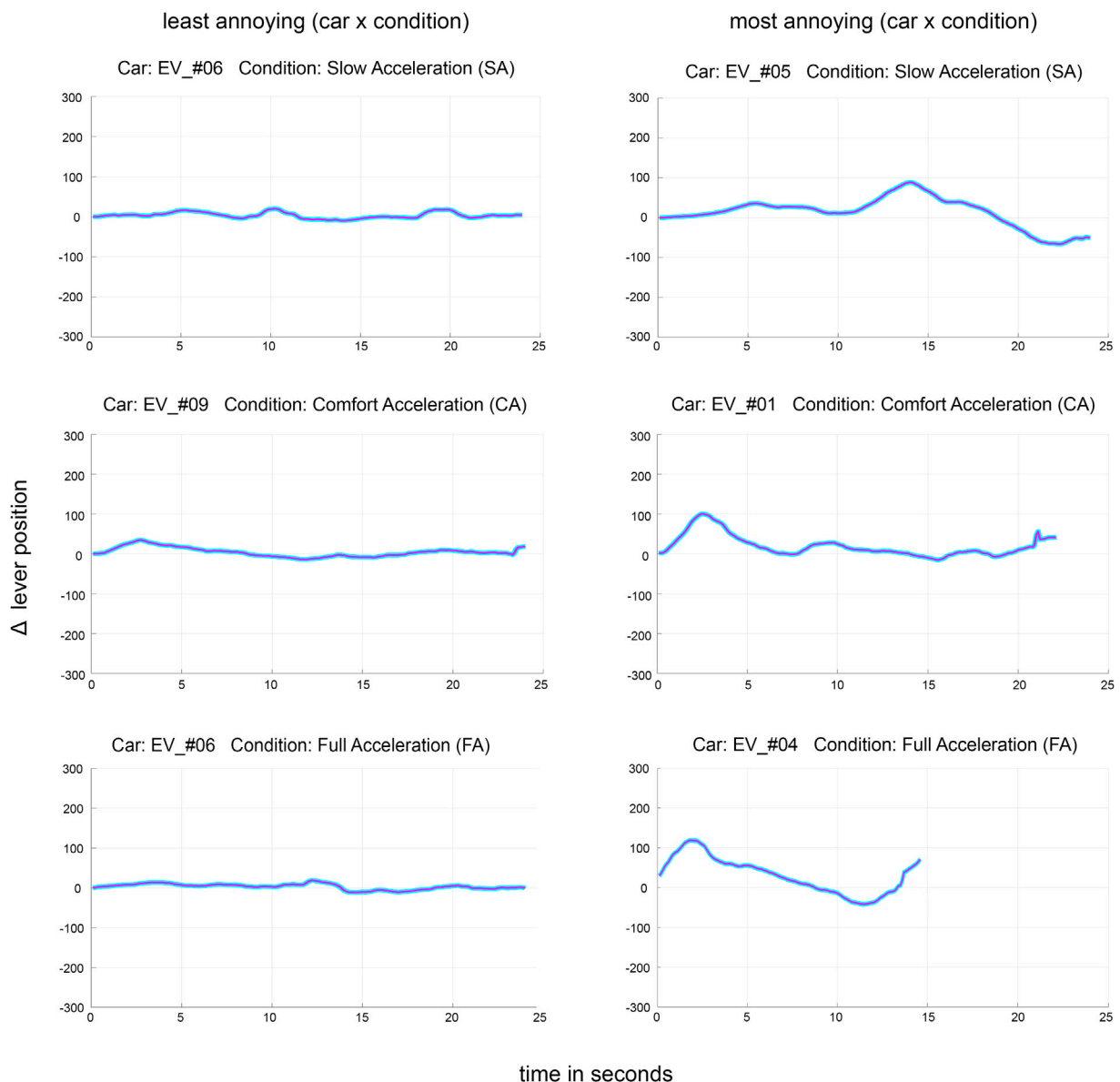


FIGURE 7

The gradients (numerical differentials for the *CEP* data over time) for the vehicles perceived as least annoying (left column) and as most annoying in each acceleration condition (SA, CA, FA; from top to bottom). Positive values indicate a rise in perceived annoyance and vice versa.

4.3 Acoustic analysis

Additionally, we analyzed the acoustic profiles of the stimuli through Campbell diagrams. These Campbell diagrams provide information about acoustic parameters, such as sound pressure level (SPL), frequency spectra and tonal components as, for example, distinct engine orders, and therefore, how the acoustic scene unfolds over time objectively regarding their physical parameters. In Figure 8 the depiction of the acoustic signal and the corresponding *CEP* diagram on the *perceived quality* of EV_#5 in the SA scenario is depicted. The stream diagrams from the continuous evaluation and the Campbell diagrams display the temporal resolution on the *x*-axis. Although

Campbell diagrams do not claim to give indications of how the acoustic stimuli would be evaluated and perceived by a human percipient, with this comparison, we want to emphasize that for purposes of deriving insights on perceptual qualia, such as the *perceived quality* of driving noise, ask for different methods than mere objective analyses of physical parameters.

Also, it can be difficult to determine why specific stimuli would be perceived as significantly less or more annoying than others. For example, when comparing the Campbell diagrams of the stimuli EV_#1 and EV_#2 in Figure 9, where EV_#2 was perceived as significantly less annoying in the comfort acceleration scenario according to our data (see Table 1;

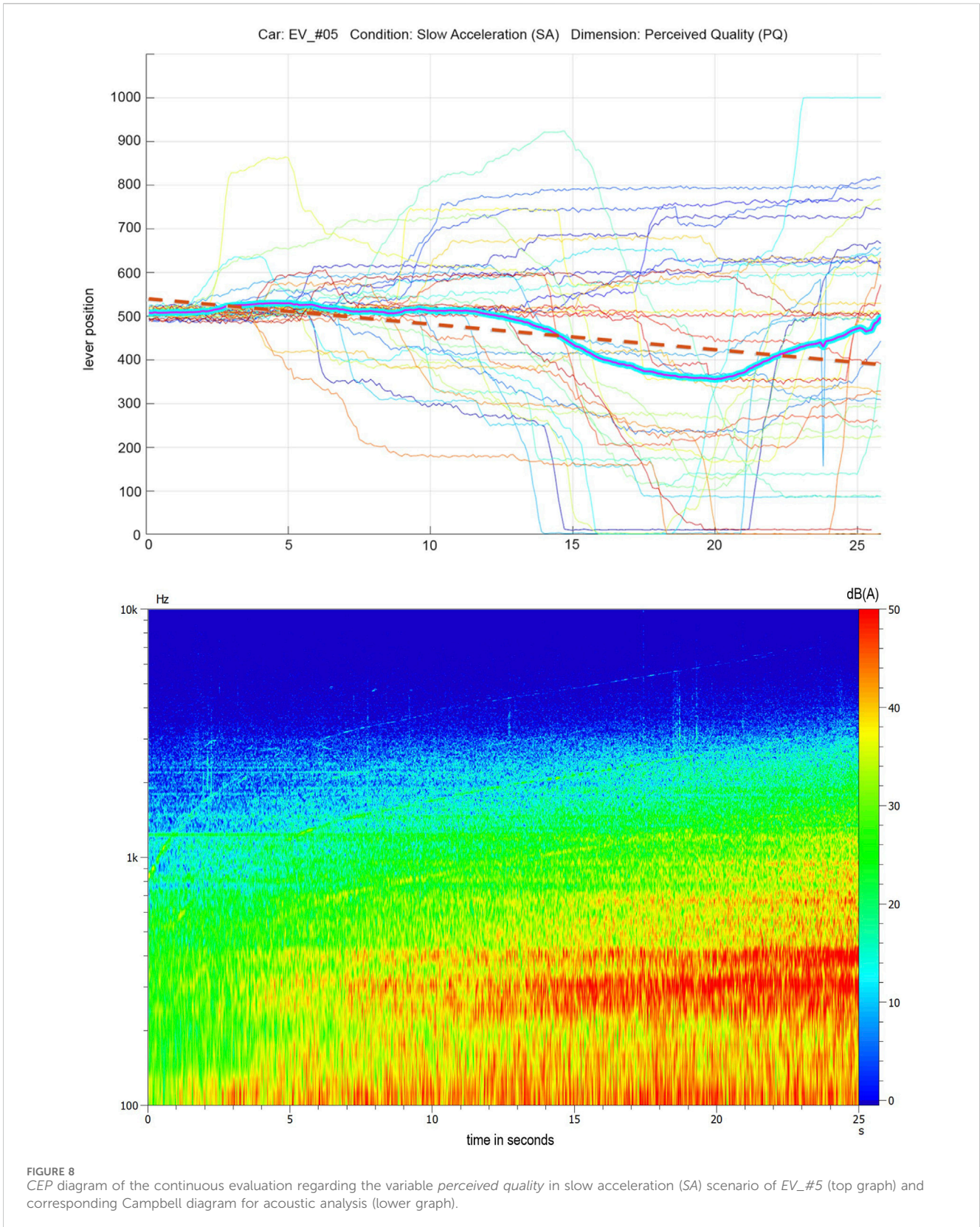
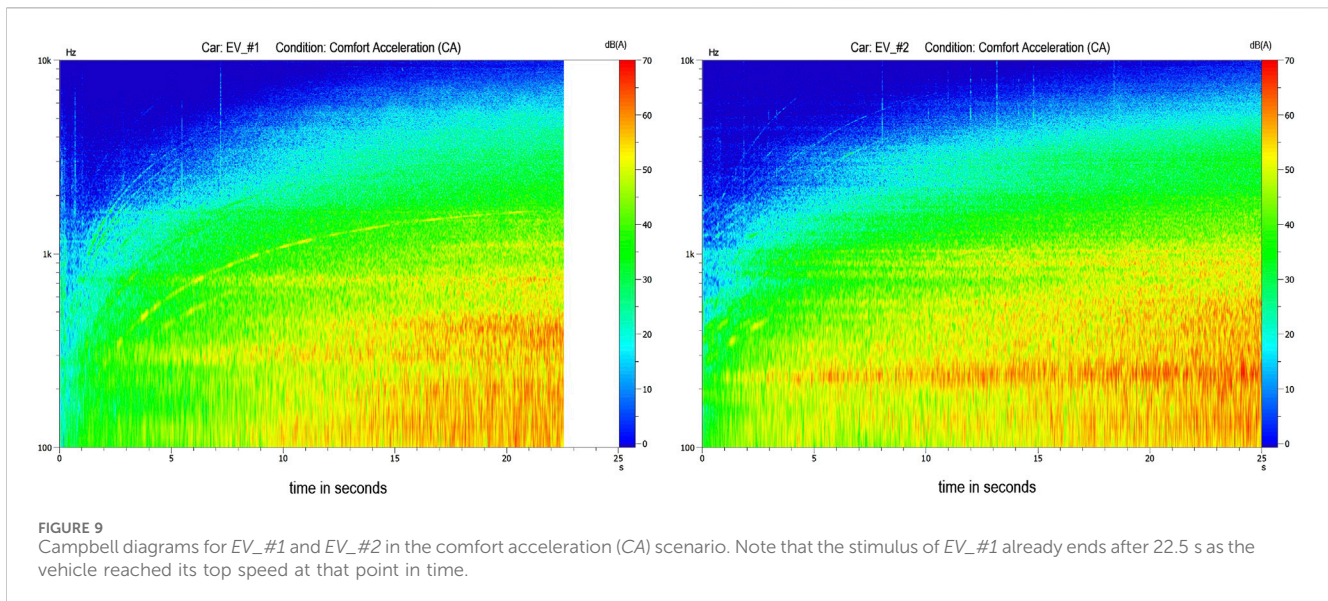


Table 2). From a brief visual comparison, one could find it difficult to decide, which of the two stimuli might be significantly more annoying than the other: EV_#1 seems to

show stronger distinct engine orders, while EV_#2 shows distinct engine orders in the higher frequency spectrum and strong resonances in the lower frequency spectrum spanning



over almost the entire acoustic scene. But which of these physical parameters are diminishing the subjective qualitative impression the most could be challenging to determine by solely looking at Campbell diagrams. Also, dynamic perceptual effects can not be derived from this depiction of the acoustic parameters.

4.4 Comparison of the evaluation methods

To compare the two different evaluation methods in this study, we furthermore compared the parameters of the continuous evaluations from the CEP slider for each stimulus with the average ISM ratings (see Table 3). As the participants' task was to evaluate the presented stimuli on two different scales—first continuously with the slider bar (signal output ranging from 0 to 1000) and second on a seven-point Likert scale—it is not permissible to simply translate the ISM ratings onto the continuous scale. Nevertheless, by looking at the rank orders of CEP and ISM data, for perceived quality as well as perceived annoyance, we see that both measures match well. In the SA scenario, EV_#06 is the least annoying regarding both measures. The same holds for EV_#09 in the CA scenario and EV_#06 in the FA scenario. For the dimension of perceived quality, the two measures seem to slightly differ as in the CEP evaluation EV_#6 was perceived as of highest quality, while with the ISM evaluation EV_#2 scored highest in the SA scenario. In the other two scenarios both measures show high correspondence again as in the CA scenario EV_#9 is perceived as of highest quality with both measures and rank order is aligned, and in the FA scenario EV_#6 is perceived as of highest quality with both evaluation measures. The correspondence of both measures is a promising indicator for reliability, as both measures arrive at very similar results by very different means.

The added benefit of CEP is visible in the temporal dynamics that are plotted in Figure 7 or as well in Figure 5 and Figure 6 on the individual level. The process of appreciation becomes

tangible and differences between vehicles with similar integral measures become apparent. For acoustic engineers, the revealed perceptual dynamics can be helpful in tackling the causes of disturbing noise, as well as guiding interventions in refining the e-NVH profiles.

4.5 Associations

Per vehicle and acceleration scenario, low scores of perceived annoyance seem to go along with higher scores in perceived quality. From the ISM data, a significant negative correlation of $\tau = -36$, $p < 0.001$ (Kendall's Tau for rank-based data) can be derived for the two key variables overall. These associations differ among the scenarios: $\tau = -28$, $p < 0.001$ for the slow acceleration, $\tau = -38$, $p < 0.001$ for the comfort acceleration and $\tau = -41$, $p < 0.001$ for the full acceleration scenario.

5 Discussion

From the ISM rating data, we can derive information about whether the stimuli were perceived as of significantly more or less quality, as well as if they were perceived as significantly more or less annoying than others. Though the ISM values provide us with an overview of the most qualitatively preferred and least annoying e-powertrain noise, these rankings lack temporal information about the course and development of the subjective assessments. The participant's individual overall "percept" is merged into a singular value. Thereby, it does not allow any differentiation, as for example, about whether a specific stimulus might have been very annoying at the beginning, at the end, or just throughout the entire acoustic scene. Especially when further analyzing specific acoustic properties, such as frequency peaks or tonalities, to further specify refinement measures for a specific e-powertrain, the ISM is not sufficient to point out which

TABLE 3 Comparison of CEP and ISM ratings.

| Stimulus | Slow acceleration (SA) | | | | | | | |
|----------|---------------------------|------|-------------|------|---------------------|-------|-------------|------|
| | Perceived Quality | | | | Perceived Annoyance | | | |
| | CEP | | ISM | | CEP | | ISM | |
| | M | SD | M | SD | M | SD | M | SD |
| EV_#1 | 54.68 | 2.88 | 4.05 | 1.63 | 16.05 | 12.06 | 3.27 | 1.64 |
| EV_#2 | 57.96 | 5.15 | 4.46 | 1.24 | 16.32 | 6.80 | 2.73 | 1.17 |
| EV_#3 | 54.49 | 4.47 | 4.24 | 1.21 | 16.89 | 6.61 | 2.78 | 1.13 |
| EV_#4 | 51.64 | 5.11 | 3.89 | 1.22 | 19.79 | 7.98 | 3.14 | 1.36 |
| EV_#5 | 46.39 | 5.91 | 3.24 | 1.26 | 27.14 | 19.25 | 4.38 | 1.98 |
| EV_#6 | 59.64 | 3.72 | 4.19 | 1.61 | 5.44 | 2.68 | 1.78 | 0.98 |
| Stimulus | Comfort Acceleration (CA) | | | | | | | |
| | Perceived Quality | | | | Perceived Annoyance | | | |
| | CEP | | ISM | | CEP | | ISM | |
| | M | SD | M | SD | M | SD | M | SD |
| EV_#1 | 52.22 | 2.45 | 4.00 | 1.78 | 30.51 | 11.32 | 3.89 | 1.65 |
| EV_#2 | 58.21 | 5.83 | 4.38 | 1.32 | 15.11 | 6.00 | 2.62 | 1.32 |
| EV_#4 | 59.43 | 6.52 | 4.43 | 1.19 | 19.21 | 6.75 | 3.05 | 1.33 |
| EV_#7 | 54.29 | 4.29 | 4.05 | 1.37 | 23.01 | 8.78 | 3.62 | 1.40 |
| EV_#8 | 55.54 | 5.56 | 3.76 | 1.64 | 19.38 | 12.36 | 3.38 | 1.40 |
| EV_#9 | 65.19 | 7.71 | 5.11 | 1.63 | 8.57 | 3.27 | 1.84 | 1.01 |
| Stimulus | Full Acceleration (FA) | | | | | | | |
| | Perceived Quality | | | | Perceived Annoyance | | | |
| | CEP | | ISM | | CEP | | ISM | |
| | M | SD | M | SD | M | SD | M | SD |
| EV_#3 | 55.51 | 4.84 | 4.65 | 1.48 | 22.85 | 12.49 | 2.89 | 1.45 |
| EV_#4 | 49.18 | 1.56 | 3.65 | 1.67 | 35.68 | 14.09 | 4.32 | 1.58 |
| EV_#6 | 62.11 | 5.21 | 4.76 | 1.61 | 6.59 | 2.80 | 1.65 | 0.89 |
| EV_#7 | 52.18 | 2.36 | 3.92 | 1.52 | 31.99 | 14.44 | 3.76 | 1.44 |
| EV_#10 | 52.29 | 3.06 | 4.54 | 1.52 | 22.66 | 11.42 | 3.22 | 1.53 |
| EV_#11 | 58.26 | 6.92 | 4.62 | 1.66 | 14.68 | 6.35 | 2.51 | 1.30 |

Statistical values for the continuous evaluation (CEP) and integral singular measure (ISM) ratings for the dimensions of perceived quality (left side) and perceived annoyance (right side) in each of the three acceleration scenarios for each vehicle. The three best-rated stimuli–high scores on perceived quality and low scores on perceived annoyance–per acceleration scenario in each dimension are highlighted in boldface type. Note that not all EV recordings are part of every acceleration scenario (see section 3.2 Stimuli for details). The evaluation for the ISM ratings was conducted through a seven-point Likert scale; the CEP ratings were semantically but not numerically scaled towards the respondents. For better readability, we transformed the CEP values in this table to 0–100 (original slider bar output ranged from 0 to 1000). Therefore, 50 represents the neutral starting point in the variable perceived quality, and 0 represents the neutral starting point in the variable perceived annoyance.

aspects are specifically diminishing the qualitative impression. The continuous evaluation approach provides the potential to analyze the criticality of different NVH phenomena and to identify acoustic characteristics that define a high qualitative impression. Therefore, the employed continuous evaluation provides a goal-oriented methodological approach suitable to tackle such problems in the applied field and can give first indications which NVH phenomena should be avoided. As shown in this study, CEP can deliver valuable insights on specific aspects that might need refinement due to its high temporal resolution of the subjective evaluation. The high correspondence of the evaluations' rank order in ISM and CEP indicates the continuous evaluations to be reliable. Moreover, our results confirm a significant negative correlation of $\tau = -0.36, p < 0.001$ (Kendall's Tau for rank-based data) between perceived annoyance and perceived quality overall, similar to the significant negative correlation between the perceptibility of e-powertrain noise in acceleration scenarios and perceived quality of $\tau = -0.32, p < 0.001$ as found by Münder and Carbon (2022). With this potential negative medium effect of e-powertrain noise on the overall qualitative impression of an EV's acoustic profile, the identification of dynamic effects in its subjective evaluation can be very helpful in the refinement of e-NVH and should be considered in the acoustic design process. However, we would like to point out that our sample shows a high level of expertise with 59% of the participants working specifically on matters of vehicle acoustics. As shown in the study of Münder and Carbon (2022) the expertise level might influence one's evaluation. In our study we utilized a widely spread repertoire of stimuli from across the whole automotive market. For the refinement of a specific e-powertrain configuration the stimulus set should focus on a more aligned set of stimuli, as for example, varying powertrain configurations within the same vehicle, in future studies. Also, specifically defined NVH-phenomena should be focused on and varied in their appearance throughout the acoustic scene, to systematically compare whether the general existence of the phenomenon or, for example, its loudness effects the qualitative impression, or if it is the specific timing that is decisive. Continuous evaluation data achieved by applying the CEP can be compared with the acoustic measurement data to derive insights on how the specific physical properties, such as frequency peaks or the onset of specific orders, impact the subjective evaluation. A methodological limitation in this study to be considered is the time lag between the individual's perception and their action on the evaluation slider. The actual adjustment of the slider is probably time-delayed, as the participant must become conscious of their impression first. Moreover, a continuously accompanying evaluation of an acoustic scene requires more focus and attention of the participants as well as a more thorough data analysis on the researchers' side. In contrast, an evaluation with an integral singular measure rating is rather time and cost-efficient. Our data indicates the concepts of perceived quality and perceived annoyance to be perceived highly interindividually. Therefore, as in our study, future research should aim for a sufficient sample size when investigating such interindividual concepts, which is defined by each participant, as general trends in perception can

only be derived with robust and reliable statistics. Furthermore, it would be interesting to investigate the effect of additional vibrational feedback on the participants' perception of EV interior soundscapes. With the emphasis on the level-correct reproduction of 3D sound recordings in our utilized acoustic simulator, such multimodal effects would be interesting to consider and add in future studies.

6 Conclusion

In the present study, we obtained an integral singular measure (*ISM*) rating on the dimensions of perceived quality and perceived annoyance of e-powertrain noise, and continuous evaluation data (*CEP*) throughout the respective acceleration process. Thereby, we were able to unfold the dynamics of our participants' experience of a non-stationary acoustic signal. Rather than assessing our participants' overall impression in retrospect—as done through singular measurement ratings – we captured their subjective evaluation while they experienced the acoustic scene. By applying such continuous evaluation techniques, researchers and acoustic engineers have the chance to analyze subjective evaluations of non-stationary acoustic events and scenes with higher timely resolution. Thereby, the dynamic perceptual effects of specific acoustic properties can be identified. In the context of automotive acoustics, such methods should be pursued in future research as they can bring further insights into the interplay of the different (e-)NVH characteristics and provide a great tool to refine a vehicle's NVH profile while already considering the resulting perceptual impressions of the resulting product.

Data availability statement

The datasets presented in this article are not readily available because of proprietary reasons. Requests to access the datasets should be directed to mara.muender@uni-bamberg.de.

Ethics statement

Ethical approval was not required for the studies involving humans because the study was in full accordance with the ethical guidelines of the University of Bamberg. It was approved by an umbrella evaluation for psychophysical testing of the University of Bamberg ethics committee (Ethikrat der Universität Bamberg) on 18 August, 2017. All participants were informed about their data protection rights and approved the usage of their data prior to the questionnaire. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written

informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MM: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Visualization, Writing—original draft, Writing—review and editing. G-JM: Resources, Writing—review and editing. MHR: Formal Analysis, Methodology, Software, Visualization, Writing—review and editing. C-CC: Conceptualization, Formal Analysis, Methodology, Writing—review and editing.

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Conflict of interest

Authors MM and G-JM were employed by BMW Group.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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4 Innovativeness in EV Sound Design

Aside from the inherent NVH sources, further aspects contribute to EVs' overall soundscape. Therefore, the aspect of active sound design should be considered for a holistic approach to the perception of interior soundscapes in EVs. As discussed in **1.2.3 Automotive Sound Design**, the active staging of a vehicle through the application of acoustic design is a standard method to shape its character (Pletschen, 2010; Zeller, 2018). Different automotive manufacturers have already pursued cooperation with renowned composers (Kleinjohann, 2020) to find exceptional sound designs to represent their products. According to Baha et al. (2012), radical innovations can lead to an imbalance in meaning, as the novel product dissociates from the existing product's meaning. In alignment with the industrial design principle *MAYA – Most Advanced Yet Acceptable* (Loewy, 1951) – it is important to ask *how* innovative a sound design for EVs can be, balancing the need to bridge the meaning gaps between familiar driving sound from past technologies while also representing a novel and appealing sound for electrified driving. Hekkert et al. (2003) demonstrate that an optimal combination of typicality and novelty is beneficial for the aesthetic preference in industrial designs within the visual domain, while the MAYA principle also seems to hold in other sensory domains (Hekkert, 2006). Therefore, investigating possible factors restraining consumers from product adoption in early design stages can benefit manufacturers when introducing innovations to the market (Heiskanen et al., 2007), such as novel sound concepts for EVs.

4.1 Introduction to the Study on Repeated Measures and EV Sound Design

In Mnder et al. (2025), we especially focused on the perception of novelty in sound designs for EVs and their appreciation. We aimed to estimate an ideal degree of innovativeness in EV sound design, which also shows high potential for long-term preference. Therefore, we worked with the composer and sound designer Renzo Vitale, who created our study's stimuli and sound design concepts. Ten stimuli were altered in their level of innovativeness (*conventional*, *progressive*, and *futuristic*) and their sound character (*technical* and *artistic*). The sound concepts were presented to $N = 83$ participants, recruited within the BMW Group ($n = 46$) and at the University of Bamberg ($n = 37$), in a listening lab setup through headphones. Not only were the stimuli evaluated regarding the two main dimensions, *Perceived Innovativeness* and *Liking*, but also on semantic dimensions as *Perceived Powerfulness*, *Perceived Sustainability*, *Perceived Pleasantness*, and *Perceived Emotionality*. The main dimensions assessing the novelty and preference for each sound concept were evaluated through the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005). Thereby, we revealed dynamic effects in the aesthetic preference and novelty perception in the domain of automotive sound design, as well as insights into the semantics that specific concepts convey. Our results support automotive engineers in

making design decisions for their products and predicting long-term effects regarding the appreciation of sound concepts with different degrees of novelty.

4.2 Back to the Future: Innovativeness in Sound Design for Electrified Vehicles

Back to the future: Innovativeness in sound design for electrified vehicles

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Abstract

With powertrain electrification, the character of a vehicle's soundscape significantly changes. Not only does it become quieter, but also the so far dominating combustion engine broadband noise, which shaped people's expectations, disappears. With the upcoming technology, we are empowered to create soundscapes with novel frequency spectra and sound design approaches. Vehicle soundscapes are dynamic by nature due to load and speed changes, and the driving situation. In this study, different active sound design concepts for electrified vehicles (EVs) have been assessed by $N = 83$ participants concerning their conveyed impressions of *Perceived Innovativeness*, *Liking*, and further relevant dimensions. The sound design concepts are varied in their general sound character and level of innovativeness and then presented in a listening laboratory. By employing the *Repeated Evaluation Technique* (RET) in the context of sound design research, we gather insightful data about dynamic effects in the perception of innovative acoustic textures in the context of active EV sound design. The findings of this study reveal dynamic effects in novelty perception and aesthetic preference, as well as insights into the semantics specific design characteristics convey. This can be helpful in shaping the character of a vehicle, making predictions about long-term appreciation of novel driving sound concepts, and assisting sound engineers and designers in creating innovative yet appreciated sound designs for EVs.

Keywords

sound design, innovation, electrified vehicle, perception, psychoacoustics, automotive, perceived quality, applied acoustics

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Introduction

Accompanied by the electrification of vehicle powertrains, we currently face a drastic change in the noise profiles and acoustic quality of such vehicles. In the present paper, we focus on the impact of electrification on the interior soundscape of electrified vehicles (EVs). On the one hand, EVs are much quieter due to the overall reduced sound pressure level of emitted noise compared to conventional internal combustion engine vehicles (ICEVs) (Blickensdorff et al., 2019; Zeller, 2018). On the other hand, novel EV soundscapes with now unmasked disturbing noises (Blickensdorff et al., 2019; Eisele et al., 2019; Gavric, 2020), as well as EV-specific tonal components and higher frequency spectra (Blickensdorff et al., 2019; Devillers et al., 2020; Gavric, 2020) pose a challenge regarding the refinement of automotive acoustics (Allman-Ward et al., 2020; Gavric, 2020; Zeller, 2018). Noise, Vibration, and Harshness (NVH) criteria play a crucial role in customer satisfaction (Qatu, 2012; Qatu et al., 2009; Sinambari & Sentpali, 2020; Zeller, 2018), as they pose an immediate, multisensorial-perceivable entity, contributing to the overall quality impression of a vehicle (Münder & Carbon, 2022a). Beyond the naturally emitted noise by the electrified powertrain, active driving noise of EVs is a crucial NVH characteristic to be considered concomitant with the new technology in terms of sound quality (Allman-Ward et al., 2020; Genuit & Fiebig, 2014; Kleinjohann, 2020).

Customer Expectations and Industry

Krishna (2021) revealed through a social media analysis that a vehicle's sound is one of the most significant assets through which customers build emotional connections and even might anthropomorphize it. Passionate car enthusiasts—so-called *petrol heads*—notoriously criticize the overall muted EV soundscapes as, for example, a “lackluster ‘appliance-like’” (p. 6) and “sterile” (p. 5) experience (Krishna, 2021). Public discourse on EV acoustics should be considered, as it determines customer expectations and acceptance (Fiebig & Schulte-Fortkamp, 2019; Genuit & Fiebig, 2014) toward the new technology in the transition phase. The association between the acoustic feedback of a vehicle and its perceived power and performance parameters has been strengthened over decades, making it difficult to resolve these links closely tied to the typical combustion engine soundscape in the customers' minds (Cerrato, 2009; Clendinning, 2018). Borg (2014) even described electrified driving as contradicting “a lifetime of experiences and expectations about cars and sound” (p. 287). Contrary to the demands of an audible and familiar combustion-like sound character, common expectations for electrified driving seem to involve a quiet, almost gliding experience with yet driving-scenario-appropriate operational feedback (Genuit & Fiebig, 2014). Moreover, progressive-futuristic vehicle concepts from media such as sci-fi books, film, and television, which have been popularized in the 20th century, have to be considered in terms of today's customer expectations regarding futuristic sound textures (Clendinning, 2018). According to Fechner's Aesthetic Association Principle, associative factors, the individual's learning experience, and its cultural and epochal background, influence the aesthetic experience even more than direct factors, such as design properties (Ortlieb et al., 2020). Due to the scarce exposition and little experience most people have with electrified driving, it remains unclear if customers can even qualify what they expect of an electric vehicle's soundscape. Cerrato (2009) even assumed a transitional phase from familiar and less innovative sound concepts—resembling typical combustion engine noise—to increasingly innovative and daring novel approaches. Therefore, amid the transitional phase, it is up to the manufacturers to set a standard

and define the driving acoustics in the era of EVs. As customers perceive pathbreaking products as more prototypical in their product domain (Carson et al., 2007), pioneering in active EV sound design can potentially be a competitive advantage. The interior of a car—including its interior soundscape—offers manifold design approaches to manufacturers (Leder & Carbon, 2005). According to Karlsson et al. (2003), it can be considered a user-driven product, making its design less restricted to technical constraints while allowing a stronger aesthetic and individualistic focus. Design facilitates the creation of emotional value and thereby potentially promotes customers' loyalty and passion for the product, according to Noble and Kumar (2008), which they find especially important in light of current economic trends of relationship-focused customer strategies. Many manufacturers already recognize the importance of their EVs' sound design, as some even team up with well-established composers and music producers (Kleinjohann, 2020), which underlines the particular importance of aesthetics and artistic facets in a car's design. Sound enhancement in EVs is discussed as a measure to re-establish familiar operational driving feedback, to create an emotionally charged and customizable driving experience, to shape distinct and product-unique characteristics or overall brand identity (Allman-Ward et al., 2020; Bodden & Belschner, 2016; Kleinjohann, 2020; Sottek et al., 2005; Streicher et al., 2021). Münder and Carbon (2022b) offer an overview of current research investigating different sound enhancement approaches to operational feedback, the semantics of sound concepts, and sound synthesis and enhancement strategies. Though some see a necessity in EV sound enhancement for various reasons (Allman-Ward et al., 2014; Kleinjohann, 2020), there is a lively debate in the field on the different possible approaches regarding its synthesis and design (Clendinning, 2018; Genuit & Fiebig, 2014). Within the target conflict of having the opportunity for quiet driving experiences versus requesting operational vehicle feedback as known (Fiebig & Schulte-Fortkamp, 2019), different strategies are discussed: conservative approaches to resemble ICEV-typical soundscapes and satisfy traditional expectations, the refinement of natural e-powertrain characteristics to preserve its authentic soundscape, or approaches with highly novel sound design concepts (Genuit, 2012; Genuit & Fiebig, 2014; Kleinjohann, 2020; Sinambari & Sentpali, 2020). Despite a large body of research, the question of the *best* strategy in EV sound enhancement seems to remain unclear, although a great variety of approaches seems feasible (Münder & Carbon, 2022b). Finding suitable driving sounds for EVs that highlight their outstanding vehicle dynamics, well-orchestrated with a unique, nearly silent driving experience, remains one of the main challenges in automotive acoustics. With these questions in mind, our study investigates what is considered a suitable degree of novelty in driving sounds for EVs and how stable preferences toward the different sound concepts are over repeated exposure.

There are also intra-individual factors that could influence the acceptance of or aversion to rather novel approaches in the design of a vehicle's interior soundscape among customers. One of these factors could be the customer's openness, one of the basic personality trait dimensions in the established five-factor models known as the *Big Five* (Rauthmann, 2017). Openness refers to how open a person tends to be toward new experiences. Soto and John (2017) adopted the label of open-mindedness instead of openness to distinguish between individual preferences regarding the range of cognitive, perceptual, and affective experiences from openness toward social experiences. In their *Big Five Inventory II* (BFI-II), they subsumed the facets of *intellectual curiosity*, *aesthetic sensitivity*, and *creative imagination* into the subscale of *Open-Mindedness* (Soto & John, 2017). A measure considering such tendencies specifically in the context of technology is the *Affinity for Technology Interaction* (ATI) scale by Franke et al. (2019), which can be helpful to characterize one's sample in technology interaction research, as it can have consequences on user experience and technology acceptance.

Design Principles

As innovations often encounter customers' resistance to adopting new products that have recently been introduced to the market, innovators should evaluate their concepts in early design stages to

find out about the factors holding up product adoption that go beyond plain novelty (Heiskanen et al., 2007). According to Baha et al. (2012), radical innovations might lead to a dissociation of the novel product due to an imbalance in meaning: the novel character dominates and overshadows the existing product meaning, which is why consumers might not be able to relate anymore and reject the product's adoption. These assumptions align with a central design theorem of innovation established by industrial design pioneer Raymond Loewy: the MAYA-principle, standing for *Most Advanced Yet Acceptable* (Loewy, 1951). To avoid customer rejection, meaning gaps between the familiar combustion engine soundscape and the novel electrified soundscape need to be identified and bridged in terms of designing a suitable yet attractive driving sound (Baha et al., 2012). A possible way to introduce new meanings, stated by Baha et al. (2012), is to either combine existing meanings, or to build upon them as they are more relatable to customers in the specific product context. Hekkert et al. (2003) found a well-balanced combination of innovative and novel elements with typical and familiar attributes to be essential for aesthetic preference in their design studies.

The Present Study

The main aim of the present study was to investigate dynamic effects in the perception of *Innovativeness* and *Liking*. Therefore, we applied the *Repeated Evaluation Technique* (RET) by Carbon and colleagues (Carbon, 2015; Carbon & Leder, 2005; Faerber et al., 2010; further details in the *Method* section), an evaluation method that, to our knowledge, has not been applied in the context of vehicle sound design before. By this novel methodological approach, we achieved a high degree of elaboration in the experimental listening lab setup and could compare the perception in those two dimensions over time to better predict a sound concept's future acceptance. The results of this study should guide automotive engineers in determining which sound design strategy to follow when shaping the sound characteristics of EVs.

Another study goal is to estimate an ideal degree of novelty in sound design approaches to identify an EV-driving sound with a high potential for long-term preference by evaluating different acoustic concepts. Therefore, we focus on sound concepts with varying levels of innovativeness and different sound characters and evaluate various dimensions such as *Liking*, *Perceived Innovativeness*, *Perceived Powerfulness*, *Perceived Sustainability*, *Perceived Pleasantness*, and *Perceived Emotionality*. The first two dimensions represent the main dimensions to investigate dynamic effects in matters of preference relating to novelty in sound concepts. The other four dimensions are chosen as they represent important characteristics of (novel) vehicles and help gather information about what certain sound textures transmit: the attributes of powerfulness and pleasantness are often discussed in research on interior sound design for EVs (e.g., Lennström et al., 2011; Ma et al., 2017; Swart et al., 2018; Swart & Bekker, 2019). Further, we were interested in the attributes of sustainability and emotionality, inspired by current design discussions in the applied field. Thereby, we are not only addressing aesthetic preference and novelty perception but also the semantic meaning the evaluated sound concepts convey. By considering these semantics in our investigation, we want to gain further insights into how powerful and strong (*Perceived Powerfulness*), how sustainable, green, and efficient (*Perceived Sustainability*), how pleasant, enjoyable, and comfortable (*Perceived Pleasantness*), and how affectively touching (*Perceived Emotionality*) the various concepts are perceived by our sample. The insights on conveyed semantic meaning can then be helpful in identifying the suitability of the different sound concepts for different vehicle types in terms of product characterization at a later stage in the design process.

In accordance with findings in the domain of visual aesthetics (see Carbon & Leder, 2005), we hypothesize that sound textures with higher degrees of novelty will be liked less in the course of a first assessment but will show increased preference ratings over further elaboration compared to less innovative sounds. For less innovative concepts, the preference ratings are suspected to remain relatively stable over time as the acoustic habits are already developed to process such sounds.

Regarding the perceived novelty of the concepts, we expect that novelty aspects will wear off with increasing elaboration as they become more familiar over repeated exposure. Moreover, we presume that specific semantics are better liked (e.g., more pleasant sound textures) as they might be less annoying and stressful (Devillers et al., 2020; Gavric, 2020), perceived as more innovative (e.g., sound textures perceived as more sustainable), and possibly go hand in hand with each other (e.g., emotionality and powerfulness) as their semantic bonds have been strengthened over decades (Krishna, 2021), or interfere with one another (e.g., powerfulness and sustainability) as they are (at least currently) contradicting each other. To control for the factors potentially influencing the acceptance or reluctance of novel concepts, we further assess our sample's scores on the subscale of open-mindedness from the BFI-II (Soto & John, 2017) and on the ATI scale (Franke et al., 2019).

Method

Participants

We conducted an a priori power analysis for a repeated-measures analysis of variance (ANOVA), run in G*Power (Faul et al., 2007), aiming at a revealed medium effect size with a set statistical test power of $1-\beta=0.8$ and an error probability of $\alpha=0.05$ to find the approximate sample size needed to test our main hypotheses.

The power analysis¹ yielded a minimal required sample size of $N \geq 34$. Two samples were recruited via email and notice board—one corporate sample at the BMW Group ($n=46$) and one student sample at the University of Bamberg ($n=37$; total sample size $N=83$), to increase the diversity of our sample. Participating was not restricted except to normal hearing ability. We compensated participation only for students in the academic sample. The study was conducted according to the ethical principles expressed by the Declaration of Helsinki, the German Professional Psychologists (BDP), and the German Psychological Society (DGPs). Furthermore, the experimental plan was approved by the local ethics committee of the University of Bamberg. Prior to the experimental testing, participants were informed about the study's rationale without providing specific details on the employed stimuli. They all gave written consent to participate and were informed about their rights to withdraw from the study at any point in time without the need to state reasons. See Table 1 for more details on the samples.

Table 1. Demographic Sample Description.

| | Overall | | Corporate | | Student | |
|----------------------------|------------------------|-----------|------------------------|-----------|------------------------|-----------|
| | <i>N</i> | | <i>n</i> | | <i>n</i> | |
| Sample size | 83 | | 46 (55% ^a) | | 37 (45% ^a) | |
| Gender | | | | | | |
| Female | 38 (46% ^a) | | 15 (33% ^b) | | 23 (62% ^b) | |
| Male | 45 (54% ^a) | | 31 (67% ^b) | | 14 (38% ^b) | |
| | <i>M</i> | <i>SD</i> | <i>M</i> | <i>SD</i> | <i>M</i> | <i>SD</i> |
| Age (years) | 30.1 | 9.0 | 33.2 | 10.3 | 26.1 | 4.8 |
| Driving experience (years) | 13 | 9 | 16 | 10 | 9 | 5 |

Note. Driving experience was defined through years of having a valid driving license; to avoid pseudo-accuracy, decimals were rounded for this variable.

^aPercentage referring to overall sample size.

^bPercentage referring to given sub-sample.

Table 2. Sample Description in Openness (BFI-II) and Affinity for Technology (ATI).

| Scale | Corporate Sample | | Student Sample | | Sample Comparison | | |
|--|------------------|-------------|----------------|-------------|-------------------|--------------------|-------------|
| | M | SD | M | SD | t(81) | p | d |
| BFI-II Openness (total score) | 46.85 | 6.20 | 46.11 | 5.49 | 0.57 | .571 | 0.13 |
| BFI-II Subscale Aesthetic Sensitivity | 14.93 | 3.50 | 15.97 | 3.12 | -1.41 | .163 | 0.31 |
| BFI-II Subscale Intellectual Curiosity | 16.35 | 2.04 | 15.81 | 2.38 | 1.11 | .271 | 0.24 |
| BFI-II Subscale Creative Imagination | 15.57 | 2.52 | 14.32 | 2.46 | 2.25 | .027* | 0.50 |
| ATI score | 4.71 | 0.82 | 3.72 | 1.01 | 4.95 | <.001*** | 1.00 |

Note. Results of *t*-test comparisons in personality variables. Significance levels: * $p < .05$; *** $p < .001$. The effect size magnitude (Cohen's *d*, according to Cohen (1988), is defined as follows: $d \sim 0.2$ as a small, $d \sim 0.5$ as a medium, and $d \sim 0.8$ as a large effect.

In total, 17% ($n = 14$) of sound design experts directly working on topics regarding automotive sound design participated in the study. Roughly a quarter of the sample ($n = 20$, i.e., 24%) has never driven an EV before—in the corporate sample, only 9% never drove electrically before, but in the student sample, it is the case for 43%. We further asked the participants for an estimate of how many hours per week they use vehicles with different powertrain systems: on average, our participants drove conventional cars with ICEVs approximately 3.5 hrs/week, followed by battery electric vehicles with 1.23 hrs/week, hybrid electric vehicles with 0.64 hrs/week, hydrogen cars 0.04 hrs/week and CNGG/LPG cars with 0.18 hrs/week. Additionally, we assessed the *Open-Mindedness* subscale for openness from the BFI II (Soto & John, 2017) and its three subscales, as well as the ATI scale (Franke et al., 2019), to further characterize our sample and control for biases between the samples. The results of the sample comparison are shown in Table 2.

Regarding openness, no significant differences were found between the two samples except on the subscale for *Creative Imagination*, as revealed by an independent *t*-test ($t(81) = 2.25$, $p = .027*$). The participants in the corporate sample ($M = 15.57$, $SD = 2.52$) reportedly score higher than the student sample ($M = 14.32$, $SD = 2.46$). The coefficient Cohen's *d* indicates a medium-sized effect ($d = 0.50$). When comparing the two samples in their scores on the ATI scale (Franke et al., 2019) through an independent *t*-test, the corporate sample ($M = 4.71$, $SD = 0.82$) shows significantly higher scores ($t(81) = 4.95$, $p < .001***$) with a large effect of $d = 1.00$ (see Table 2). When conducting *t*-tests, the assumptions regarding normality and homogeneity were met. Though the samples show slight differences in the variables mentioned above, no significant differences were found between the samples regarding the sound evaluation ratings in this study. Therefore, further analyses in this work were made with the overall sample.

Apparatus

The study's centerpieces are the selected stimuli, all supposed to represent the acceleration of an EV. Due to proprietary reasons the authors cannot provide the employed stimuli to the public. However, we will do our best to describe the utilized material in the following passage. For the composition of the sound concepts, we focused on two variation parameters: the level of *Innovativeness* and the *Sound Character*. The level of *Innovativeness* represents a variation of more familiar concepts toward highly novel sound concepts. As there is no standard for innovativeness in sound design, we aimed for a wide variety of concepts without drifting off the actual context or having noncomparable concepts that are too far apart. Therefore, we utilized relatable and well-known noise spectra from familiar driving noise of ICEVs in the conventional category. For the progressive category, we used familiar elements in combination with novel acoustic features, for example, the combination of

combustion engine-like pedal application in the vehicle's acceleration process with higher frequency spectra and tonal components or floating acoustic accompaniment throughout the entire acoustic scene. The novelty content then peaked in the futuristic category, where we employed musical sound components, dissociative running soundtracks, and abstract sound elements that have not been applied to standard production vehicles so far. Less innovative concepts were therefore assigned to the conventional category, novel sound elements and spherically floating soundscapes composed the progressive level, which was then developed further in the futuristic category in terms of even more spherically floating, cloudier, and enfolding soundscapes with unprecedented sound elements in the context of vehicle acoustics. This way, the familiarity with the sound concepts decreases with progressing *Innovativeness*. At the same time, the three levels of *Innovativeness* increasingly consider novel aspects in the two different *Sound Character* domains. For the variation in the *Sound Character*, determining the general, underlying sound character of the sound texture, we used either artistically or technically oriented sound elements. While musical elements guided the artistic concepts to create novel soundscapes, the technical concepts were oriented toward familiar acceleration mapping and mechanical concepts, resembling authentic machinery soundscapes.

From a wide range of sound concepts and drafted ideas gathered throughout different design processes within the BMW Group's acoustic and design department, the authors selected 15 sound concepts in the first step. Secondly, each author assigned the different concepts to the different cells within the variation matrix by themselves. Next, the authors brought together their categorizations of the sound concepts and discussed which stimuli represent each category best. After several internal review loops and careful consideration among the authors of this work, the sound material was narrowed down to 10 stimuli in total—all composed and produced by the composer and sound designer Renzo Vitale. The number of stimuli, all ranging between 14 and 25 s, was selected considering the experiment's duration and cognitive capacities of the study participants. As the conventional category appeared to be the most unambiguous due to its high degrees of familiarity, we decided to include only one stimulus to represent each of the *Sound Character* × *Innovativeness* combinations. The variation matrix is shown in Table 3: our final preset of stimuli consisted of 10 sound concepts in total, two for the conventional *Innovativeness Level* and four stimuli, each representing the progressive and the futuristic level. The stimuli were evenly distributed in the two *Sound Character* categories.

To evaluate the sound concepts, we applied the RET developed by Carbon and colleagues (Carbon, 2015; Carbon & Leder, 2005; Faerber et al., 2010). Participants evaluated the aesthetics of the sound concepts regarding the two main dimensions, *Perceived Innovativeness* and *Liking*, as well as in the four semantic dimensions of *Perceived Sustainability*, *Perceived Powerfulness*, *Perceived Emotionality*, and *Perceived Pleasantness*, and finally on the two main dimensions again, a second time to gather data on potential dynamic perceptual changes due to the repeated exposure. As Carbon and Leder (2005) demonstrated that the familiarization phase provides a sufficient elaboration of the stimulus material, we gathered semantic data from the whole sample during the

Table 3. Stimulus Variation Matrix.

| Variation Matrix (Innovativeness × Sound Character) | | Innovativeness | | |
|--|-----------|----------------|---------------|---------------|
| | | Conventional | Progressive | Futuristic |
| Sound character | Artistic | <i>Stim05</i> | <i>Stim06</i> | <i>Stim02</i> |
| | | | <i>Stim07</i> | <i>Stim03</i> |
| | Technical | <i>Stim10</i> | <i>Stim01</i> | <i>Stim04</i> |
| | | | <i>Stim08</i> | <i>Stim09</i> |

Note. Stimulus matrix of the variation in *Innovativeness* and *Sound Character*.

familiarization phase in terms of a within-participants experimental design. The study was self-programmed in Python and the acoustic stimuli were presented via Beyerdynamic® DT 770 headphones while the scales were displayed on a computer screen. The playback volume for the stimuli was set to the same level for all participants after determining a suitable loudness among a small expert sample ($n = 5$) throughout the entire range of stimuli.

Procedure

Each participant evaluated the sound concepts in a single evaluation session, lasting approximately one hour. Prior to the sound concept evaluation, the participants were each shown the same collage of nine different futuristic concept car interiors by various manufacturers (logos were blurred) for a total of 25 seconds (not skippable) to give them additional context for the following acoustic evaluation. All instructions were shown on a screen so the participants could go through the experiment at their own pace and take listening breaks between the test blocks whenever needed. The participants were encouraged to close their eyes while listening to foster the imagery of the EV context and acceleration process. In the first test block, the two main dimensions, *Perceived Innovativeness* and *Liking*, were evaluated, followed by the familiarization phase test block with the evaluation of the four semantic dimensions. The last test block consisted of the second evaluation of the two main dimensions. For each dimension, the stimuli were presented in randomized order, while the dimensions themselves in each test block were randomized in order as well. All evaluations were conducted on a seven-point Likert scale, where only the extrema were labeled, ranging from 1 (*not at all*) to 7 (*very much*). The questioned item was always visualized above the scale. For the preference dimension of *Liking*, we asked: “How do you like the sound?”, for the other dimensions, the question pattern stayed the same: “How **dimension** does this sound?” (**innovative**, **powerful**, **sustainable**, **emotional**, **pleasant**). All words within the items referring to the respective dimension were highlighted in bold and blue-colored letters. After the experiment, the participants were asked for qualitative feedback on the study and the different sound concepts, which the study manager documented.

Statistical Analysis

The statistical analysis was conducted through the open-source software R with the latest version available (version 4.4.1). Through the process of the analyses, we decided to switch from generalized linear models to linear mixed models (LMMs). The used models with their fixed and random effects are further described in the *Results* section when reported.

Results

Associations Between Preference, Novelty, and Semantic Dimensions

We analyzed correlations between our tested main dimensions as well as between the main dimensions and the evaluated semantic dimensions. An overview of the associations between the evaluation dimensions is given in Table 4. *Liking* and *Perceived Innovativeness* are significantly positively correlated by $r = .64$ ($p = .047^*$) at time point *T1* and by $r = .73$ ($p = .015^*$) at *T2*. Therefore, the correlation seems to intensify over time from *T1* to *T2* as the correlation coefficient increases. The semantic dimensions *Perceived Pleasantness* ($r = .88$, $p = .001^{**}$), which is consistent with our previous assumption (see *The Present Study*), and *Perceived Sustainability* ($r = .82$, $p = .004^{**}$) are also significantly positively correlated with the dimension of *Liking*. The strongest correlation for the dimension of *Perceived Innovativeness* is significantly positive with *Perceived Sustainability* ($r = .94$, $p < .001^{***}$), which is consistent with our previous assumption (see *The Present Study*), followed

Table 4. Correlations of Evaluation Dimensions.

| Pearson's R | Liking | Perceived Innovativeness | Perceived Powerfulness | Perceived Sustainability | Perceived Emotionality | Perceived Pleasantness |
|--------------------------|--------------|--------------------------|------------------------|--------------------------|------------------------|------------------------|
| <i>T1</i> | | | | | | |
| Liking | | .64* | -.44 | .82** | .12 | .88** |
| p-value | | .047 | .206 | .004 | .735 | .001 |
| df | | 8 | 8 | 8 | 8 | 8 |
| Perceived innovativeness | .64* | | -.49 | .94*** | .38 | .69* |
| p-value | .047 | | .149 | <.001 | .274 | .028 |
| df | 8 | | 8 | 8 | 8 | 8 |
| Perceived powerfulness | -.44 | -.49 | | -.61 | .23 | -.57 |
| p-value | .206 | .149 | | .062 | .520 | .087 |
| df | 8 | 8 | | 8 | 8 | 8 |
| Perceived sustainability | .82** | .94*** | -.61 | | .33 | .86** |
| p-value | .004 | <.001 | .062 | | .350 | .001 |
| df | 8 | 8 | 8 | | 8 | 8 |
| Perceived emotionality | .12 | .38 | .23 | .33 | | .38 |
| p-value | .735 | .274 | .520 | .350 | | .282 |
| df | 8 | 8 | 8 | 8 | | 8 |
| Perceived Pleasantness | .88** | .69* | -.57 | .86** | .38 | |
| p-value | .001 | .028 | .087 | .001 | .282 | |
| df | 8 | 8 | 8 | 8 | 8 | |
| <i>T2</i> | | | | | | |
| Liking | | .73* | | | | |
| p-value | | .015 | | | | |
| df | | 8 | | | | |
| Perceived innovativeness | .73* | | | | | |
| p-value | .015 | | | | | |
| df | 8 | | | | | |

Note. Cross table for Pearson's correlations between the evaluation dimensions and semantic dimensions. The correlations reflect the relationships among the variables as explained by the stimuli, independent of participant-level effects. Note that the second measurement time point T2 was only assessed for the two main dimensions *Liking* and *Perceived Innovativeness*. Significant results are indicated by boldface type. Significance levels: * $p < .05$; ** $p < .01$; *** $p < .001$. Interpretation of correlation coefficients following Cohen (1988) as follows: $r \geq .10$ and $r < .30$ as a weak correlation, $r \geq .30$ and $r < .50$ as a moderate correlation, and $r \geq .50$ as a strong correlation.

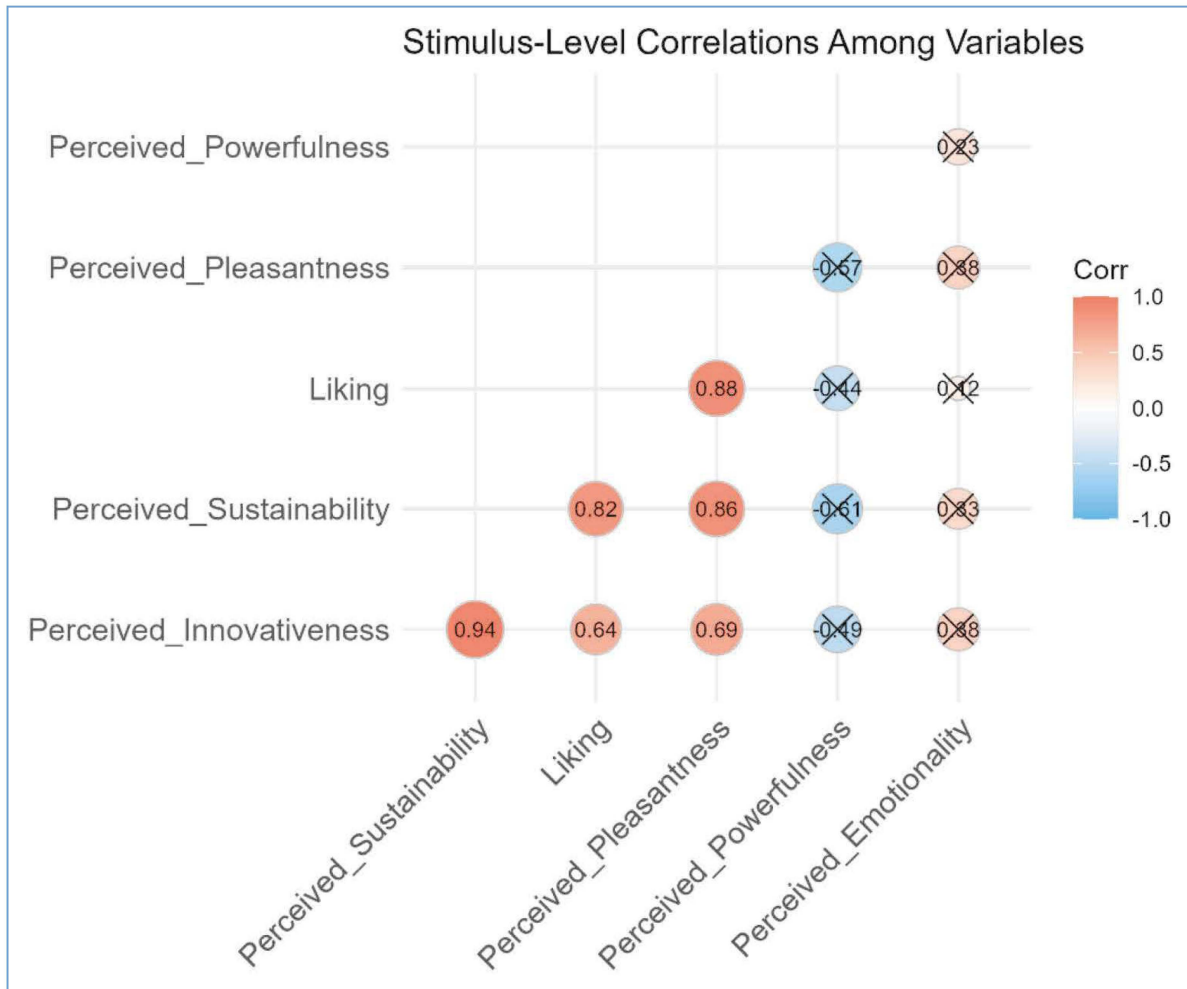


Figure 1. Correlation matrix in *TI*.

Note. Graphical depiction of the Pearson's correlations amongst the evaluated dimensions in *TI*. The correlations reflect the relationships among the variables as explained by the stimuli, independent of participant-level effects. The color indicates the valence of the correlation, the size of the circle its magnitude. Crossed coefficient circles are not significant.

by a strong association with *Perceived Pleasantness* ($r = .69, p = .028^*$). For *Perceived Powerfulness* and *Perceived Emotionality* no significant correlations are found. These findings support our hypothesis that specific semantics are associated with our main variables—such as pleasant sounds being liked better and sounds conveying sustainability being associated with high degrees of novelty. Among the semantic dimensions, only *Perceived Sustainability* and *Perceived Pleasantness* are significantly associated with one another ($r = .86, p = .001^{**}$). Our study's results could not confirm a significant negative correlation between *Perceived Powerfulness* and *Perceived Sustainability* as stated in our assumptions (see *The Present Study*), but a trend toward a negative correlation was quite obvious ($r = -.61, p = .062$). Nevertheless, we could not confirm a significant association between *Perceived Powerfulness* and *Perceived Emotionality* ($r = .23, p = .520$). Figure 1 graphically depicts the correlations among the variables.

Data Distribution for Liking and Perceived Innovativeness

For the evaluation of the *Liking* dimension, the participants used the full range of the scale (see Figure 2), demonstrating a high degree of interindividuality in the preference for one or the other sound concept. The stimulus *Stim08* was liked the most, followed by *Stim07* and *Stim03*.

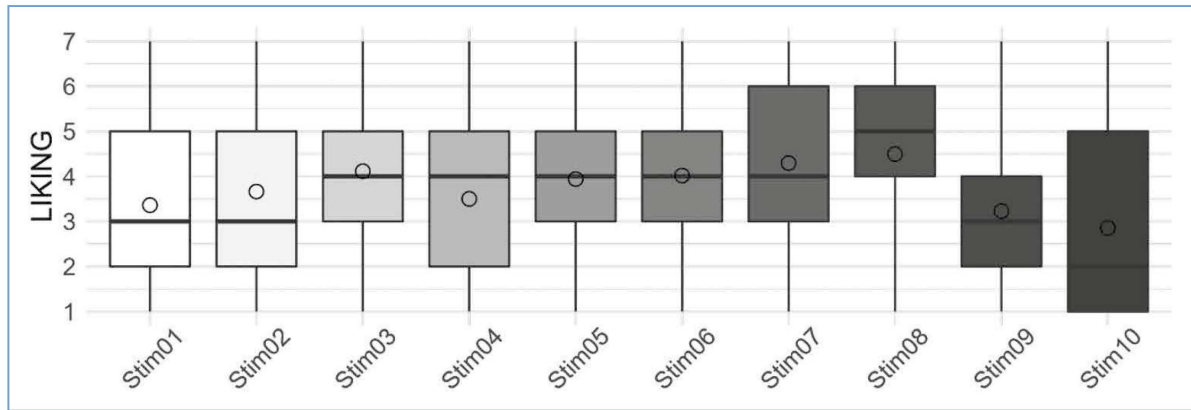


Figure 2. Liking ratings across stimuli.

Note. Ratings for each stimulus in the dimension of *Liking*. The boxplots show the rating distribution for each stimulus; the black bar in the box represents the median, while the circles represent the mean ratings.

Table 5. Statistical values of *Perceived Innovativeness*.

| Stimulus | M | SD | MD | Stimulus | M | SD | MD |
|----------|------|------|------|----------|------|------|------|
| Stim01 | 3.07 | 1.37 | 3.00 | Stim06 | 4.84 | 1.30 | 5.00 |
| Stim02 | 5.63 | 1.18 | 6.00 | Stim07 | 5.59 | 1.27 | 6.00 |
| Stim03 | 5.02 | 1.24 | 5.00 | Stim08 | 4.63 | 1.79 | 5.00 |
| Stim04 | 5.15 | 1.26 | 5.00 | Stim09 | 4.27 | 1.41 | 4.00 |
| Stim05 | 4.84 | 1.19 | 5.00 | Stim10 | 1.44 | 0.93 | 1.00 |

Note. Statistical values for the dimension of *Perceived Innovativeness*. For each stimulus, both evaluation time points (test block one and test block three) are considered.

We analyzed the empirical innovativeness that the stimuli conveyed, as we could not resort to a defined standard for innovativeness in EV sound design and settled for a wide range of stimuli through our expertise. Table 5 shows the statistical values in the dimension of *Perceived Innovativeness* for our 10 stimuli.

According to the empirical values, our preset shows a good fit regarding the different innovativeness levels overall. If we split up our 7-point Likert scale into three segments—corresponding to three innovativeness levels—we have a cut-off and maximum value for the *conventional* level at a mean of 3.00, for the *progressive* level at a mean of 5.00 and for the *futuristic* level a mean that needs to be higher than 5.00. The ascription of the different stimuli to the segmented innovativeness levels by their empirical *Perceived Innovativeness* is depicted in Figure 3.

To simplify the attribution to the variation matrix, the stimuli are, from now on, encoded more descriptively by indicating their category of *Sound Character* by the first letter (“A” = *artistic*, “T” = *technical*), the *Innovativeness Level* by a second letter (“C” = *conventional*, “P” = *progressive*, “F” = *futuristic*), and a serial number from the conception phase. This results in TC01 (Stim01; slightly tearing the maximum value but considered as conventional to have a better stimulus distribution amongst the innovativeness groups) and TC10 (Stim10) to be ascribed to the *conventional* level. None of the artistic concepts are ascribed to the *conventional* level, considering their empirical values. AP05 (Stim05), AP06 (stim06), TP08 (Stim08), and TP09 (Stim09) define the *progressive* level, and AF02 (Stim02), AF03 (Stim03), TF04 (Stim04), and AF07 (Stim07) are ascribed to the *futuristic* level. Regarding the rating distribution in the dimension of *Perceived Innovativeness* only for AP05, TC01, and TP09, the full range of the scale is used. At the same time, the participants seem to agree more with the innovativeness estimation for TC10 and TP08.

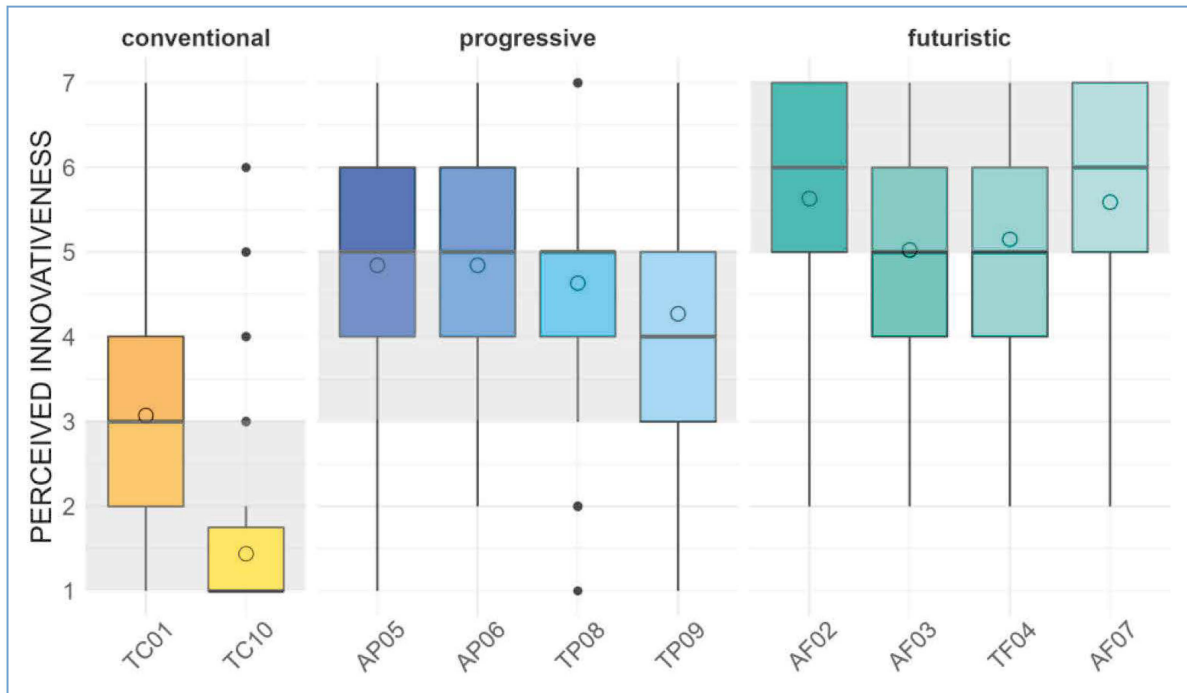


Figure 3. Ratings for *Perceived Innovativeness* across stimuli.

Note. Empirical data distribution for each stimulus in the dimension of *Perceived Innovativeness* grouped by *Innovativeness Level*. The segmentation of the scale into the three different *Innovativeness Levels* is indicated by the highlighted shadowed areas. The boxplots show the rating distribution; the median is indicated by the thick black line across the box, the whiskers of the boxes extend to the most extreme data points, while the black dots represent outliers. The hollow black circles indicate the mean value (both evaluation time points included).

To compare the effects of different variables on our participants' ratings, we statistically tested the effect of different degrees of novelty in a sound concept (conventional, progressive, futuristic) and a variation of the base sound character (technical, artistic) on the ratings, as well as the effect of repeated evaluation (time point) on the perceived impression of novelty and the preference for a sound concept (the two main dimensions: *Liking*, *Perceived Innovativeness*) by means of LMMs. We first defined a null model (M_0) considering factors for which we only considered the random effects of each participant (ID) on the ratings. In our model M_1 we added variables, for which we had no specific hypothesis in mind: *age* (of the participant), *gender* (of the participant), *ATI* (affinity toward technology measured by the numeric score from the *ATI*), and *Open* (numeric score from the *BFI-II* regarding the participant's open-mindedness toward new experiences) as fixed effects and the ID (participant) as random effect. Proceeding from this model M_1 we added further fixed effects we suspected to influence our participant's ratings to our M_2 : *InnoLev* (the novelty variation within our sound concepts by the *Innovativeness Level*: conventional, progressive, futuristic), *SoundChar* (the basic *Sound Character* of our sound concepts technical, artistic), *time* (indicating if the evaluation was repeated, i.e., test phase 1 and 2, so T_1 and T_2 in the two main dimensions of *Liking* and *Perceived Innovativeness*), *profession* (sound design, acoustics, innovations, other), and the respective *dimension*. For the model M_3 we then added the interaction of the variation variables of our stimuli (*SoundChar* and *InnoLev*) within each evaluation dimension, following the idea that a specific combination of the variation parameters creates specific impressions that are more suitable for specific dimensions than others. The different models are described in Table 6.

Table 6. Models.

| Model | <i>Npar</i> | AIC | -2LL | <i>df</i> | χ^2 | <i>p</i> |
|--|-------------|---------------|----------------|-----------|---------------|--------------------|
| <i>M0</i> : I + (I ID) | 7 | 25,664 | -12,825 | | | |
| <i>M1</i> : I + age + gender + ATI + Open + (I ID) | 8 | 24,695 | -12,340 | 1 | 971.18 | <.001*** |
| <i>M2</i> : I + age + gender + ATI + Open + profession + dimension + InnoLev + SoundChar + time + (I ID) | 20 | 24,502 | -12,231 | 12 | 217.69 | <.001*** |
| <i>M3</i> : I + age + gender + ATI + Open + profession + dimension + InnoLev*SoundChar + time + (I ID) | 21 | 24,503 | -12,231 | 1 | 0.14 | 0.711 |

Note. *Npar* = number of model's parameters; AIC = Akaike information criterion, an estimator of prediction error; -2LL = likelihood ratio; *df* = degrees of freedom; *p* = *p*-value of the regarding χ^2 -test. Significant results are indicated by boldface type. Comparison of the models amongst each other (always comparing the present model with the preceding one, e.g., the line for *M2* indicates the comparison between *M1* and *M2*). Significance levels: **p* < .05; ***p* < .01; ****p* < .001.

When comparing our models with the *anova()* function, further demographic variables (*M1*) and further fixed effects (*M2*) explain significantly more variance compared to *M0*. The inclusion of the interaction effect between our variation parameters of novelty in the sound concept (*InnoLev*) and its basic sound character (*SoundChar*) does not significantly explain more variance in our model (comparison of *M2* and *M3*). Therefore, we proceeded with the evaluation of *M2* within each dimension (*Liking*, *Perceived Innovativeness*, *Perceived Sustainability*, *Perceived Powerfulness*, *Perceived Emotionality*, *Perceived Pleasantness*), displaying the fixed effects for each variable in Table 7.

Throughout all dimensions the demographic variables seem to have no to little influence on the perception of the presented sound concepts. An exception seems to be the professional background regarding some of the rating dimensions. According to our results, students seem to have liked the sound concepts less overall ($b = -0.41$, $p = .047^*$) and perceived them as significantly less powerful overall ($b = -0.56$, $p = .023^*$) compared to the other professional groups. The group of sound designers within our sample there again perceived the sound concepts as less emotional overall ($b = -0.63$, $p = .022^*$) compared to the other professional groups in the study. The variation of novelty (*Innovativeness Level*) within the sound concepts showed significant effects in various dimensions: the progressive ($b = 0.67$, $p < .001^{***}$) and futuristic ($b = 0.57$, $p < .001^{***}$) sound concepts seem to be better liked compared to the presented conventional sounds. Both innovativeness levels are also perceived as more innovative compared to the conventional level, with the futuristic level ($b = 2.84$, $p < .001^{***}$) being perceived as more innovative than the progressive level ($b = 2.22$, $p < .001^{***}$), which further supports the categorization of our variation matrix. Further, the sound concepts of the progressive and futuristic levels are perceived as significantly more sustainable (progressive: $b = 1.57$, $p < .001^{***}$; futuristic: $b = 2.00$, $p < .001^{***}$), pleasant (both levels: $b = 0.84$, $p < .001^{***}$), and emotional (progressive: $b = 0.42$, $p = .011^*$; futuristic: $b = 0.76$, $p < .001^{***}$), while for the *Perceived Powerfulness* we could not find a significant effect of the variation within the three *Innovativeness Levels*. The variation of the general *Sound Character* of the stimulus shows significant effects throughout all evaluated dimensions: more technical sound concepts are overall less liked ($b = -0.29$, $p = .001^{**}$) and perceived as less innovative ($b = -0.34$, $p < .001^{***}$), less sustainable ($b = -0.63$, $p < .001^{***}$), less pleasant ($b = -0.59$, $p < .001^{***}$), and less emotional ($b = -0.46$, $p < .001^{***}$), while being perceived as more powerful ($b = 0.63$, $p < .001^{***}$) compared to the artistic sound concepts. Regarding the dynamic effects, which we tested for the main dimensions of *Liking* and *Perceived Innovativeness* through repeated evaluation, our results indicate that the sound concepts are better liked ($b = 0.23$, $p = .003^{**}$) and perceived as less innovative ($b = -0.21$, $p < .001^{***}$) over time.

Table 7. Detailed Results of Model M2.

| Predictors | Liking | | | Perceived Innovativeness | | |
|------------------------|----------------|-----------------|--------------|--------------------------|-----------------|--------------|
| | Estimates | p | df | Estimates | p | df |
| (Intercept) | 3.96*** | <.001 | 79.53 | 3.31*** | <.001 | 78.25 |
| age | −0.02** | .002 | 75 | −0.01* | .045 | 75 |
| ATI score | 0.01 | .873 | 75 | −0.01 | .885 | 75 |
| Openness score | 0.00 | .684 | 75 | 0.00 | .968 | 75 |
| gender_female | Reference | | | Reference | | |
| gender_male | 0.10 | .506 | 75 | −0.04 | .784 | 75 |
| profession_acoustics | Reference | | | Reference | | |
| profession_sounddesign | −0.36 | .118 | 75 | −0.36 | .091 | 75 |
| profession_other | −0.32 | .129 | 75 | −0.11 | .591 | 75 |
| profession_student | −0.41* | .047 | 75 | −0.17 | .386 | 75 |
| InnoLev_conventional | Reference | | | Reference | | |
| InnoLev_progressive | 0.67*** | <.001 | 1573 | 2.22*** | <.001 | 1573 |
| InnoLev_futuristic | 0.57*** | <.001 | 1573 | 2.84*** | <.001 | 1573 |
| SoundChar_artistic | Reference | | | Reference | | |
| SoundChar_technical | −0.29** | .001 | 1573 | −0.34*** | <.001 | 1573 |
| Time_T1 | Reference | | | Reference | | |
| Time_T2 | 0.23** | .003 | 1573 | −0.21*** | <.001 | 1573 |

| Predictors | Perceived Powerfulness | | | Perceived Sustainability | | |
|------------------------|------------------------|-----------------|--------------|--------------------------|-----------------|--------------|
| | Estimates | p | df | Estimates | p | df |
| (Intercept) | 4.94*** | <.001 | 80.22 | 3.87*** | <.001 | 77.99 |
| age | −0.02* | .013 | 75 | −0.01 | .161 | 75 |
| ATI score | −0.06 | .526 | 75 | −0.06 | .564 | 75 |
| Openness score | 0.01 | .586 | 75 | −0.00 | .980 | 75 |
| gender_female | Reference | | | Reference | | |
| gender_male | −0.05 | .784 | 75 | −0.07 | .730 | 75 |
| profession_acoustics | Reference | | | Reference | | |
| profession_sounddesign | −0.28 | .303 | 75 | −0.36 | .237 | 75 |
| profession_other | −0.38 | .132 | 75 | −0.35 | .237 | 75 |
| profession_student | −0.56* | .023 | 75 | −0.31 | .285 | 75 |
| InnoLev_conventional | Reference | | | Reference | | |
| InnoLev_progressive | −0.10 | .509 | 744 | 1.75*** | <.001 | 744 |
| InnoLev_futuristic | 0.02 | .884 | 744 | 2.00*** | <.001 | 744 |
| SoundChar_artistic | Reference | | | Reference | | |
| SoundChar_technical | 0.63*** | <.001 | 744 | −0.63*** | <.001 | 744 |

| Predictors | Perceived Pleasantness | | | Perceived Emotionality | | |
|------------------------|------------------------|-----------------|--------------|------------------------|-----------------|--------------|
| | Estimates | p | df | Estimates | p | df |
| (Intercept) | 5.04*** | <.001 | 79.30 | 3.22*** | <.001 | 80.95 |
| age | −0.01 | .346 | 75 | 0.00 | .846 | 75 |
| ATI score | −0.06 | .576 | 75 | 0.05 | .558 | 75 |
| Openness score | −0.02 | .283 | 75 | 0.02 | .188 | 75 |
| gender_female | Reference | | | Reference | | |
| gender_male | −0.05 | .787 | 75 | −0.23 | .178 | 75 |
| profession_acoustics | Reference | | | Reference | | |
| profession_sounddesign | −0.47 | .125 | 75 | −0.63* | .022 | 75 |

(continued)

Table 7. Continued.

| Predictors | Perceived Pleasantness | | | Perceived Emotionality | | |
|----------------------|------------------------|-----------------|------------|------------------------|-----------------|------------|
| | Estimates | p | df | Estimates | p | df |
| profession_other | −0.04 | .889 | 75 | −0.30 | .241 | 75 |
| profession_student | −0.14 | .619 | 75 | −0.23 | .345 | 75 |
| InnoLev_conventional | Reference | | | Reference | | |
| InnoLev_progressive | 0.84*** | <.001 | 744 | 0.42* | .011 | 744 |
| InnoLev_futuristic | 0.84*** | <.001 | 744 | 0.76*** | <.001 | 744 |
| SoundChar_artistic | Reference | | | Reference | | |
| SoundChar_technical | −0.59*** | <.001 | 744 | −0.46*** | <.001 | 744 |

Note. Fixed effects for different predictor variables in the six evaluation dimensions. The time variable is only included in the two main dimensions of *Liking* and *Perceived Innovativeness* as the other dimension variables were only evaluated at one time point. Significant results are indicated by boldface type. Significance levels: * $p < .05$; ** $p < .01$; *** $p < .001$.

Analysis of Dynamic Effects in Liking and Perceived Innovativeness

As we asked for a repeated evaluation of the dimensions of *Liking* and *Perceived Innovativeness*, we can compare the participants' ratings over time. Figure 4 shows the ratings on the mentioned dimensions per stimulus in the first evaluation ($T1$) and the second evaluation after the extended elaboration of the sound concepts ($T2$).

To analyze the variances in the ratings over time, we considered the *time* (first or second evaluation time point) and the *stimulus* as fixed effects and the individual participants (*ID*) as random effect in a smaller model. In the resulting LMM, we found the sound concepts *AF03* ($b = 0.64$, $p < .01^{**}$), *AP06* ($b = 0.54$, $p < .05^*$), *AF07* ($b = 0.48$, $p < .05^*$), and *TP08* ($b = 0.82$, $p < .001^{***}$) to be significantly liked better, while *TC10* was significantly liked less ($b = -0.67$, $p < .01^{**}$) overall. After extended elaboration (in $T2$), the sound concepts of *AF02* ($b = 0.70$, $p < .05^*$) and *AF07* ($b = 0.90$, $p < .01^{**}$) were even liked significantly better than in the first evaluation ($T1$). For the time points, the model does not find any significant dynamic effects, whereas when solely considering the time points as fixed effects, the *Liking* seems to increase over time ($T2$: $b = 0.23$, $p < .01^{**}$). Though no significant dynamic effects for the individual stimuli were found in the dimension of *Perceived Innovativeness*, overall, it seems to wear off with time as a significant dynamic effect for $T2$ ($b = -0.41$, $p < .05^*$) is found within our model.

Dynamic Effects for the Variation of Sound Character and Innovativeness Level

The following section focuses on our research questions regarding the dynamic effects of aesthetic preference and novelty perception over time. At first, we will take a closer look at the underlying character of the sound textures, determined by the *Sound Character* groups. Figure 5 shows the overall mean ratings for all six evaluation dimensions per *technical* and *artistic* group.

The dynamic effects in the evaluation of the two main dimensions *Liking* and *Perceived Innovativeness* are depicted in Figure 6.

In an LMM, considering the time point of evaluation and the *Sound Character* as fixed effects and the individual participant as random intercept, the *Liking* overall significantly increases over time ($b = 0.33$, $p < .01^{**}$). This is consistent with our hypothesis (see *The Present Study*) and indicates elaboration to play an important role in terms of preference evaluation. The *technical* sound concepts are found to be significantly less liked ($b = -0.41$, $p < .001^{***}$) compared to the *artistic* sound concepts. No significant dynamic effects when comparing the two *Sound Character* groups were found. However, the graph shows a slightly more positive trend for the *artistic* sound concepts

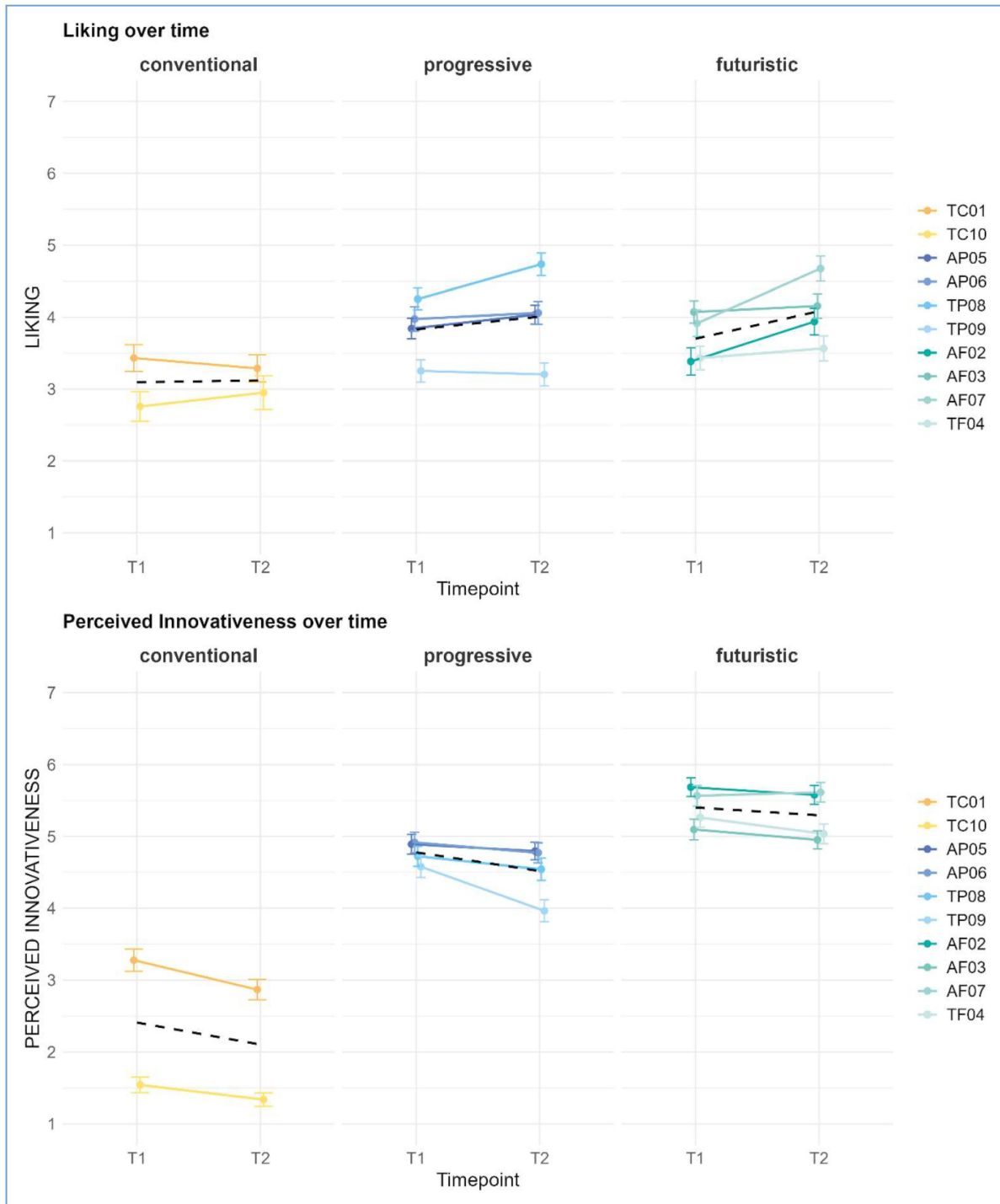


Figure 4. Dynamic effects in *Liking* and *Perceived Innovativeness*.

Note. *Liking* and *Perceived Innovativeness* ratings per stimulus over time for each *Innovativeness Level*. The overall trend is indicated by the black dashed line (no error bars) depicting the overall mean of all stimuli in the given dimension. The order of the items in the legends corresponds to their scores in T2 to reduce complexity while reading. Error bars indicate ± 1 standard deviation.

in T2 than for the *technical* concepts. In the LMM for *Perceived Innovativeness*, we found a significant dynamic effect of *Perceived Innovativeness* decreasing with time ($b = -0.33$, $p < .01^{**}$), supporting our hypothesis that perceived novelty in the sound concepts wears off over time. Moreover, the *artistic* sound concepts were perceived as significantly more innovative overall ($b = 1.35$, $p < .001^{***}$) than the *technical* ones. Per *Sound Character* group, no significant dynamic effects

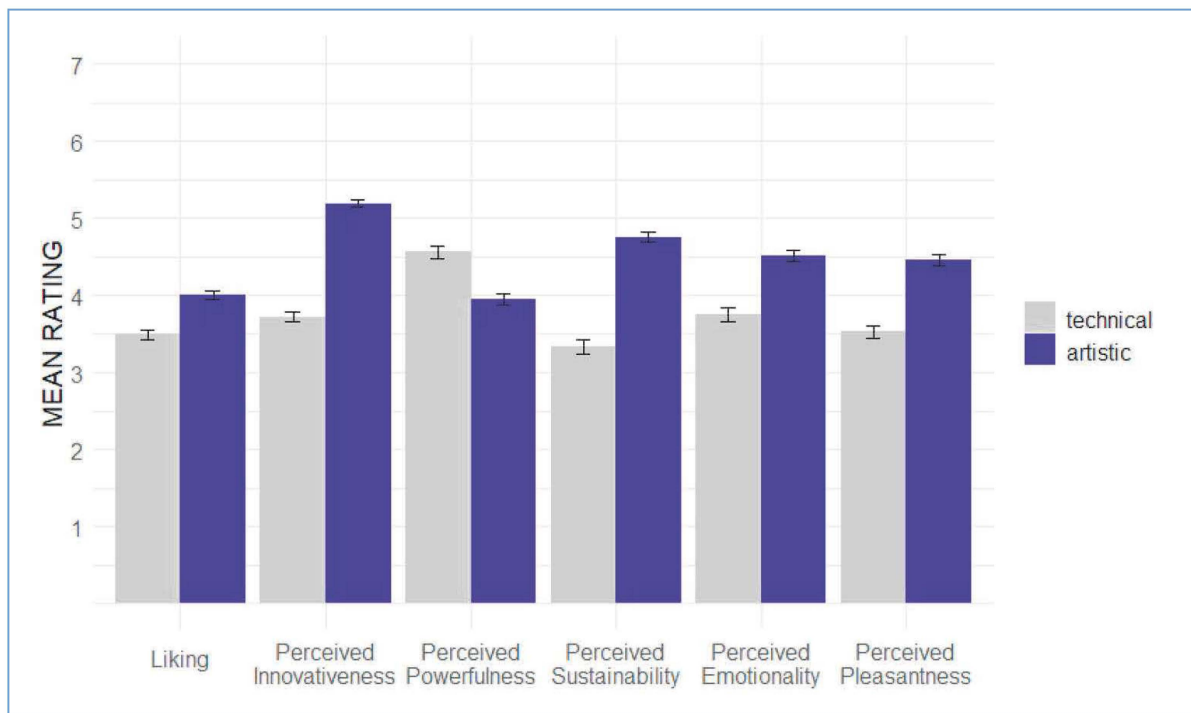


Figure 5. Mean ratings per Sound Character group.

Note. Mean ratings per evaluation dimension (both time points considered for the dimensions of *Liking* and *Perceived Innovativeness*) grouped by Sound Character (*technical* and *artistic*). Error bars indicate ± 1 standard deviation.

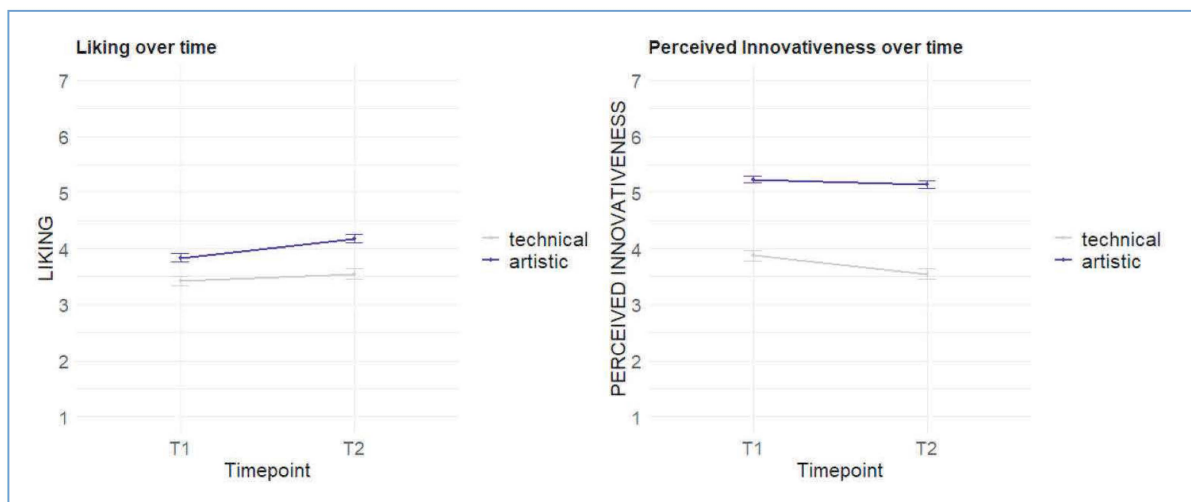


Figure 6. Dynamic effects per Sound Character group.

Note. Mean ratings of *Liking* and *Perceived Innovativeness* over time (first evaluation *T1* and second evaluation after extended elaboration *T2*) grouped by Sound Character (*technical* and *artistic*). Error bars indicate ± 1 standard deviation.

were found, though the graph for the *technical* group shows a steeper decrease, whereas the novelty impression seems to be more stable over time for *artistic* concepts.

After grouping the sound concepts according to their general sound character, we focused on the different *Innovativeness Levels*. The overall mean ratings for the three different levels in all six evaluation dimensions are shown in Figure 7.

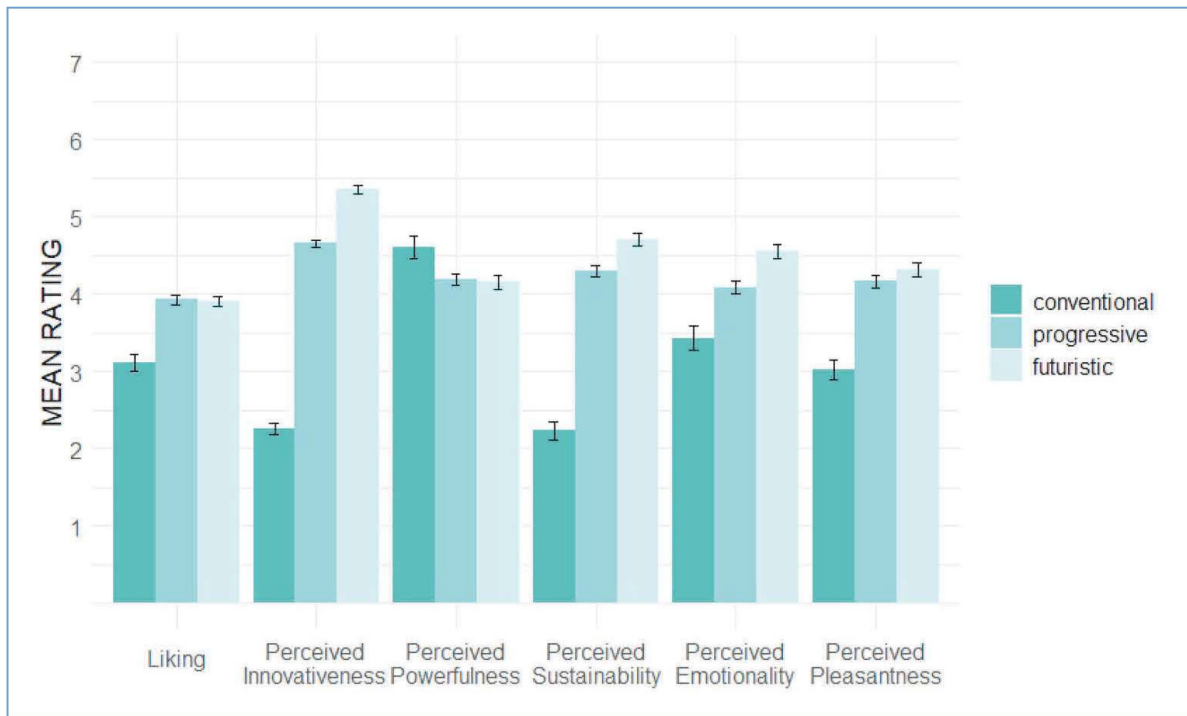


Figure 7. Mean ratings per *Innovativeness Level*.

Note. Mean ratings per evaluation dimension (both time points considered for *Liking* and *Perceived Innovativeness*) are grouped by *Innovativeness Level* (*conventional*, *progressive*, *futuristic*). Error bars indicate ± 1 standard deviation.

In our LMM, we considered the *Innovativeness Level* as a fixed effect and the individual participant as random intercept for each dimension. The *progressive* ($b = 0.81, p < .001^{***}$) and *futuristic* ($b = 0.78, p < .001^{***}$) levels are significantly more liked than the *conventional* one. Regarding the *Perceived Innovativeness*, all levels are perceived as significantly innovative and in the expected order: the *futuristic* ($b = 3.09, p < .001^{***}$) and *progressive* ($b = 2.39, p < .001^{***}$) levels are perceived as significantly more innovative than the *conventional*. The concepts of the latter, nonetheless, seem to be perceived as more powerful, as the *futuristic* ($b = -0.45, p < .01^{**}$) and *progressive* ($b = -0.41, p < .01^{**}$) levels are perceived as significantly less powerful. Thereagainst, the two higher levels are perceived as significantly more sustainable (*futuristic*: $b = 2.47, p < .001^{***}$; *progressive*: $b = 2.06, p < .001^{***}$), as well as perceived as significantly more pleasant (*futuristic*: $b = 1.29, p < .001^{***}$; *progressive*: $b = 1.14, p < .001^{***}$) compared to the *conventional* level. Moreover, the *futuristic* level ($b = 1.11, p < .001^{***}$), followed by the *progressive* level ($b = 0.65, p < .001^{***}$), is perceived as significantly more emotional in comparison with the *conventional* level.

The dynamic effects in the evaluation of *Liking* and *Perceived Innovativeness* from the first and second evaluation is depicted in Figure 8. To analyze the time-dependent differences, we fitted an LMM with time points and *Innovativeness Level* as fixed effects and the individual as a random intercept. Sound concepts from the *futuristic* ($b = 0.61, p < .001^{***}$) and *progressive* ($b = 0.73, p < .001^{***}$) levels are significantly better liked compared to the *conventional*. For the *Perceived Innovativeness*, we applied a similar LMM, finding the *futuristic* ($b = 2.99, p < .001^{***}$) and *progressive* ($b = 2.37, p < .001^{***}$) levels to be perceived as significantly more innovative compared to the *conventional*. In contrast, the overall *Perceived Innovativeness* in this model is significantly lower in T2 ($b = -0.31, p < .05^*$), again supporting our hypothesis that the perceived novelty in sound textures decreases with advancing elaboration. There are no other significant dynamic effects found in these models regarding the different levels of *Innovativeness*.

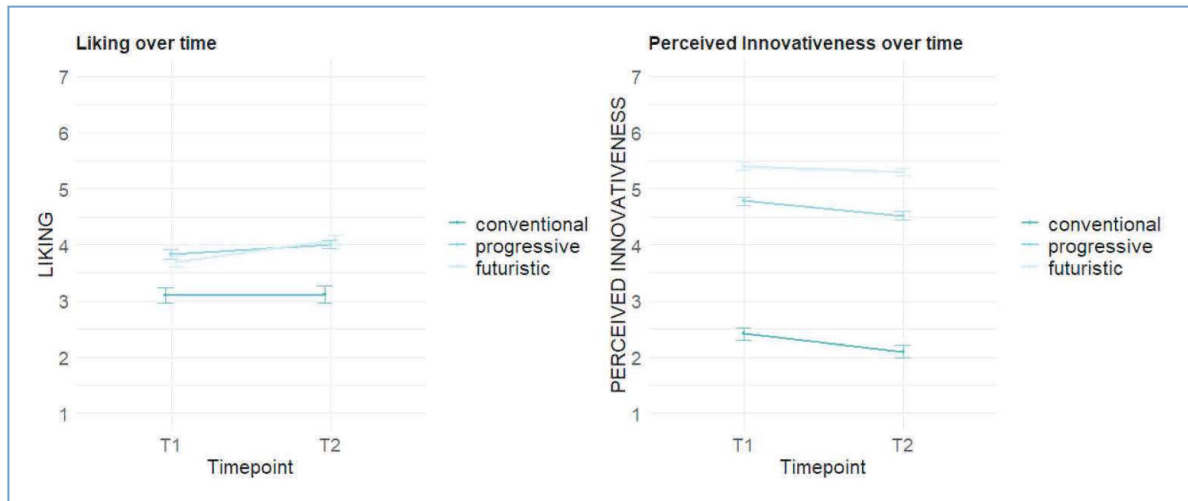


Figure 8. Dynamic effects per *Innovativeness Level*.

Note. Mean ratings in *Liking* and *Perceived Innovativeness* over time (first evaluation *T1* and second evaluation after extended elaboration *T2*) grouped by *Innovativeness Level* (*conventional*, *progressive*, *futuristic*). Error bars indicate ± 1 standard deviation.

Discussion

Our study focused on evaluating different acoustic concepts to determine a balanced degree of novelty in EV sound designs. In terms of the aesthetic preference for a suitable sound design of an EV's acceleration process, our results indicate that higher degrees of novelty are appreciated (dimension of *Liking*), as overall, the *progressive* and *futuristic* concepts in our study are liked significantly more than the less innovative concepts. The empirical data of *Perceived Innovativeness* can validate our conception of novelty content in the used stimuli: the *progressive* and *futuristic* levels are perceived as significantly more innovative. In contrast, the *technical* group of *Sound Character* is perceived as significantly less innovative and significantly liked less. As aesthetic preference and novelty perception are time-dependent variables and develop with increasing elaboration and exposure to a product, our study methodologically focused on dynamic effects in perception. This was achieved by applying repeated evaluation of the core dimensions through the *RET* (Carbon, 2015; Carbon & Leder, 2005; Faerber et al., 2010). Our findings demonstrate the *Perceived Innovativeness* to wear off over time with increasing elaboration (comparison of *T1* and *T2*) of the sound textures. For the specific factor levels, we did not find significant differences. Nonetheless, our graphs (Figures 6 and 8) indicate that this decreasing effect seems to be weaker for concepts with novel elements (*artistic* concepts) and more innovativeness (*progressive* and especially the *futuristic* level). These tendencies should be further investigated in future research. Regarding the aesthetic preference, our findings found *Liking* overall to increase with extended elaboration. Though our data shows no significant differences between the *Innovativeness Levels* or *Sound Character* groups, the graphical depictions (Figures 6 and 8) show slight tendencies that stimuli with higher novelty content (*artistic* and/or *futuristic* sound textures) have a steeper increase of *Liking* over time. This as well should be further investigated in future research.

Regarding the semantics conveyed by the sound textures used in this study, *technical* sound concepts are perceived as significantly less sustainable, pleasant, and emotional than *artistic* concepts. The data also shows this effect for the more innovative sound concepts: the more innovative stimuli, represented by the *futuristic* and *progressive* levels, are perceived as significantly more sustainable, pleasant, and emotional. These effects are even stronger for our study's *futuristic* level, comprising the highest degree of innovative content. In the context of EV sound design, these semantics

(*Perceived Sustainability*, *Perceived Pleasantness*, *Perceived Emotionality*) should be considered closely, as such characteristics might be beneficial in creating a suitable sound design for such novel vehicle types in the future. For the semantic dimension of *Perceived Powerfulness* though, the more familiar concepts seem to be beneficial, as the stimuli from the *technical* concepts (*Sound Character*) are perceived as significantly more powerful. Although the correlation between the semantic dimensions between *Perceived Powerfulness* and *Perceived Sustainability* ($r = -.61$, $p = .062$) does not confirm a significant negative association, it indicates a clear negative trend. Whether this trend and the higher scores of more *technical* sound concepts in *Perceived Powerfulness* can be assumed as an artifact effect due to decades of associative learning or proves to be a time-stable finding is to be ascertained by future research. These as specifically powerful perceived sound characteristics, incorporated in the more familiar sound textures, might just be a temporary, but well-established link to the prevailing idea of a powerful vehicle. This should, therefore, be re-considered and reviewed when more people have had a chance to experience electrified driving more thoroughly and build upon their learning history. For the moment, our results indicate that *Perceived Powerfulness*, as we construe it from more ICEV-oriented sound concepts, is a killer for *Perceived Sustainability*.

Another important finding that should be considered for EV sound design in the context of the investigated semantic dimensions in this study is that some semantics are associated with each other, as for example, *Perceived Pleasantness* and *Perceived Sustainability*, or *Perceived Innovativeness* with *Perceived Sustainability*. Another important finding of our research is that aesthetic preference and novelty perception are significantly positively correlated, indicating innovativeness in the sound design of EVs to be appreciated. Interestingly, most associations between *Liking* and *Perceived Innovativeness* with the other semantic dimensions intensify with increasing elaboration. These findings emphasize that repeated exposure to novel sound material is needed to obtain more thorough evaluations and should be accounted for in future studies on aesthetic preference.

Future studies should also address the limitations of the present study. For example, more immersive experimental environments, such as simulators or real vehicles, could be considered in upcoming research, as in the current setup, we were limited to a listening lab. Moreover, further sound textures should be investigated in the future. The stimulus set was carefully considered but is limited to the 10 chosen sound textures. While the number of evaluated stimuli is suitable for an experiment with repeated evaluation considering cognitive capacities on the side of the participants, future studies should carefully consider their sound concepts for the evaluation. To preselect a final stimulus set, we recommend a representative sample to evaluate the sound material in a pre-study. In our case, the preassignment through experts worked well, but we see possible improvement in this aspect of our study. With a carefully chosen stimulus set for a final study, researchers can aim at a more balanced ratio among the levels of the variation factors and validate the preassigned categories. As a last point, our study showed dynamic effects in the appreciation of novelty in EV sound concepts over time. Therefore, the results of our study, just as well as any study investigating the preference for innovative sound material at a certain time, might be confounded with *Zeitgeist* effects, similar to the findings from Carbon (2010) regarding the appreciation of curvature in design. To consider such effects in EV sound concepts in future studies would be interesting to determine long-term trends in EV sound design.

Conclusion

The findings of this study provide an initial orientation regarding the degree of innovativeness in sound textures that can be used for acoustic enhancement in electrified driving. Consistent with our hypothesis, our results indicate that sound concepts that are perceived as more innovative and characterized by high degrees of novelty and unprecedented sound elements seem to be liked

less at first glance—or, in this case, audition—and rejected by customers. With increasing user experience and exposure to the novel EV soundscapes, such sound design approaches will be accepted and even increasingly appreciated and preferred. Our results suggest that more progressive, futuristic, and artistic sound concepts are more suitable for EVs that represent a novel era of transportation technology. Moreover, the importance of extended elaboration through repeated exposure when it comes to the evaluation of innovative designs with novel content is demonstrated in this study. Manufacturers are still left with the decision to direct their sound design strategies toward one of many possible approaches: to resemble familiar, well-established driving sound from the combustion engine's era or to dare innovative approaches, shaping novel vehicle soundscapes. This study, though, indicates that, especially in the context of electrified driving, high degrees of innovativeness and novel elements in sound concepts are appreciated in an EV's acoustic design. Through applied sound textures in the product's design, the vehicle's character can be diversified in manifold ways. Consistent with our hypotheses, the results of this study confirm that specific sound characteristics are associated with specific semantics: more pleasant perceived sounds are better liked, more innovative concepts are perceived as more sustainable. Here, the orchestration of actively enhanced acoustic feedback and passive soundscape design needs to be carefully considered, as the sound textures potentially influence the customers' overall user experience, performance, and interaction with the product. As an outlook, we would like to encourage future studies to consider holistic development approaches in the acoustic design of EVs and to consider dynamic effects in novelty perception and aesthetic preference.

Author Contribution(s)

Mara Münder: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing.

Renzo Vitale: Conceptualization; Methodology; Writing – review & editing.

Claus-Christian Carbon: Conceptualization; Methodology; Project administration; Resources; Writing – review & editing.

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Note

1. We originally planned to perform standard GLMs to analyze the data and are aware that using G*Power is not the most suitable tool to perform power analyses for LMMs. We would like to stress that fixed effects in LMMs overlap with those in GLMs, and running a power analysis on the GLM gives at least a good approximation for how well the study is powered to detect main effects.

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5 Integration of Results and Main Findings

In the following section, I summarize the main results of my research and integrate them into the overall context of this thesis. All embedded thesis contributions are focused on how humans – ultimately, the customers and drivers – perceive and evaluate the interior soundscape of electrified vehicles. Therefore, we applied different methodological approaches throughout the presented publications and assessed the subjective evaluations of different EV interior soundscapes in different experimental environments. As the interior soundscape of EVs is composed of many different noise sources, it was a methodological challenge to narrow down on specific NVH characteristics to draw conclusions for the applied field while also considering the holistic Gestalt of the soundscape. With its massive influence on a vehicle's noise profile and its acoustic character, the technological shift from combustion engine to electrified powertrain is one of the most substantial factors to be considered (Barton & Fieldhouse, 2024; Qatu et al., 2009), as it directly alters the (acoustic) customer driving experience. Hence, I specifically focused on powertrain-related NVH characteristics, encompassing e-powertrain noise and active sound design.

Our literature review (Münder & Carbon, 2022a; see *Manuscript #1* in section 2.2) provides an initial overview of the current state of research on the perception of interior soundscapes of EVs. With this review, the reader is provided an overview of identified gaps in the current field of research. Our review emphasizes that a large body of research on the perception of EV acoustics already exists, but at the same time, lacks studies considering psychological effects when investigating these perceptual aspects. As the shift to a novel powertrain solution in EVs represents an opportunity to reimagine automotive soundscapes, scientific insights based on customer-oriented perception data from real-world context should guide this process. All experimental studies presented in this dissertation tackle outstanding challenges identified within our literature review. Their findings contribute to the current knowledge within research and the applied field. Münder and Carbon (2022b; see *Manuscript #2* in section 3.2) and Münder et al. (2024; see *Manuscript #3* in section 3.4) delve into the perceptibility of e-powertrain noise and its influence on perceived quality. In Münder et al. (2025; see *Manuscript #4* in section 4.2), we focus on active driving sound design for EVs and investigate perceptual aspects of preference, innovativeness, and semantic dimensions such as powerfulness, sustainability, emotionality, and pleasantness of various sound concepts. With the methodological experimental designs within all the presented studies, we introduced methods that, to our knowledge, have never been applied before in research on the perception of automotive acoustics. In Münder and Carbon (2022b; see *Manuscript #2* in section 3.2) and in Münder et al. (2025; see *Manuscript #4* in section 4.2), we applied the *Repeated Evaluation Technique* (RET; Carbon and Leder, 2005) to reveal dynamic effects in perception data. In Münder et al. (2024; see *Manuscript #3* in section 3.4), we applied the

Continuous Evaluation Procedure (CEP; Muth et al., 2015) for an even higher degree of timely resolution, tracking the perceptual process of subjective e-powertrain noise evaluations over time. The following sections present the most relevant findings from these studies in the context of this thesis.

5.1 Acoustics Contributing to the Overall Product Experience

The dimension of *Perceived Quality* in e-powertrain noise was evaluated in two of our studies: one employing repeated evaluation (Münder & Carbon, 2022b; see *Manuscript #2* in section 3.2) and the other utilizing continuous evaluation (Münder et al., 2024; see *Manuscript #3* in section 3.4). Both studies indicate significant negative correlations between perceived e-powertrain noise and perceived quality. The results of Münder and Carbon (2022b) reveal a significant negative correlation of $\tau = -.32, p < 0.001^{***}$ between the *Perceived Emergence* of e-powertrain noise and its *Perceived Quality*. Münder et al. (2024) find a significant negative correlation of $\tau = -.36, p < 0.001^{***}$ between *Perceived Quality* and the *Perceived Annoyance* conveyed by the presented e-powertrain noise stimuli.

In Münder et al. (2025; see *Manuscript #4* in section 4.2), we focus on active sound enhancement for EVs and evaluate various driving sound design concepts across the two main dimensions of *Liking* and *Perceived Innovativeness*, along with the semantic dimensions of *Perceived Powerfulness*, *Sustainability*, *Pleasantness*, and *Emotionality*. The findings indicate significant positive correlations between the main dimension *Liking* and the second main dimension *Perceived Innovativeness* ($r = .64, p = 0.047^*$), as well as with the semantic dimensions *Perceived Sustainability* ($r = .82, p = 0.004^{**}$), and *Perceived Pleasantness* ($r = .88, p = 0.001^{**}$; Münder et al., 2025). The main dimension of *Perceived Innovativeness* is significantly positively associated with *Perceived Pleasantness* ($r = .69, p = 0.028^*$) and *Perceived Sustainability* ($r = .94, p < 0.001^{***}$) as well (Münder et al., 2025). Furthermore, the results reveal a strong positive correlation between *Perceived Sustainability* and *Perceived Pleasantness* ($r = .86, p = 0.001^{**}$), while no significant correlations are found for the dimensions of *Perceived Powerfulness* or *Perceived Emotionality* (Münder et al., 2025).

5.2 The Role of Context, Customer Expectations, and Associations in the Perception of Automotive Acoustics

The results of Münder and Carbon (2022b; see *Manuscript #2* in section 3.2) and Münder et al. (2024; see *Manuscript #3* in section 3.4) not only indicate a moderately negative relationship between the presence of e-powertrain noise and perceived quality within EV interior acoustics, but these associations also seem to depend on the specific use case and its operational load. Although both studies requested an evaluation of *Perceived Quality*, the second main dimension differs. In Münder and Carbon (2022b), participants were asked to assess how strongly they perceived the e-powertrain noise breaking through the overall soundscape (*Perceived Emergence*), while in Münder et al. (2024), they were asked to evaluate the *Perceived Annoyance* conveyed by the overall soundscape. Despite

this difference in the connotation of the dimensions, the negative correlations across all acceleration use cases in both studies suggest that the presence of e-powertrain noise generally diminishes the perceived quality of an EV (Münder et al., 2024; Münder & Carbon, 2022b). The different correlation coefficients with varying magnitudes in the corresponding acceleration scenarios are summarized in **Table 1**. Since the shear/recuperation scenario was not part of Münder et al.'s (2024) study, only the coefficients for the first three scenarios of *Slow*, *Comfort*, and *Full Acceleration* are compared.

Table 1

| Acceleration Scenario | <i>Perceived Quality</i> x <i>Perceived Emergence</i> ¹ | | <i>Perceived Quality</i> x <i>Perceived Annoyance</i> ² | |
|---------------------------|---|------------|---|------------|
| | τ | p | τ | p |
| Overall | -.32 | < 0.001*** | -.36 | < 0.001*** |
| Slow Acceleration (SA) | -.34 | < 0.001*** | -.28 | < 0.001*** |
| Comfort Acceleration (CA) | -.30 | < 0.001*** | -.38 | < 0.001*** |
| Full Acceleration (FA) | -.18 | < 0.001*** | -.41 | < 0.001*** |
| Shear/ Recuperation (SR) | -.46 | < 0.001*** | - | - |

Note. Comparison of correlational measures from the two studies investigating e-powertrain noise and perceived quality. Kendall's Tau is used for rank-based data. According to Cohen (1988), correlation coefficients are interpreted as follows: $r \geq .10$ as a small correlation, $r \geq .30$ as a moderate correlation, and $r \geq .50$ as a strong correlation. ***= $p < 0.001$.

¹ Münder and Carbon (2022b).

² Münder et al. (2024); the data from the integral singular measure (ISM) ratings was taken to compute the rank-based correlations; the use case shear/recuperation is not included in this study.

Both studies find significant moderate negative correlations between *Perceived Quality* and their second main dimension overall (Münder et al., 2024; Münder & Carbon, 2022b). In Münder and Carbon (2022b), the first two operational load use cases of *Slow Acceleration (SA)* and *Comfort Acceleration (CA)* indicate significant moderate negative correlations, while for the *Full Acceleration (FA)* scenario, we found a significant weak correlation. In Münder et al. (2024), the coefficients slightly increase over the use cases from *SA* over *CA* to *FA* from a weak-to-moderate to moderate magnitude. Both studies show significant negative correlations for the *FA* scenario but with a different magnitude: while the results in Münder and Carbon (2022b) indicate a significant small negative correlation ($\tau = -.18, p < 0.001^{***}$) between the *Perceived Quality* and the *Perceived Emergence*, the results in Münder et al. (2024) indicate a significant moderate negative correlation ($\tau = -.41, p < 0.001^{***}$) between *Perceived Quality* and *Perceived Annoyance*. These results suggest that the perceived impact of e-powertrain noise is context-dependent on the specific acceleration use case.

In Münder et al. (2025; see *Manuscript #4* in section 4.2), we asked our sample to rate which of the various EV driving sound design concepts they preferred the most (dimension of *Liking*). Overall, one of the *technical-progressive* concepts (stimulus *TP08*) was liked the most, followed by the *artistic-futuristic* concepts (stimuli *AF07* and *AF03*; Münder et al., 2025). Further findings from the linear mixed models suggest that more *progressive* ($b = 0.67, p < .001^{***}$ in the overall model and $b = 0.81, p <$

.001*** in the model considering the innovativeness levels) and *futuristic* ($b = 0.57, p < .001***$ in the overall model and $b = 0.78, p < .001***$ in the model considering the innovativeness models) sound concepts are significantly more liked compared to the *conventional* ones (Münder et al., 2025). Also, the *progressive* ($b = 2.22, p < .001***$ in the overall model and $b = 2.39, p < .001***$ in the model considering the innovativeness levels) and *futuristic* ($b = 2.84, p < .001***$ in the overall model and $b = 3.09, p < .001***$ in the model considering the innovativeness levels) categories are perceived as significantly more innovative compared to the *conventional* sounds (Münder et al., 2025). From the perspective of the varied *Sound Characters*, the *technical* sound concepts are significantly less liked ($b = -0.29, p < .001***$ in the overall model and $b = -0.41, p < .001***$ in the model considering the sound character groups) and perceived as significantly less innovative ($b = -0.34, p < .001***$ in the overall model) compared to the *artistic* ones (Münder et al., 2025). In contrast, the artistic concepts are perceived as significantly more innovative ($b = 1.35, p < .001***$ in the model considering the sound character groups; Münder et al., 2025). Furthermore, the findings indicate that specific sound groups convey a powerful impression. Overall, the *technical* sound concepts are perceived as significantly more powerful ($b = 0.63, p < .001***$) and, in the model considering the innovativeness level as a fixed effect, the *progressive* ($b = -0.41, p < .01**$) and *futuristic* ($b = -0.45, p < .01**$) concepts are perceived as significantly less powerful compared to the *conventional* sounds (Münder et al., 2025).

5.3 Perception of Vehicle Acoustics: Individual Differences and General Tendencies

All three of our experimental studies suggest interindividual differences, particularly when investigating more complex dimensions such as preference or perceived quality, which depend highly on personal factors. The participants in Münder et al. (2025; see *Manuscript #4* in section 4.2) used the complete range of rating scales for every stimulus in the preference ratings (dimension of *Liking*), with most averages scoring somewhere in the mid-range. The findings regarding the dimension of *Perceived Quality* in Münder and Carbon (2022b; see *Manuscript #2* in section 3.2) and Münder et al. (2024; see *Manuscript #3* in section 3.4) reveal similar patterns, as ratings span around the entire range or far stretches of the scales for most stimuli, with few exceptions. These observations indicate that different individuals may perceive the same stimulus quite differently. Furthermore, the qualitative feedback in Münder and Carbon (2022b) about participants' expectations for a qualitatively high e-powertrain and its soundscape in various operating modes reflects significant interindividual preferences. These differences in *Perceived Quality* are also evident in the high variance of individual *CEP* streams in Münder et al. (2024), sometimes indicating even opposing impressions for the same acoustic event.

Nevertheless, depending on the evaluated dimension, we also found more universal patterns and general tendencies in the perception of e-powertrain noise and EV sound design within our studies.

For example, some stimuli's perceived emergence of e-powertrain noise showed a general trend of being collectively perceived as either quieter (e.g., stimulus *Car 7* in *CA*) or louder (e.g., stimulus *Car 3* in *FA*; Mnder & Carbon, 2022b). The visualized evaluation streams for the dimension of *Perceived Annoyance* from Mnder et al. (2024) as well indicate some general trends: e.g., *Figure 6* depicts the *Perceived Annoyance* for the stimulus *EV_#05* and most of the levers being raised between the seconds 10 to 15, indicating that something in the acoustic Gestalt was collectively perceived as annoying. Furthermore, our pre-assigned innovativeness levels for our stimuli in Mnder et al. (2025) show a good fit with the assessed *Perceived Innovativeness* of the participants.

5.4 Demographic Variables

Throughout the experimental studies presented, we also considered demographic variables. For most general variables, such as age or gender, we found mostly non-substantial relationships, if any significant ones at all. However, for the variable of *professional background*, we identified a significant effect when comparing the ratings for *Perceived Quality* between the expert group and laypersons: the expert groups provided significantly lower ratings on *Perceived Quality* ($b = -0.32$, $t(63) = -3.84$, $p < 0.001$; Mnder & Carbon, 2022b). Additionally, we observed small negative correlations for the different expert grouping variables ($\tau = -.13$, $p < 0.001^{***}$ for the respective professional context and $\tau = -.14$, $p < 0.001^{***}$ for the affiliation with the acoustics and vibrations department; Mnder & Carbon, 2022b). In Mnder et al. (2025), most demographic variables also seem to have little to no influence on the perception of various sound concepts, except for *professional background*. Our results indicate that the students in our sample liked the presented sound concepts significantly less ($b = -0.41$, $p = 0.047^*$) and perceived them as significantly less powerful ($b = -0.56$, $p = .023^*$; Mnder et al., 2025). However, the group of sound designers perceived them as significantly less emotional ($b = -0.63$, $p = .022^*$) compared to the other professional groups in the study (Mnder et al., 2025).

5.5 Perceptual Dynamics in Vehicle Acoustics

We address perceptual dynamics within our experimental studies by applying repeated and continuous evaluation methods. The *RET* by Carbon and Leder (2005) provides a tool to investigate the dynamic effects between the evaluations of the initial experience and subsequent experiences after repeated exposure. In Mnder et al. (2025; see *Manuscript #4* in section **4.2**), the various innovative sound concepts are evaluated based on the main dimensions of *Perceived Innovativeness* and *Liking* through repeated evaluation. Overall, the preference ratings increase with repeated exposure (e.g., $T2$: $b = 0.23$, $p < .01^{**}$ in the stimulus-based model and $T2$: $b = 0.33$, $p < .01^{**}$ in the sound character model; Mnder et al., 2025). Another dynamic effect is observed for the novelty perception in the sound designs: our results indicate that *Perceived Innovativeness* wears off with time and increasing familiarization (e.g., $T2$: $b = -0.41$, $p < .05^*$ in the stimulus-based model, $T2$: $b = -0.33$, $p < .01^{**}$ in the

sound character model, and T2: $b = -0.31$, $p < .05^*$ in the innovativeness level model; Mnder et al., 2025). No significant dynamic effects are indicated for the individual innovativeness levels (*conventional*, *progressive*, *futuristic*) or sound character groups (*technical*, *artistic*) within our models in Mnder et al. (2025). Nonetheless, the graphical depictions in *Figure 6* and *Figure 8* show a steeper increase in *Liking* for the *artistic* and *futuristic* groups, with *Perceived Innovativeness* remaining more stable over time for the *artistic* and *futuristic* groups compared to the others (Mnder et al., 2025). Our stimulus-based model further indicates significant dynamic effects in the preference ratings of two of the *artistic-futuristic* stimuli: *AF02* (T2: $b = 0.70$, $p < .05^*$) and *AF07* (T2: $b = 0.90$, $p < .01^{**}$), suggesting they are liked better after extended elaboration (Mnder et al., 2025).

No significant dynamic effects were observed among the three different evaluation time points when assessing the *Perceived Quality* and *Perceived Emergence* of e-powertrain noise in Mnder and Carbon (2022b; see *Manuscript #2* in section 3.2). However, qualitative feedback highlights the need for a dynamic measure, as participants reported difficulties in adequately representing the dynamic nature of the presented acceleration processes (Mnder & Carbon, 2022b). We therefore applied such a dynamic measurement technique for the subjective impression in Mnder et al. (2024; see *Manuscript #3* in section 3.4). Instead of comparing different measurement time points of single ratings with one another, we focused on the process of a singular evaluation during the ongoing presentation of an e-powertrain noise stimulus. By applying the *CEP* developed by Muth et al. (2015), we further enhanced the temporal resolution of the evaluations. Each evaluation stream could be traced throughout its entire playback. As the participants in Mnder et al. (2024) continuously evaluated the dimensions of *Perceived Quality* and *Perceived Annoyance* conveyed by the e-powertrain noise stimulus, the individual fluctuations in each perception stream over time became apparent. The captured individual streams can be displayed graphically. The example of stimulus *EV_#5* in Mnder et al. (2024) not only depicts the individual streams and their differences (see *Figure 5* for *Perceived Quality* and *Figure 6* for *Perceived Annoyance*). Also, the overall trend of how the respective stimulus is generally perceived is indicated by a dashed regression line, as well as the overall mean of all the continuous evaluation streams at each time point, which is indicated by a thick pink-blue line (Mnder et al., 2024). Moreover, the illustrated gradients (numerical differentials) in *Figure 7* emphasize the variations within the continuous streams and reveal the perceptual dynamics within the perception of the respective stimulus (Mnder et al., 2024). After each continuous evaluation, the participants were also asked to rate their impressions on a seven-point numeric Likert scale. The rankings in *Table 3* indicate that the continuous evaluation data obtained through *CEP* and the integral singular measure (ISM) ratings align well overall (Mnder et al., 2024).

6 Discussion: Result Interpretation, Methodological and Practical Implications for Future Research and the Applied Field

In section **1 Introduction and Theoretical Background**, we addressed current questions within the automotive industry regarding how EV noise profiles are perceived and which acoustic characteristics customers appreciate or reject. The key findings from the embedded thesis contributions are presented in section **5 Integration of Results and Main Findings** and offer guidance in answering the stated questions. In this section, I interpret the summarized results and discuss overarching findings as they provide various methodological and practical implications. The implications derived from my research contribute to a deeper understanding of the perception of interior EV soundscapes. They are intended to support both interdisciplinary researchers in perceptual science and vehicle acoustics and professionals from across the applied field within the automotive industry. Furthermore, I will address some overarching limitations that go beyond the limitations of each manuscript and provide an outlook for future research.

6.1 Influence of Vehicle Acoustics on the Overall Product Experience

The reported coefficients in **5.1 Acoustics Contributing to the Overall Product Experience** emphasize the importance of the acoustic impression of the vehicle for the overall product evaluation. Our studies on e-powertrain noise perception (Münder et al., 2024; Münder & Carbon, 2022b) suggest that perceivable e-powertrain noise diminishes the perceived quality. The differently connotated secondary main dimensions, *Perceived Emergence* and *Perceived Annoyance*, must be considered when interpreting these correlation parameters. While rating the *Perceived Emergence* (Münder & Carbon, 2022b) of e-powertrain noise is a neutral question, evaluating *Perceived Annoyance* (Münder et al., 2024) inherently carries a negative connotation. Nevertheless, this comparison is valid as, without the perceived emergence of e-powertrain noise from the overall sound carpet, the e-powertrain noise could not be perceived as annoying. Concluding from these findings, the presence of perceivable e-powertrain noise impacts the perceived quality of the given soundscape. Therefore, e-powertrain noise can adversely affect the holistic Gestalt of an EV's acoustics. Since vehicle acoustics are an important customer attribute, unfavorable acoustic impressions can harm the overall product experience.

The reported correlations for *Perceived Innovativeness* and *Perceived Sustainability* in Münder et al. (2025) indicate strong associations between these semantic attributes. Considering such semantic associations within specific sound design concepts for the vehicle development process could guide EV sound engineers in fine-tuning the acoustic design and help them sharpen a specific vehicle character for the target product. Furthermore, the reported effects in Münder et al. (2025; see also section **5.2**) point to a potential association between ICEV-typical sound elements and powerfulness, as the

technical concepts are perceived as significantly more powerful than the *artistic* ones. However, given that there are no significant effects on the level of the innovativeness variation groups concerning *Perceived Powerfulness*, this finding should be re-evaluated in further studies. Furthermore, the findings also suggest that *progressive*, *futuristic*, and *artistic* sound conceptualizations are perceived as significantly more innovative and can therefore be assumed to be better suited for the design of novel EV soundscapes (Münder et al., 2025).

6.2 Considering Psychological Effects in the Assessment of Perceptual Evaluation Data

The findings of Münder et al. (2024) and Münder and Carbon (2022b) report negative correlations between perceivable e-powertrain noise and perceived quality throughout all tested acceleration use cases (see section 5.2). However, this relation seems to be context-sensitive. Specifically, the general presence of e-powertrain noise as operational feedback during higher load demand use cases – such as in the *Fast Acceleration* scenario – appears to be less detrimental to *Perceived Quality* than in use cases with lower load demand (Münder & Carbon, 2022b). This suggests that operational feedback during intense driving conditions is more likely to be interpreted as acceptable or even expected. Qualitative data from Münder and Carbon (2022b) support this interpretation, indicating that in highly demanding driving contexts, participants were more tolerant of operational noise, reinforcing the contextual nature of acoustic perception. Nonetheless, when such feedback is perceived as annoying, its negative impact on quality evaluations becomes significantly stronger (Münder et al., 2024).

The context, within which the respective evaluation is being captured, is a variable tremendously affecting our perception (Carbon, 2019b; Genuit et al., 2010; Jakesch et al., 2011). As context is even explicitly mentioned in the definition of the term *soundscape* by the International Organization for Standardization within the ISO 12913-1:2014(en) (2014), its consideration within the study design is an absolute necessity for researchers aiming to follow a holistic approach in the field of acoustic perception. Considering contextual factors in the design of an experimental study is essential for obtaining ecologically valid insights that can be applied to the external world and, therefore, the applied field. The findings of all three experimental studies (Münder et al., 2025; Münder et al., 2024; Münder & Carbon, 2022b) emphasize the importance of considering context when investigating the perception of EV acoustics. In acoustics, problematic issues during the NVH development of EVs such as masking or disturbance from environmental noise, such as wind, tire, or road noise (Eisele et al., 2019; Gavric, 2020), as well as the impact of specific refinement measures, can be effectively addressed by considering the realistic context during the evaluation. When assessed in isolation, the e-powertrain noise, for example, is removed from its original context, preventing the recipient from forming a holistic *percept*. Its acoustic Gestalt lacks critical contextual information, decontextualizing the resulting qualitative assessment and susceptible to misinterpretation. By including the naturalistic

driving noise in our studies on the perception of e-powertrain noise (Münder et al., 2024; Münder & Carbon, 2022b), the findings allow us to derive evaluations of holistic perceptions from the presented e-powertrain noise with a high degree of ecological validity. The experimental setup in Münder and Carbon (2022b) is confirmed to represent an ecologically valid context by the support of the gathered qualitative feedback: Some participants reported difficulties in singling out the e-powertrain noise from the general sound carpet, including the general driving noise from wind, tires, and the surrounding environment. For achieving a high degree of ecologically valid context conditions while maintaining standardization and reproducibility of the testing conditions in an experiment, so-called Path #2 testing approaches are recommended (Carbon, 2019a).

Even in our experimental study on sound design concepts (Münder et al., 2025), which was based solely on a mobile lab-oriented setup, we made every effort to consider contextual factors. By showcasing a collage of nine futuristic concept car interiors, we aimed to provide additional context and stimulate participants' imagination about sitting in an innovative EV that accelerates while evaluating the presented soundscapes. Although every participant is free to imagine their version of a typical EV, providing additional context for the following sound evaluation increases the likelihood of establishing a common contextual basis within the sample. When interpreting the study results (see section 5.2), it is important to consider the context from which the evaluation data originates. In Münder et al. (2025), participants provided their evaluations with a novel type of EV in mind. Hence, the findings suggest more *progressive*, *futuristic*, and *artistic* sound design approaches may be better suited for active sound enhancement in EVs, as these concepts were preferred overall and may more effectively reflect the novel character of electrified driving technology (Münder et al., 2025).

In addition to contextual aspects, further psychological effects on perception, such as knowledge, framing, expectations, habituation, and the effects of Gestalt and Zeitgeist (Carbon, 2019b), are essential to consider in the assessment of perceptual evaluation data. These psychological effects are essential as they influence cognitive top-down processes that, aside from cognitive bottom-up processes, affect our perception. Psychological effects can determine whether a specific design will be appreciated or rejected, especially when considering innovative designs with high levels of novelty (Carbon, 2019b). As Zeitgeist evolves with technological progress (e.g., in powertrain electrification) and societal changes (e.g., adaptation to novel technologies), it is important to consider my presented research as a snapshot of time. With electrified driving becoming more common over time, more people will be exposed to e-powertrain noise and active e-sound design. The perception of EVs might change due to increasing familiarity, a changing level of knowledge, and adapted expectations towards the sound of electrified driving. The very same sound concepts from Münder et al. (2025) or e-powertrain noise stimuli from Münder and Carbon (2022b) and Münder et al. (2024), therefore, might

be perceived and evaluated significantly differently with time passing. It will be especially interesting to observe the development of the association between powerfulness and the typical noise of ICEVs. This association may represent a *Zeitgeist* artifact, reflecting decades of experience with ICEV sound characteristics that have formed a general perception of what a powerful vehicle should sound like (Borg, 2014).

Another important factor is that a *percept* is under constant construction of aligning personal predictions and conveyed impressions from external stimulation (Carbon, 2019b). The perception of the same stimulus can change due to the influence of current psychological factors. By applying methods like the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005) as in the presented studies by Mnder and Carbon (2022b) and Mnder et al. (2025), such psychological effects find consideration, and dynamic effects in perception can be controlled. Especially when assessing preference evaluations of stimuli with a high degree of novelty content, the familiarization with the material and its elaboration can have a significant influence on the final evaluation and the subsequent interpretation of the results (e.g., Carbon, 2015a, 2019b; Carbon & Leder, 2005; Faerber et al., 2010). Only through methods considering such psychological effects can perceptual dynamics be captured, leading to more valid customer experience evaluations and, therefore, more sustainable predictions.

Conclusively, methodological implications for assessing subjective evaluations and perceptual data in the field of vehicle acoustics and interior soundscapes can be derived. Researchers should consider their study designs to be more human-centered. This means considering cognitive and affective processes that influence our experience and perception and, therefore, have a massive influence on a design's success (Carbon, 2019b). Ecologically valid conclusions from gathered perception data can be derived by integrating psychological effects relevant to human information processing within a study's design. This integration of human perceptual habits within the evaluation assessment can be achieved, for example, as in the presented experimental studies within this dissertation (Mnder et al., 2024, 2025; Mnder & Carbon, 2022b). As identified by our literature review (Mnder & Carbon 2022a), current research lacks studies that consider psychological effects sufficiently. However, the psychological effects, with their significant influence on human perception, should be considered more often and as early as possible within the conceptual phase of acoustic refinement and sound design.

6.3 Balancing Individual Preferences and General Tendencies in Vehicle Acoustics

In pursuing customer-optimized sound designs and noise profiles for EVs, manufacturers face the greatest challenge in balancing individual preferences with general perceptual tendencies. Our study findings (see section 5.3) report that both individual and shared perceptual mechanisms significantly shape the evaluation of automotive acoustics. Consequently, it is essential for automotive engineers

and sound designers to account for overarching general tendencies in acoustic perception and individual-specific preferences for specific acoustic designs in the vehicle development process.

General tendencies in the perception of e-powertrain noise, such as the aversion to specific NVH characteristics, provide valuable guidance for acoustic refinement, as shown in our studies on e-powertrain noise (Münder et al., 2024; Münder & Carbon, 2022b). These insights allow for targeted adjustment or elimination of acoustically undesired features during the technical refinement process of EV acoustics. Additionally, general effects regarding semantic associations evoked by a vehicle's noise profile or sound design play a pivotal role in acoustic engineering. As Münder et al. (2025) and other studies on EV sound design (e.g., Swart et al., 2018; Swart & Bekker, 2019) demonstrate, the driving sound of a vehicle conveys specific semantic meaning and significantly contributes to the overall product experience. With this much influence on shaping the vehicle's impression, the contributions by associated semantics should be strategically considered within the design process and aligned with the vehicle's intended positioning in the market. The semantic contributions by the vehicle's acoustics should further be aligned with other vehicle characteristics, such as exterior design and performance parameters, but also factors as the overarching brand identity. By carefully considering the semantic impressions conveyed by applied sound enhancement strategies, manufacturers can precisely shape their product's character and stage it in targeted market segments.

Conversely, our findings (see section 5.3) also highlight that individual differences in the perception of vehicle acoustics exist. Particularly, in the personal preference for specific, load-dependent design characteristics in e-powertrain noise (Münder et al., 2024; Münder & Carbon, 2022b), as well as in the conceptualization of active sound design (Münder et al., 2025). These variations suggest the potential for customizable or adaptive sound profiles that cater to user preferences and situational needs. Providing customers with a range of sound profile options—ideally curated with both perceptual and technical sophistication—could enhance product personalization and customer satisfaction.

6.4 Influence of Demographic Variables on Acoustic Evaluations

The reported findings in **5.4 Demographic Variables** indicate that demographic factors can influence acoustic evaluation data. For example, the results of Münder and Carbon (2022b) show that experts are stricter and more conservative in their ratings of perceived quality. Also, in Münder et al. (2025), the professional background of the participants implied an influence on how the sound concepts were perceived. While the students liked the sound design concepts significantly less, the group of sound designers within the sample perceived the stimuli as significantly less emotional (Münder et al., 2025). The results in Münder and Carbon (2022b) and Münder et al. (2024) not only indicate that experts in the field of vehicle acoustics, who presumably have a trained hearing for NVH phenomena due to their expertise, show different evaluation patterns than other groups. Additionally, the participants'

expectations play an essential role in their evaluations, as they accepted louder operational feedback from the EVs in faster acceleration scenarios (Münder et al., 2024; Münder & Carbon, 2022b; see also section 5.2).

The results of the studies presented in this thesis emphasize the importance of considering demographic variables in perceptual evaluations to control for them in the analysis. These demographics represent individual factors of human cognitive and affective capacities, such as the individual frame of reference, experience, and expectations, and are essential to consider in design evaluation (Carbon, 2019b). As cognitive bottom-up and top-down processes are often intertwined in shaping our perception (Goldstein, 2010) and are influenced by individual factors like knowledge and experience, the findings further illustrate the importance of considering these aspects. Especially when evaluating more complex dimensions, such as the qualitative impression or preference for the interior soundscapes in EVs, our perception seems to be influenced by top-down processes. Depending on the specific research question, considering individual factors can be decisive for deriving ecologically valid implications from the resulting evaluation data.

6.5 Dynamic Effects in Perception

We applied evaluation methods considering perceptual dynamic effects across all experimental studies presented in this thesis (Münder et al., 2025; Münder et al., 2024; Münder & Carbon, 2022b). The utilized methods employ different approaches to capture the temporal process of perception. While the timely resolution of the continuous evaluation method used in Münder et al. (2024) refers to dynamic changes in the perception of an acoustic scene, the methods employed in Münder et al. (2025) and Münder and Carbon (2022b) capture changes in perception and evaluation of the stimuli throughout repeated exposure. The reported results in **5.5 Perceptual Dynamics in Vehicle Acoustics** illustrate the methods used to be applicable within the context of vehicle acoustics.

Dynamics in perception can be observed in relatively short intervals within an experiment (e.g., Carbon et al., 2008; Carbon & Leder, 2005; Faerber et al., 2010; Münder et al., 2025). By applying methods such as the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005), participants can familiarize themselves with the stimulus material and elaborate on it before a final assessment is derived. This leads to more valid evaluations than singular assessments neglecting such psychological effects (Carbon et al., 2008). Through repeated evaluation, the participants in Münder et al. (2025) could familiarize themselves with the novel sound design concepts within the relatively short duration of the experimental session. Both our hypotheses, that *Liking* would increase and *Perceived Innovativeness* would wear off over time, can be confirmed (Münder et al., 2025). Our findings highlight the importance of repeated elaboration when evaluating the preference in the context of acoustic design. Aligned with our findings, different studies indicate (e.g., Carbon & Leder, 2005; Faerber et al., 2010)

that dynamic perceptual effects in preference evaluations are especially important to be considered when evaluating innovative material with high degrees of novelty. Currently, most people's perceptual habits regarding vehicle acoustics are predominantly based on the experience of driving an ICEV. When evaluating so far unfamiliar sound profiles and novel sound designs within the context of electrified driving, it is crucial to consider the perceptual habits of potentially new EV customers.

Furthermore, applying methods with high temporal resolution not only allows the identification of dynamic effects in perception but also facilitates the alignment of objectively analyzed acoustic parameters with their corresponding subjective impressions. While the *Repeated Evaluation Technique* (RET; Carbon & Leder, 2005) captures the perceptive evaluation at multiple discrete time points through repeated measures, the *Continuous Evaluation Procedure* (CEP; Muth et al., 2015) continuously tracks an individual's perceptual experience in real time. Instead of assessing single value responses from the participants at a singular time point – such as through traditional single measure rating scales – CEP allows for the continuous evaluation on a continuous scale of each stimulus throughout the entire length of its presentation. Nevertheless, aside from the continuous evaluation streams about the perception of the presented e-powertrain noise, we also obtained integral singular measure ratings (Münder et al., 2024). When comparing the rankings of the stimuli across both measurement types, we found a high correspondence in most of the first picks for both dimensions, indicating the reliability of both measures.

The sole objective analysis of the physical parameters of an acoustic stimulus does not sufficiently represent human perception. Conversely, only considering subjective data from the individual perception of a soundscape does not allow pinpointing which specific acoustic parameter is responsible for the perceptual outcome. However, when objective and subjective evaluation data is aligned – such as on a shared temporal axis representing the evaluation over time – relations between stimulus properties and perceptual responses can be identified. Comparing the continuous evaluation streams and the objective Campbell diagrams depicting physical parameters, as shown in Münder et al. (2024), demonstrates the great potential of complementary methods. This integration, as demonstrated in Münder et al. (2024), enables the identification of acoustic characteristics and their effect on the perceptual impression to be considered within further development cycles. By tracing the subjective evaluations illustrated through the continuous evaluation streams, the perceptual impression can be directly compared with the corresponding acoustic parameters in the signal for each stimulus. Identifying the technical components underlying these specific acoustic phenomena and their perceptual effects provides automotive engineers with actionable insights for refining the acoustic design of EVs.

To our knowledge, and as reviewed in Mnder and Carbon (2022a), the presented experimental studies within this thesis (Mnder et al., 2024, 2025; Mnder & Carbon, 2022b) are the first to consider perceptual dynamics and the non-stationary character of transient acoustic scenes in the assessment methodology for subjective evaluations in the context of electrified vehicle acoustics. Mnder et al. (2024) demonstrate the feasibility of applying *CEP* for the subjective evaluation of interior vehicle soundscapes and illustrate the high potential when combining interdisciplinary methods for an integrated development approach. Further, we demonstrate the feasibility of applying *RET* within the context of e-powertrain noise and novel sound design concept evaluation (Mnder et al., 2025; Mnder & Carbon, 2022b). The findings highlight that only by considering such psychological effects, a sustainable acoustic design for EVs, i.e., its acoustic design staying appealing over time, can succeed. Following such data-driven development approaches ensures that critical sound characteristics influencing customer perception are addressed systematically, ultimately supporting the creation of soundscapes that align with customer expectations and enhance the overall driving experience.

6.6 Overarching Limitations

The limitations of each presented publication are discussed within the respective manuscripts (see Mnder et al., 2024, 2025; Mnder & Carbon, 2022b, 2022a or sections **2.2**, **3.2**, **3.4**, and **4.2**). Nevertheless, I would like to point out some limitations within the overall context of this dissertation.

First, I would like to point out that the research on the perception of EV interior soundscapes presented within this thesis solely represents a snapshot in time. Psychological effects, such as the current *Zeitgeist* and individual time-dependent factors, such as a person's knowledge of, habituation with, and expectations towards electrified driving and its acoustics, can tremendously affect their perception. Therefore, our study results are influenced by the current representations of the individuals questioned within our samples and their experiences until the day their evaluations were captured. As EVs progressively become more present in our day-to-day lives, we will become increasingly exposed to e-powertrain noise and novel, actively enhanced sound designs. As EV soundscapes become more common, we will naturally become familiar with them, which will change our individual frame of reference, knowledge, expectations, and many other psychological effects. At the moment, EVs are frequently criticized for their lack of operational feedback (Blickensdorff et al., 2019; Kleinjohann, 2020; Mnder & Carbon, 2022b) and an association of the predominant ICEV-typical noise characteristics with powerfulness is often reported (Jennings et al., 2010; Lanslots et al., 2020; Maunder & Munday, 2017; Swart & Bekker, 2014). These findings could reflect the respective time of evaluation as well. Also, the association of powerfulness with rather traditional ICEV noise characteristics, for example, must be tested in future studies. The correlative measures within Mnder et al. (2025) could not confirm this association of a prevailing concept of powerful vehicle acoustics

linked to traditional noise characteristics. The future will tell if this indicates that other acoustic characteristics could convey the concept of powerfulness within the context of EVs or that the prevailing ICEV-colored conception of powerfulness is crumbling. As stated by Carbon (2019b), “nothing is more constant than change,” and by technological progress, designers striving for innovations, and societal change, there is no such thing as fixed laws for the appreciation of aesthetics. Future research will be needed iteratively to control for these effects of time, as psychological effects and Zeitgeist are ever-changing, and our perception of current and novel acoustics will be under constant perpetual change.

Besides this, the results of our experimental studies (Münder et al., 2024, 2025; Münder & Carbon, 2022b) refer to the specific stimuli that were presented. With technological progress, e-powertrain noise profiles of EVs become increasingly refined, and active driving sound designs become progressively sophisticated across the market. Thereby, not only will the psychological effects weigh in differently over time, but the general Gestalt of EV soundscapes will also evolve.

Second, the results of my research refer to the respective samples that were questioned. Statistical standards should be considered (i.e., a sufficient sample size), and sample criteria should ideally represent the general population of interest. Knowing your sample’s characteristics helps control for specific influential factors and to better understand and interpret the findings. All presented studies are sufficiently powered and therefore statistically reliable, as we conducted a priori power analyses to determine sufficient sample sizes for each experiment (Münder et al., 2024, 2025; Münder & Carbon, 2022b). Nonetheless, in two of our studies (Münder et al., 2024; Münder & Carbon, 2022b), we could only recruit our samples within the BMW Group. By assessing demographic information about our participants, we could control for group differences, such as professional background. In Münder et al. (2025), we conducted one part of the sample company internally and one part of the sample at the University of Bamberg, recruiting outside the automotive company context. Though not many demographic variables have significantly affected how EV soundscapes were perceived in our studies, some findings illustrate the importance of sample composition and controlling for sample demographics. In Münder and Carbon (2022b), a significant effect for the professional background variable indicates that experts are stricter in assessing perceived quality. In Münder et al. (2025), again, significant effects for the professional background indicate that students perceive the presented EV sound design concepts as less likeable and powerful, while the expert group for sound design perceived the stimuli as less emotional. Therefore, future research should consider demographic variables within their evaluations to better understand the derived findings.

Third, the applied methods of repeated and continuous evaluation in the presented experimental studies were overall well-accepted by the respective samples (Münder et al., 2024, 2025; Münder &

Carbon, 2022b). Nevertheless, it is important to state that the continuous measure applied in Mnder et al. (2024) is more demanding of the participants' cognitive capacities, as they were required to adjust their current evaluation continuously. Compared to the computation of objective parameters from acoustic measurements or conducting singular subjective ratings, the applied methods are slightly more time-consuming and can be significantly more cost-intensive depending on the targeted sample. Nevertheless, the applied methods proved to be applicable within the context of automotive acoustics. They can contribute significantly to achieving a deeper, more holistic, and sustainable understanding of the EV soundscape and acoustic perception. This work has elaborated on the many beneficial insights that the applied methods offer. I want to encourage future research to consider the stated psychological effects when capturing human perception data on soundscapes as well. Nonetheless, the findings of subjective evaluations on acoustic perception are only one of many puzzle pieces necessary to better understand the refinement of a soundscape. While subjective evaluations of the perceived acoustic impression can provide the target definition of a refinement process, physical parameters of the different technical vehicle components must also be mastered to provide measures on how to refine the vehicle's soundscape.

6.6 Outlook for Future Research

As discussed, the presented research offers various methodological and practical implications for further investigations on the perception of interior EV soundscapes. First, I hope my work encourages professionals in the applied field of vehicle acoustics to engage more actively in interdisciplinary collaboration. For instance, evaluating customer satisfaction with a specific e-powertrain noise profile through a singular measure would be insufficient. Objective data – such as frequency spectra, order analysis, or psychoacoustic parameters – offers valuable insights on physical parameters but neglects the subjective product experience. Likewise, isolated subjective assessments, whether from expert panels, laboratory studies, or small samples, represent good indicators for perceptual impressions but may fail to identify the specific characteristics that require adjustment. Combining methodological approaches from across different disciplines enables the integration of diverse data sources, ultimately allowing more confident design decisions.

A human-centered product design can be ensured and aligned to customer needs by pursuing an interdisciplinary and holistic approach to tackle technological progress challenges. By applying the *Continuous Evaluation Procedure* (CEP; Muth et al., 2015), we demonstrated how professionals can be provided a tool to assess subjective evaluations that can be aligned to objective parameters of the acoustic analyses (Mnder et al., 2024). The alignment of subjective and objective data facilitates the identification of specific noise characteristics that significantly influence customer perception, allowing engineers to address them directly within the vehicle's acoustic refinement. Only by such a holistic

approach, combining interdisciplinary methods and various data sources, can a truly comprehensive and customer-oriented development process be achieved.

The field of EV acoustics is full of challenges, such as the uncertainties in customer expectations regarding EV noise configuration and sound design, as identified by our literature review (Münder & Carbon, 2022a). Further research on the perceptual domain of EV interior soundscapes is needed to better understand the perceptual processes in the customers' experience of the physical phenomena of vehicle acoustics. By considering psychological factors within the evaluation assessment, a deeper and more holistic understanding of human perception of EV soundscapes can be achieved. The experimental studies within this thesis (Münder et al., 2024, 2025; Münder & Carbon, 2022b) applied methods that are new to the field of vehicle acoustics and demonstrate how to acknowledge such psychological effects. The obtained data enables researchers and practitioners to derive ecologically valid interpretations from the results. These insights can then support manufacturers in developing valuable tools, comprehensive guidelines, and design targets to create appealing and assertive acoustic profiles for EVs. As our understanding of EV acoustics and its perception deepens, additional opportunities for technological innovation and novel design will open.

I would like to encourage fellow researchers and practitioners to collaborate in interdisciplinary teams as I did in my research. Researchers should be on the qui vive for experimental environments that offer the best fit in terms of context for their research questions while ensuring a high degree of experimental control. I always strived for the best implementable experimental environment within my work, aiming to realize experimental conditions as realistically and closely to the intended context as possible. We realized our e-powertrain studies in an already highly sophisticated acoustic simulator that fulfills high standards of acoustic playback, haptic and visual impressions of a real vehicle, and a highly immersive visual impression of a dynamic driving scene (Münder et al., 2024; Münder & Carbon, 2022b). Although this experimental environment provides a more realistic context than just capturing evaluations in a simple listening lab, factors such as the kinesthetic impressions of the dynamic driving scene or the interactivity with the vehicle by self-regulating its dynamics could be improved. Future research should, therefore, strive to develop increasingly immersive experimental conditions by considering novel technological solutions and optimizing the impressions of different modalities in an integrated simulator setup.

Through the examples provided in this thesis and its contributions, I hope to encourage the application of complementary, cross-disciplinary methods that can integrate diverse data sources and incorporate them into existing development processes within the automotive industry. Following such integrative approaches facilitates the development process of vehicle experiences that are acoustically refined and genuinely customer-oriented.

7 Conclusion

With the altered noise profile in EVs due to the electrification of powertrain systems, the automotive industry faces challenges in defining novel yet pleasing and customer-oriented vehicle soundscapes. At the same time, this technological shift presents promising opportunities to innovate general driving noise and pioneer active sound design for a novel transportation era. Electrified driving allows us to rethink urban soundscapes through traffic noise reduction, reduce acoustic strain on long car journeys with lower in-vehicle sound pressure levels, and accentuate vehicle types acoustically with active sound enhancement. Besides the technological development necessary to implement these improvements within the vehicle, the main challenge will be to determine an overall soundscape configuration for EVs so that it satisfies the great variety of customer needs.

There is no *golden* NVH configuration or a *one-fits-all* sound design to enhance the vehicle's character. The success of an EV's acoustic configuration and design is not only determined by objective parameters such as its physical design parameters or the technical implementation within the vehicle. In the end, it depends on the understanding of the percipient of the soundscape and their experience, influenced by a variety of psychological factors such as, for example, the suitability to the given context, individual preference and expectations, affective and cognitive prerequisites, or time-dependent factors such as exposure and familiarization. Within this thesis, however, different empirical studies are presented that provide guidance in understanding the influence of e-powertrain noise on perceived quality, matters of preference for novel EV sound design concepts, and how to methodologically approach perceptual questions on vehicle acoustics. Through the applied methods, various psychological effects on the perception of EV soundscapes are considered in the assessment of subjective evaluation data. The general presence of e-powertrain noise has the potential to diminish the perceived quality of the overall vehicle soundscape, but its influence is dependent on the respective acceleration scenario. Continuous evaluation measures can detect specific acoustic parameters that impact acoustic perception. The identified parameters can then be refined to a customer-tailored and perception-aligned NVH profile. After the elaboration of and familiarization with novel sound concepts, dynamic effects can be observed within perceived preference and innovativeness. More progressive, futuristic, and artistic sound design concepts seem to be preferred within electrified driving compared to more conventional, technical concepts. Furthermore, active sound designs convey specific semantics that need to be considered within the overall design of a vehicle when shaping its character and placing it in the targeted market segment.

This thesis advocates implementing a stronger psychological approach to (electrified) vehicle acoustics and to promote a more holistic understanding among researchers and practitioners across the different disciplines and the applied field. As the perception of EV soundscapes is an inherently

subjective experience, their evaluation must consider perceptual, affective, and cognitive factors. Integrating the psychological perspective into vehicle acoustic research and the design process of EV soundscapes will facilitate interdisciplinary collaboration, support the development of reliable evaluation methods, enhance the determination of long-term design trends, and foster a deeper understanding of customer expectations and preferences. To create not only acoustically refined but also customer-oriented, meaningful soundscapes, the integration of perceptual insights is crucial within the development process. Only by taking a psychological turn on vehicle acoustics is it possible to design soundscapes that genuinely resonate with customers, meeting and exceeding their expectations through a holistic product experience.

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