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ORIGINAL ARTICLE

Proteus effect or bodily affordance? The influence of virtual high-heels on gait behavior

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Abstract
Shoes are an important part of the fashion industry, stereotypically affect our self-awareness as well as external perception, and can even biomechanically modify our gait pattern. Immersive Virtual Reality (VR) enables users not only to explore virtual environments, but also to control an avatar as a proxy for themselves. These avatars can wear any kind of shoe which might similarly affect self-awareness due to the Proteus Effect and even cause a bodily affordance to change the gait pattern. Bodily affordance describes a behavioral change in accordance with the expected constraints of the avatar a user is embodied with. In this article, we present the results of three user studies investigating potential changes in the gait pattern evoked by wearing virtual high-heels. Two user studies targeted female participants and one user study focused male participants. The participants wore either virtual sneakers or virtual high-heels while constantly wearing sneakers or socks in reality. To measure the gait pattern, the participants walked on a treadmill that also was added to the virtual environment. We measured significant differences in stride length and in the flexion of the hips and knees at heel strike and partly at toe off. Also, participants reported to walk more comfortably in the virtual sneakers in contrast to the virtual high-heels. This indicates a strong acceptance of the virtual shoes as their real shoes and hence suggests the existence of a bodily affordance. While sparking a discussion about the boundaries as well as aspects of the Proteus Effect and providing another insight into the effects of embodiment in VR, our results might also be important for researchers and developers.

Keywords Virtual reality · Embodiment · Proteus Effect · Gait · Intermodal illusion

1 Introduction

Shoes are an important branch of the fashion industry and generally important to protect our feet. Small changes in their design can have a huge impact of their wearer's self-perception, external perception, and gait pattern. While running shoes improve our performance in sports, dress shoes result in a formal self-awareness as well as formal external perception. Shoes with high-heels even drastically affect the gait pattern and generally lead to a self-perception and external perception of being more attractive (Morris et al. 2013). Hence, high-heels evoke behavioral changes on a stereotypical level while simultaneously causing biomechanical changes when walking by forcing physical constraints on the wearer.

Immersive Virtual Reality (VR) enables users not only to explore virtual environments (VEs), but also to control an avatar acting as a proxy for themselves (IJsselsteijn et al. 2006; Lugrin et al. 2015). Being embodied with an avatar can lead to a higher degree of presence (Slater et al. 2010). Presence describes the subjective acceptance of the virtual environment as the real environment despite being physically located in a completed different environment (Slater 2009). At the same time, the avatar itself can induce the Proteus Effect and hence influence user behavior. The Proteus Effect describes the conformation of an individual's

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behavior to their digital self-representation (Yee and Bailenson 2007). In this way, a user takes over certain behavioral patterns associated with the respective avatar like drumming differently when a light-skinned user is embodied in a dark-skinned avatar (Kilteni et al. 2013). Similar to an increase in bodily thoughts when using an avatar dressed in a sexualized outfit (Fox et al. 2013), potential behavioral changes on a stereotypical level such as a different self-perception as being more attractive by wearing virtual high-heels might be contributed to the Proteus Effect. However, changes on the biomechanical level by wearing virtual high-heels might not necessarily be caused by a conformation to a specific stereotypical behavior and hence cannot only be associated with the Proteus Effect. Instead, such a behavioral change would be rather a result of a bodily affordance. We define a bodily affordance as the cause for a behavioral change in accordance with the expected constraints of the avatar a user is embodied with. Bodily affordances are a result of intermodal integrations (Biocca et al. 2001) with reference to the own body. Embodied users produce perceptual illusions of missing physical effects on their virtual bodies to complete their mental model of the VR experience (Biocca et al. 2001). Since these cross-modal effects have not been explored with respect to the embodiment of a user, the question arises whether the virtual wearing of objects that cause physical constraints also induces such bodily affordance in the user.

To investigate this research question and to evaluate the existence of a bodily affordance in addition to the Proteus Effect, we propose to inspect a user's gait patterns when wearing different virtual shoes. Finding differences in the gait pattern could indicate a strong acceptance of the virtual shoe as the physically worn shoe. This would indicate a second level of behavioral change besides the Proteus Effect: the bodily affordance.

1.1 Contribution

We present the results of three user studies investigating potential behavioral changes when walking in virtual high-heels in an embodied VE. In particular, we analyzed the users' gait pattern during a walking task in VR and their subjective perception. The walking task took place in a virtual shoe shop and simulated trying on shoes. To allow for a constant motion, the participants walked on a treadmill as displayed in Fig. 1. The participants wore either virtual sneakers or high-heels while constantly wearing sneakers or socks in reality. While the first two studies focused on female users, the third study targeted male users. The first study included a virtual mirror allowing the participants to observe themselves while walking. The other two experiments disabled the virtual mirror after a shoe-specific acclimation phase to avoid potential confounds by the motion of the avatar in the mirror. We found significant differences in the gait patterns between the two shoe conditions with respect to stride length and phases in the gait cycle that include ground contact of the foot. In addition, we observed several medium and large effect sizes between the two shoe types.

Fig. 1 Participants immersed themselves in a virtual shoe shop and walked with two different pairs of shoes on a treadmill

Analyzing the gait of female participants, we measured large effect sizes for stride length, right knee flexion at heel strike, right hip flexion at toe-off, and left knee flexion at heel strike. Also, we observed medium effect sizes for the right hip flexion at heel strike, and the left hip flexion at heel strike as well as toe off. Inspecting the walking behavior of male participants, we found medium effect sizes for the right knee flexion at toe off, maximum knee flexion at stance, and the left hip flexion at heel strike as well as toe off. This indicates that the participants were subconsciously trying to compensate for the typical constraints caused by walking in high-heels. Also, participants reported in a qualitative interview that they could walk better in virtual sneakers. These results are notable. They support an intermodal integration of the missing physical effects on the own body and potentially provide first evidence for a bodily affordance.

2 Theoretical background

Immersive VR allows users to enter any VE and to perform any interaction provided within the boundaries of these artificial spaces. Immersion is "*the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant*" (Slater and Wilbur 1997). Immersion depends on a system's objective properties blocking out real-world sensory inputs and replacing them with computer-generated information. This, for instance, can be achieved by wearing a Head-Mounted Display (HMD). The objective characteristics further include possible actions of a user within a given system (Slater 2009).

Immersion directly evokes and influences presence (Slater et al. 1996; Waltemate et al. 2018). *Presence* describes the subjective illusion of being in a real place despite being physically located in a different place (Slater 2009). Maintaining presence requires a support of sensorimotor contingencies (Slater 2009) and a continuous stream of stimuli and experience (Witmer and Singer 1998). Indicating the perceived realness of a virtual experience (Skarbez et al. 2017), presence is an important prerequisite for a user to react to certain stimuli and to include them and their effects into their mental model of the experienced virtual situation. In particular, a high degree of presence could result in users perceiving virtual shoes as real shoes and hence integrate them in their mental model of the virtual experience.

2.1 Embodiment, Proteus Effect, and affordance

In VR, users can be embodied with an avatar. Typically, users are (1) not represented at all, (2) represented by 3D models of their game controllers or of human hands, i.e., a *minimal embodiment*, or (3) represented by an avatar, i.e., a *full embodiment* (Oberdörfer et al. 2018). User can also be represented by a partial embodiment such as a torso and hands (Lugrin et al. 2018). The feeling of being inside an avatar, owning and controlling it, is called embodiment (IJsselsteijn et al. 2006; Kilteni et al. 2012). The quale of embodiment consists of the subconcepts virtual body ownership, agency, and self-location. Virtual body ownership is the subjective experience of assigning a virtual body to oneself, agency describes the subjective experience of controlling a body, and self-location is the perception of being in one place (Kilteni et al. 2012). High virtual body ownership, agency, and self-location increase the credibility of the embodiment and lead to higher acceptance of the virtual body and thus to more presence (Slater et al. 2010). However, other studies did not find a positive effect on presence evoked by an embodiment (Lugrin et al. 2018). The quale can be positively influenced by providing photorealistic or even personalized avatars (Waltemate et al. 2018).

Embodiment can be used to achieve perceptual or behavioral changes by altering the appearance of the avatar (Latoschik et al. 2016; Roth et al. 2016). According to the Proteus Effect, users adopt the expected characteristics of the avatar during virtual social interactions (Yee and Bailenson 2007). This not only leads to different movement patterns in a drumming task when a light-skinned user is embodied in a dark-skinned avatar (Kilteni et al. 2013), a lower walking speed when embodied in an elderly avatar (Reinhard et al. 2020), and the perception of objects being larger when embodied as a child (Banakou et al. 2013), but also in a reduction of implicit racial bias and hence a change in interpersonal attitudes (Peck et al. 2013; Banakou et al. 2016). Moreover, avatars can influence the performance of physical activities. Avatars associated with a higher fitness level can reduce perceived effort and heart rate during physical activity in VR (Kocur et al. 2021), and avatars with a more pronounced muscular appearance can increase grip strength of male users (Kocur et al. 2020). The cause for the behavioral changes is not limited to the body of the avatar, but also encompasses the clothing and general appearance. While more sexualized avatars lead to more body-related thoughts (Fox et al. 2013), sweaty avatars can reduce the perceived intensity and exertion of a cycling task compared to non-sweaty avatars (Kocur et al. 2022). Even externally modified avatars that differ from normal human bodies are accepted as the user's own body such as being a gorilla (Charbonneau et al. 2017). Due to the high plasticity of the own representation in the brain, even the use of new body parts of the avatar, such as a virtual tail, can be learned (Steptoe et al. 2013).

However, the behavioral changes evoked by factors other than specific stereotypical aspects cannot necessarily be contributed to the Proteus Effect alone. In such a situation, the resulting behavior must not stem from a conformation with the expected behavior of the avatar, but rather from an acceptance of the affordance caused by external elements. This effect would be in line with well-researched concepts of haptic illusions experienced in the absence of physical haptic stimulation as well as the effects of pseudo-haptic feedback (Lederman and Jones 2011). Haptic illusions result from cross-modal enhancements or cross-modal transfers (Biocca et al. 2001). While cross-modal enhancements can lead to changes in detectability as well as perceived location or perceived intensity of haptic force evoked by visual cues, cross-modal transfers lead to an illusion of haptic sensations from visual cues (Biocca et al. 2001). These haptic illusions even occur in the absence of any haptic stimulation such as feeling physical resistance when interacting with virtual objects attached to a spring (Biocca et al. 2001). Additionally, users can experience haptic feedback when pseudo-haptic feedback, such as compressing the same elastic ball, in conjunction with different visual feedback is provided (Lecuyer et al. 2000; Lécuyer 2009). For instance, pseudo-haptic feedback enabled users to sense the stiffness of a spring (Lécuyer 2009). These intermodal integrations occur when users fill in the lacking sensory information to complete their mental model of a virtual experience (Biocca et al. 2001). Following the concept of these intermodal integrations, a user might also feel physical restrictions and forces applied to the own body even if only visual cues are provided. These visualized constraints are bodily affordances leading to a potential behavioral change.

To investigate this assumption, the effects of commonly experienced modifications that not only affect behavior but ideally also movements must be evaluated. One of these modifications are shoes and in particular high-heels.

2.2 Shoes and gait pattern

Wearing high-heels has a long tradition among women, although it can produce painful and irreversible biomechanical effects (Linder and Saltzman 1998). Until today, one reason of women to wear high-heels in public could be a sexual signal to the opposite sex (Prokop and Švancárová 2020). Wearing these shoes, women may not only feel more attractive, but may also be perceived by men as more attractive (Morris et al. 2013).

From a heel height of about 5 cm, the shoes change the mechanics of walking (Simonsen et al. 2012; Ebbeling et al. 1994). Morris et al. (Morris et al. 2013) analyzed the biomechanical walking behavior of women in high-heeled shoes in a laboratory study. For this, 12 women walked in flat shoes and high-heels on a treadmill for four minutes at 1% incline and 4 km/h, respectively. Retroreflective markers were placed on the participant's bodies to track their movements during the last two minutes of walking using an optoelectronic motion capture system. For the analysis of time and joint angle data, data of five consecutive gait cycles at the end of the walking interval were averaged. At different time points in the gait cycle, knee flexion relative to the static joint and various hip angles were measured. In addition, the stride length, duration, and frequency were determined. Morris et al. (2013) found that women in high-heels take shorter, faster steps, bend their knees and hips less, but rotate and tilt their hips more than in flat shoes. There are no differences between experienced and unexperienced high-heel wearers (Ebbeling et al. 1994).

Wearing high-heels represents an ideal external modification of the human body. It not only affects stereotypical behavior and self-perception, but can also change the gait cycle due to the physical constraints applied to a wearer's body. Finding differences in the gait pattern when wearing either virtual high-heels or virtual flat shoes would not only indicate a high acceptance of the virtual shoes, but also provide evidence for behavioral changes evoked by avatar constraints and not stereotypical aspects. This would provide first indications for the existence of a bodily affordance besides the Proteus Effect.

3 Materials and methods

We embedded the evaluation of the effects of wearing virtual high-heels in a cover story to avoid priming the participants. Participants should begin the experiment with the thought of testing a novel method to try on and buy shoes in VR. Hence, the overall goal of our system was to simulate a test environment for a VR-based trying on of shoes concept. We designed a VR shoe store where subjects could try on two pairs of shoes, one flat and one high-heeled, and test walk them on a treadmill. The shoe store resembled a small boutique located at a harbor promenade. The surrounding environment was visible through large windows. Inside of the store, shelves full of various shoes and shoe boxes stood at the walls. In the middle of the room, we placed a 3D model of a treadmill which was adjusted with respect to the location and dimensions of the physical treadmill. We further added two full-body-sized mirrors allowing users to watch their avatars frontally and laterally while standing on the treadmill. The mirror image of the avatar followed the motions of the users. For safety reasons, we disabled the side mirror at the beginning of a treadmill walk. We took further safety precautions by attaching an elastic belt to the participants as described by Birnstiel et al. (2022).

Our VR system represented the participants with a realistic generic avatar created with the o3n asset (o3n Studio 2020) as displayed in Fig. 2. A personalized photorealistic avatar might have resulted in a higher acceptance of the virtual body, but could also have caused confounds due to

Fig. 2 Female participants were represented by a generic female avatar

a potential mismatch of the shoe 3D models and the avatar itself. Using the o3n asset allowed us to dress the avatar with virtual shoes specifically adjusted to it as displayed in Fig. 1 right. This is important to avoid breaking the plausibility and hence the acceptance of the virtual shoes. Also, generic avatars ensured that the resulting conditions only differed with respect to the virtual shoes. We scaled the size of the avatar according to the subject's height. Following the approach of Morris et al. (2013), we used a motion capture system to track the gait cycle of the participants by logging their movements in the system for a follow-up analysis. This approach further enabled us to use the motion capture data stream to animate the avatar.

We prepared three versions of the avatar: (1) barefoot, (2) flat sneaker-like shoes, and (3) high-heels with a heel height of approximately 10 cm. We purely focused on the visual illusion of wearing virtual shoes and hence decided against playing respective walking sounds. Participants used the barefoot avatar during an acclimatization phase to avoid a priming. The two other conditions were experienced in counterbalanced order. To update the shoes, we used the simulated blink transition technique (Oberdörfer et al. 2018).

Our VR system included auditory information for the acclimatization phase and the presentation of the individual shoes. This approach ensured that all participants received the exact same instructions, thus avoiding potential confounds. To enhance the virtual body ownership, the participants performed auditory-guided exercises in front of the mirrors after the start of the application during the acclimatization phase. We based the audio instructions for the exercises on the body movements used by Wolf et al. (2021). After receiving a new pair of shoes, we auditorily instructed the participants to closely inspect the shoes by looking at them and looking at themselves in the mirrors.

We developed the VR system with Unity 2020.1.4 (Unity 2021). We used the OptiTrack motion capture system (OptiTrack 2021a) and streamed the data to Unity using the OptiTrack plugin (OptiTrack 2021b).

3.1 Study design

In our experiment, we wanted to find out whether walking behavior can be influenced by virtual high-heels while users wear flat shoes in reality. Based on the considerations in section 2 and section 3, we assume the following hypothesis:

When participants wear virtual high-heels while walking in VR, they elicit the walking behavior of walking in real high-heels: taking smaller, more frequent steps, having less knee and hip bend, but more hip rotation and tilt than in flat shoes.

Replicating the study of Morris et al. (2013), we make a decision about a joint null hypothesis after rejecting *all* of it constituent null hypotheses, thus conducting *conjunction testing* (Rubin 2021). In particular, our main hypothesis of eliciting a walking behavior of wearing real high-heels consists of the constituent hypotheses of taking smaller, more frequent steps, having less knee and hip bend, but more hip rotation and tilt than in flat shoes. Hence, for our main hypothesis to be accepted, all constituent hypotheses must be accepted.

We tested this hypothesis by conducting user studies following a within-subject design. The independent variable of heel height was manipulated at two levels: virtual shoes with a flat heel and virtual shoes with a high heel of approximately 10 cm. In reality, participants wore the same flat shoes or only socks throughout the experiment. The order of the conditions was counterbalanced.

To gain more insight into the behavioral and movement changes, we conducted three studies. In a first study, we examined the gait behavior of women, while they were able to observe themselves walking in the frontal virtual mirror. In a second study, we deactivated all mirrors when the walking interval began to examine the influence of self-observation while walking. In a third study, we repeated the previous study with male participants. We provided a generic female avatar in the studies targeting women and a generic male avatar in the study targeting men.

3.2 Measures

As dependent variable, we considered the gait pattern of the walking behavior in VR and qualitative reports of the walking experience. Additionally, we recorded supplementary measures to control for potential affecting factors. This resulted in the following measurements:

3.2.1 Demography

In a self-designed questionnaire, we collected demographic data of the test subjects. This includes their height, age, gender, and occupation. We also collected the frequency of use of various media, such as computers, the internet, computer games, smartphones, AR, and VR. In addition, we asked about possible relevant limitations of the participants, such as visual and hearing impairments, language skills, and handedness. At the end of the experiment, we also asked about the experience of walking with high-heels.

3.2.2 Gait pattern

To measure and analyze the walking behavior, we followed the approach of Morris et al. (2013). Using OptiTrack, we recorded the participant's movements while walking on the treadmill for follow-up analyses. To measure the participant's steps, we attached colliders to the toes and heels of the two avatars in Unity. Since the participants wore only flat shoes in reality, we used the sneaker condition of the avatars and animated them using the recorded motion data. As in the study of Morris et al. (2013), only 5 strides per participant at the end of the walking interval were included in the statistical analysis. Following their study design, we assumed that the subjects were already walking uniformly on the treadmill with the respective shoes at this stage.

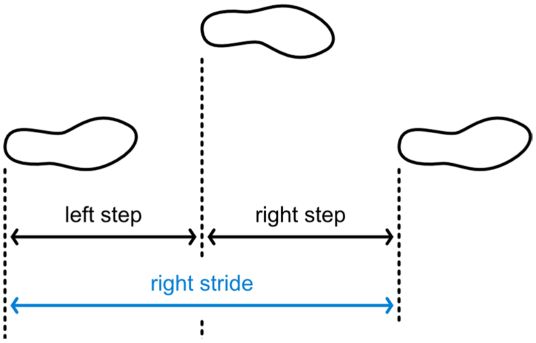

Fig. 3 We defined a stride as interval between two heel strikes of the right foot

We computed the length in meters and duration in seconds of each stride, which we defined as interval between two heel strikes of the right foot as displayed in Fig. 3. We determined the heel strike based on the spatial and temporal collision of the heel with the treadmill model and the toe-off by the end of the collision of the toes with the ground. In addition, various angles of knee and hip joints were recorded in degrees at different stages in the gait cycle and stored alongside the stride data as depicted in Fig. 4. The knee flexion was determined relative to the static leg, which was defined at the start of the VR application during a T-pose of the subject. For each heel strike and toe-off, the flexion of knee and hip was calculated for both legs, respectively. In addition, the maximum flexion of knee and hip for both legs was determined in two different stages: stance and swing. The stance stage is the time interval in which a foot is in contact with the ground. It begins with heel strike and ends with toe-off of the same foot. The swing stage, on the other hand, is the temporal interval in which a foot is in swing and thus has no contact with the ground. It begins with toe-off and ends with heel strike of the same foot. Additionally, the difference in hip tilt and hip rotation during each stride was calculated.

3.2.3 Simulator sickness

Before and after the experiment, we assessed the Simulator Sickness with the Simulator Sickness Questionnaire (SSQ) (Kennedy et al. 1993). The SSQ scales range from 0 to 3. The total score was calculated as described by Kennedy et al. (1993). Low scores indicate low simulator sickness.

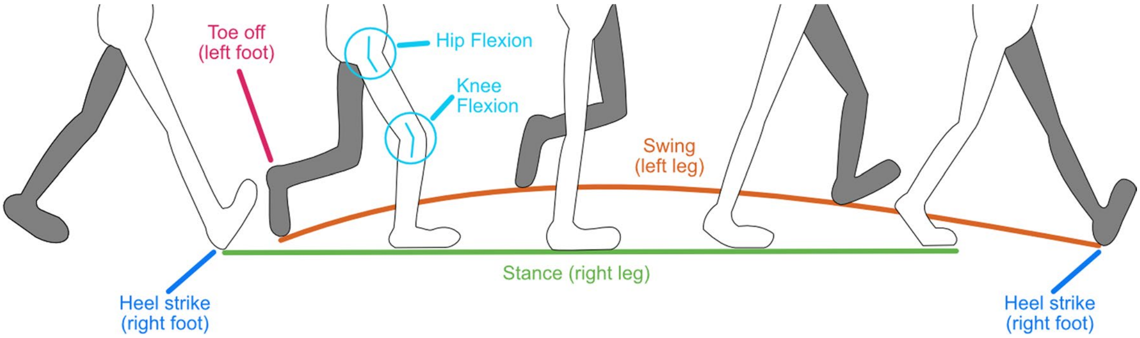

Fig. 4 The schematic illustrates a human walk cycle. We computed the flexion of the hip and knee at each phase of the gait

3.2.4 Qualitative measures

We included qualitative questions at the end of the questionnaire to evaluate the application. We asked about the participant's shoe of choice, the reasoning for their choice, and the acceptance of the shoes as well as the shoe store. The questions about the participants' choice were added to gauge whether the participants experienced the virtual high-heels as too uncomfortable to frequently walk with. In this way, these two questions might reveal some additional subjective insights about the effects of walking in two different types of virtual shoes. Finally, we asked the participants about their experience with walking in high-heels and the number of high-heels they own.

3.3 Procedure

First, the participant was welcomed and received a short information sheet on the experiment and a consent form to read and sign. Then, the subject put on a motion capture suit and placed the markers on it in order to start the experiment directly after completing the pre-questionnaire. The questionnaire was completed on a separate PC and included demographic data and the SSQ. This was followed by an information text about the procedure of the experiment. Subsequently, four stages on the treadmill followed:

1. The participant entered the treadmill; the safety precautions were explained and implemented as displayed in Fig. 1 upper left. The subject did not leave the treadmill until the 4th stage was completed. Subsequently, a test walk on the treadmill started, for which the experimenter counted a countdown loudly and started the treadmill, so that the participant could easily estimate the start of movement. After 2 min of walking, the experimenter counted down loudly again and stopped the treadmill.
2. The subject put on the VR headset and found themself in the virtual shoe store. There they could observe their embodiment without shoes in a mirror while following auditory instructions to familiarize themself with the body. Next, the treadmill was started and stopped after 2 min, as described in stage 1.
3. In this stage, the subject's avatar was fitted with flat shoes. An audio instruction to familiarize with the shoes followed. The remaining procedure is identical to stage 2.
4. In this stage, the subject's avatar was fitted with high-heeled shoes. The remaining procedure is identical to stage 2.

The order of the last two stages was counterbalanced. Subsequently, the participant answered the post-questionnaire on the PC consisting of SSQ, qualitative questions and questions about their high-heel experience. A disclosure text appeared at the end of the questionnaire. Each study session lasted about 1 h.

The study took place during the COVID-19 pandemic. To ensure for protection and hygiene, we took the following precautions. (1) Each participant was required to constantly wear a mask. (2) The experimenter was required to constantly wear a mask. (3) The experimenter and the participant were required to keep at least a distance of 1.5 ms. (4) All touched surfaces and used devices, like HMD and keyboard, had to be cleaned with a disinfectant product after each experimental trial.

3.4 Apparatus

The experimental setup consisted of a computer (CPU: Intel i7-9700K @3.6GHz, RAM: 32GB, GPU: NVIDIA GeForce RTX 2070 SUPER), an HTC Vive Pro (1440x1600 px resolution per eye, 110° FOV), the OptiTrack motion capture system and a treadmill. The OptiTrack motion capture system, consisting of 18 Prime^{x}13 infrared cameras, was used to track the subjects' movements. We used the baseline 37-marker setup for all participants. We used a cardiostrong TR-30 treadmill for the first study which experienced a mechanical failure in the time between the first and second study. Hence, we needed to replace it and used a Nautilus T628 treadmill for the second and third study. We adapted the treadmill settings of the study of Morris et al. (2013) by adjusting it to a secure and comfortable walking speed when immersed in the virtual environment. Specifically, we reduced the walking pace to 3 km/h, kept the 1% incline and reduced the walking time to two minutes per experimental stage.

3.5 Ethics

We implemented an elastic safety belt as described by Birnstiel et al. (2022) to limit the risk of injury when walking on a treadmill in VR. Also, we trained with the participants to walk on the treadmill while wearing the HMD.

Our study was approved by the Human-Computer-Media Institutional Ethics Review Board of the University of Würzburg.

3.6 Statistical analyses

To analyze the measures performed in our three studies, we compute paired sample t tests. To validate the normality assumption for the analysis, we use Shapiro–Wilk tests. In cases where the Shapiro–Wilk analysis does not support the assumption of a normal distribution, we use a nonparametric test instead, specifically Wilcoxon's signed rank test.

Implementing a conjunction testing approach, no alpha adjustment is necessary for our multiple testing analysis (Rubin 2021). Hence, we use an alpha level of .05 for all of our statistical comparisons. We report Cohen's d as the effect size for the analyses. We calculate and interpret the effect sizes as both, the effect size and statistical significance, are essential to understand the impact of our results (Sullivan and Feinn 2012; Lakens 2013; Schäfer and Schwarz 2019). Therefore, we use the common thresholds for Cohen's d for effect size interpretation of 0.2 as small, 0.5 as medium, 0.8 as large, and 1.3 as very large.

4 Results—study 1

The first study targeted woman and represented the inaugural experiment of this series of studies.

4.1 Participants

We recruited 18 female undergraduate students enrolled at the University of Würzburg. We used an online participant recruitment system that rewards students with credits mandatory for obtaining their bachelor's degrees. Due to technical issues, we had to exclude the data sets of four participants. The remaining 14 subjects were on average 20.50 years old (*SD* = 1.45) and 167.00 cm tall (*SD* = 4.58). Two of them were left-handed and one person participated with uncorrected visual impairment. Regarding immersive media use, only 4 participants had not experienced VR before. The subjects owned an average of 5 pairs of high-heeled shoes (*SD* = 6.47) and mostly wore them only monthly or annually, with 3 participants never wearing them.

4.2 Gait analysis

The gait data collected were averaged per person and shoe pair of 5 consecutive gait cycles at the end of the walking interval. A Shapiro–Wilk test indicated that no normal distribution can be assumed for some of the measurements.

Hence, we computed paired sample *t* tests in cases where a normal distribution could be assumed, and Wilcoxon's signed rank tests where a normal distribution could not be assumed, as indicated in Table 1.

The analysis revealed a significantly greater maximum right hip flexion at stance when wearing the virtual high-heels, as shown in Table 1. Also, we observed trends for

Table 1 Study 1: descriptive data are presented in *M*(*SD*) format

Factor	Flat shoes	High-heels	Statistics	*p*	*d*
Stride duration	1.30 s (0.10)	1.33 s (0.10)	− 1.11	0.285	− 0.30
Stride length	0.89 m (0.12)	0.87 m (0.14)	1.16	0.266	0.31
Pelvic tilt	6.49° (1.25)	6.47° (1.42)	0.06	0.951	0.02
Pelvic rotation†	7.71° (4.35)	8.98° (6.69)	44	0.626	− 0.35
Right					
Knee flexion (Heel strike)	8.81° (5.16)	8.46° (6.90)	0.22	0.826	0.06
Knee flexion (Toe-off)†	35.76° (10.53)	37.17° (15.42)	31	0.194	− 0.12
Max. Knee flexion (Stance)†	33.32° (9.61)	35.48° (12.96)	28	0.135	− 0.22
Max. Knee flexion (Swing)	65.49° (7.01)	64.11° (8.92)	0.92	0.374	0.25
Hip flexion (Heel strike)	28.48° (2.73)	30.07° (2.99)	− 2.14	0.052	− 0.57
Hip flexion (Toe-off)†	15.87° (3.38)	18.42° (4.78)	28	0.135	− 0.52
Max. Hip flexion (Stance)	28.35° (2.85)	30.34° (2.69)	− 2.47	0.028*	− 0.66
Max. Hip flexion (Swing)†	33.33° (4.26)	33.52° (4.16)	61	0.626	0.08
Left					
Knee flexion (Heel strike)	11.22° (5.94)	12.65° (5.60)	− 1.30	0.216	− 0.35
Knee flexion (Toe-off)†	40.35° (7.39)	40.66° (8.66)	27	0.119	− 0.04
Max. Knee flexion (Stance)†	38.17° (9.06)	39.83° (8.79)	35	0.296	− 0.30
Max. Knee flexion (Swing)	64.34° (8.18)	62.42° (5.25)	0.91	0.380	0.24
Hip flexion (Heel strike)	26.70° (2.27)	28.66° (4.29)	− 1.74	0.105	− 0.47
Hip flexion (Toe-off)†	15.87° (5.29)	17.31° (6.58)	30	0.173	− 0.47
Max. Hip flexion (Stance)	27.75° (2.44)	28.84° (4.11)	− 1.25	0.235	− 0.33
Max. Hip flexion (Swing)	32.11° (5.03)	32.31° (4.86)	− 0.39	0.703	− 0.10

†indicates nonparametric analysis due to violation of the normality assumption. The statistics column reports the t-statistic for parametric cases and W for nonparametric cases. An asterisk indicates significant results at $p < 0.05$

a greater right hip flexion at heel strike for the high-heel condition.

Calculating Cohen's d, we found a small effect size for stride duration, stride length, pelvic rotation, maximum knee flexion at stance as well as swing for the right leg, and for the left leg at knee flexion at heel strike, maximum knee flexion at stance as well as swing, hip flexion at heel strike as well as toe off, and maximum hip flexion at stance. We observed medium effect sizes for the right hip flexion at heel strike as well as toe off and for the right maximum hip flexion at stance. Table 1 provides an overview of the effect sizes.

4.3 Simulator sickness

Since a Shapiro–Wilk test indicated that the measurements could not be assumed to be normally distributed, we computed Wilcoxon's signed rank tests for analysis. Simulator sickness increased significantly between the two measurement time points before and after the experiment, as shown in Table 2. Investigating the subscales shows that only oculomotor issues were rated significantly more negatively. According to Stanney et al. 1997), the post-values of nausea are negligible. The post-values of the other subcategories and the total score are at the lower threshold of the range for significant symptoms.

4.4 Qualitative reports

Half of the participants would have bought the flat shoes in the virtual shoe store. They found them to be more comfortable, better to walk with, and more realistic with respect to their appearance. The other half would have decided for the high-heels because they judged them to be prettier. However, they found the idea of a virtual shoe store rather impractical, as they lacked the feeling of wearing the shoes and would have preferred to see them on their own bodies. For assessing the appearance of the shoes, though, the virtual version is well suited, although the quality of the representation should be improved in terms of the resolution of the HMD and the level of detail of the shoes.

Table 2 Study 1: we evaluated the SSQ computing by Wilcoxon's signed rank tests, as the assumption of normality is violated

Factor	Pre	Post	*W*	*p*	*d*
Nausea	2.73 (5.83)	4.77 (6.21)	2	0.345	− 0.31
Oculomotor	5.96 (5.30)	11.77 (10.19)	0	0.010*	− 0.98
Disorientation	1.99 (5.05)	11.93 (17.14)	0	0.054	− 0.56
Total score	4.54 (4.20)	10.69 (9.38)	0	0.006*	− 1.03

Descriptive data are presented in *M*(SD) format. An asterisk indicates significant results at $p < 0.05$

4.5 Discussion

Besides a significant difference for the maximum right hip flexion at stance and a trend for the right hip flexion at heel strike, measured gait behavior did not differ significantly between the two conditions.

Nevertheless, we found medium effect sizes for the right hip flexion at heel strike as well as toe off and for the right maximum hip flexion at stance. In addition, we observed several small effect sizes for stride duration, stride length, pelvic rotation, maximum knee flexion at stance as well as swing for the right leg, and for the left leg at knee flexion at heel strike, maximum knee flexion at stance as well swing, hip flexion at heel strike as well as toe off, and maximum hip flexion at stance when comparing the individual phases in the gait between the two shoes. However, besides the expected shorter stride length, the measurements are contrary to our assumptions and hypothesis. The participants bent their knees and hips more when walking in high-heels compared to when walking in sneakers. Also, it stands in contrast to the otherwise expected gait change to conform the stereotypical behavior according to the Proteus Effect. The participants did not change their whole gait cycle to conform to the stereotypical increased hip tilt and rotation.

The unexpected direction of the changes in the gait might be explained by the physical influence of real high-heels on gait. In contrast to a sneaker shoe, weight distribution and walking in high-heels are more stable when the heel touches the ground at less of an angle. This especially can be of importance when wearing stilettos with a narrow heel like the ones we used in our studies. When wearing physical high-heels, this is achieved by making smaller steps, thus avoiding overextending the stride and resulting in a more vertical landing of the shoe at heel strike compared to when walking in sneaker shoes. Hence, it is possible to assume that the participants intended to mimic this approach. Due to a lack of a real stiff heel extending the length of a leg, they needed to bend the hip and hence the knee more to achieve a slightly reduced angle of attack of the foot at heel strike. Also, by less extending the stride, the leg must be lifted higher to get the toes off the ground. The expected lower hip flexion would have been the case when wearing physical high-heels causing a higher pitch in the foot and hence a more straight leg. As a result of this, our measurements suggest that the walking behavior of real high-heels was successfully imitated at these measurement points in the gait cycle.

In addition, the responses to our qualitative questions further indicate an influence of the virtual shoes on the wearers' perceptions. Half of the participants mentioned that they could better walk in the flat pair of shoes. This suggests that they accepted the virtual shoes as their real shoes and subjectively noticed a difference in the walking experience. Also, it confirms our initial assumption of an intermodal integration and experience of haptic forces when the own body is visually constrained. The participants produced perceptual illusions to complete their mental model of walking in high-heels (Biocca et al. 2001). This result further extends the previous findings (Biocca et al. 2001; Lederman and Jones 2011) by indicating that illusions of haptic sensation can even occur when they are directly applied to the user's virtual body. These results are notable. They indicate that developing an awareness for the shoes of the own avatar leads to an acceptance of these shoes as the real shoes and a subsequent change in the gait cycle. More importantly, our results indicate that intermodal integrations go beyond a mere sensational illusion and can even lead to changes in motion patterns such as gait. Taken together, our findings provide first evidence for the existence of a bodily affordance.

A potential explanation for the generally insignificant differences in the objective measurements could be the existence of the frontal mirror. Throughout the walking phases, the participants could watch their avatars walking on the treadmill. Wearing the respective type of shoe, the animation of the avatar's gait was already influenced by the physical constraints of the shoes even when the user walked normally. Since watching ourselves in a mirror allows for a better learning (Dearborn and Ross 2006) and correction (Kushner et al. 2015) of movements, the participants might have focused on their mirror image and assumed to walk differently while still walking normally in reality, thus ignoring the subjective influence of the virtual shoes. As a result of this, the avatar's gait instead of the virtual shoes might have influenced the gait of the participants. However, the subjective reports in conjunction with the measured right hip flexion differences indicate a possible influence of the virtual shoes that goes beyond the mere mirror image.

While we found a significant increase on the SSQ, our gait measurements suggest that an increase in the symptoms of cybersickness did not influence the participants' movements. We exposed the participants to the two types of shoes in counterbalanced order. Since the participants walked almost uniformly, it seems unlikely that cybersickness influenced their movements. Also, the post-SSQ measurements are still rather low which might overall limit the effects of experienced cybersickness. On a more general level, our measurements provide further evidence for the discussed issue of the assumed zero baseline on the SSQ (Brown et al. 2022). The participants already reported symptoms before the start of the experiment which increased over the course of the experiment. This reduces the interpretability and comparability of concrete measurements. Focusing on changes in the SSQ total score instead could potentially result in a better interpretability. In this study, the total score increased by 6.15 on average which is in the acceptable range.

Hence, to investigate the potential effects of the frontal mirror as well as the virtual shoes, the second study followed in which the body could not be observed in a mirror during walking.

5 Results—study 2

We kept the system and the study design the same for study 2 except for two changes. First, we not only disabled the lateral mirror, but also the frontal mirror during the walking phases. This should rule out potential influences on the gait cycle caused by a focus on the virtual appearance in the frontal mirror. Second, we replaced the previous treadmill which unfortunately stopped working in between the experiments with a Nautilus T628 treadmill. We kept the same settings of 3 km/h and 1% incline for a walk of two minutes per experimental stage.

5.1 Participants

We recruited 15 female undergraduate students using our internal participant recruitment system again. The participants were on average 22.30 years old ($SD = 1.83$) and 169.00 cm tall ($SD = 8.32$). Two of them were left-handed and no one participated with limited vision. Only one subject had not experienced VR before. On average, participants owned 3.47 pairs of high-heeled shoes ($SD = 2.53$), but they also tended to be used very rarely. Two subjects participated barefoot because their shoes were not compatible with the motion capture suit.

5.2 Gait analysis

Again, five consecutive gait cycles at the end of the walking interval were averaged. Because of the lack of normality indicated by Shapiro–Wilk tests for some measurements, we calculated paired sample t tests in cases where a normal distribution could be assumed, and Wilcoxon's signed rank tests for measurement pairs where a normal distribution could not be assumed, as indicated in Table 3.

The results show that stride length was significantly shorter in high-heels. Also, knee flexion at heel strike for both legs, right hip flexion at toe-off, and left hip flexion at heel strike were significantly greater in high-heels. Lastly, we observed a trend for a greater right hip flexion at heel strike and maximum right hip flexion at stance when walking in virtual high-heels. Figure 5 visualizes the measured differences.

Calculating Cohen's d, we found a small effect size for stride duration, pelvic tilt, knee flexion at toe off, maximum

Fig. 5 Schematic visualization of the differences in the gait cycle between the two conditions. The left picture depicts the heel strike and the right picture the toe-off

Table 3 Study 2: differences in gait pattern between virtual flat and high-heeled shoes, when the participants could not watch themselves in a mirror while walking

Factor	Flat shoes	High-heels	Statistics	*p*	*d*
Stride duration	1.19 s (0.10)	1.20 s (0.11)	– 0.93	0.366	– 0.24
Stride length	0.90 m (0.12)	0.81 m (0.15)	4.16	< 0.001*	1.07
Pelvic tilt	5.99° (0.99)	6.38° (1.42)	– 1.40	0.184	– 0.36
Pelvic rotation	8.16° (3.32)	7.93° (3.36)	0.60	0.559	0.15
Right					
Knee flexion (Heel strike)	11.83° (4.25)	16.43° (6.11)	– 3.15	0.007*	– 0.81
Knee flexion (Toe-off)	25.92° (15.25)	30.50° (12.96)	– 1.31	0.212	– 0.34
Max. Knee flexion (Stance)	30.25° (11.55)	34.34° (6.81)	– 1.21	0.248	– 0.31
Max. Knee flexion (Swing)†	65.58° (8.55)	66.13° (7.39)	60	1.000	0.18
Hip flexion (Heel strike)†	27.90° (3.94)	29.15° (3.73)	26	0.055	– 0.52
Hip flexion (Toe-off)	14.94° (4.45)	18.52° (5.10)	– 3.44	0.004*	– 0.90
Max. Hip flexion (Stance)†	28.29° (3.53)	29.55° (3.78)	26	0.055	– 0.48
Max. Hip flexion (Swing)†	31.09° (4.74)	31.44° (4.63)	60	1.000	0.15
Left					
Knee flexion (Heel strike)	10.33° (7.07)	16.58° (8.92)	3.90	0.002*	– 1.01
Knee flexion (Toe-off)	31.20° (18.43)	33.77° (16.32)	– 0.66	0.521	– 0.17
Max. Knee flexion (Stance)	32.31° (13.74)	35.48° (12.19)	1.28	0.221	– 0.33
Max. Knee flexion (Swing)†	68.12° (4.09)	67.04° (5.45)	59	0.978	– 0.30
Hip flexion (Heel strike)	27.04° (4.08)	28.40° (3.95)	– 2.76	0.015*	– 0.71
Hip flexion (Toe-off)	17.32° (3.95)	19.17° (3.87)	– 1.96	0.071	– 0.51
Max. Hip flexion (Stance)	27.47° (3.75)	27.96° (4.38)	– 0.96	0.355	– 0.25
Max. Hip flexion (Swing)	30.21° (4.07)	30.40° (4.12)	0.98	0.344	– 0.25

Descriptive data are presented in *M*(*SD*) format. †indicates nonparametric analysis due to violation of the normality assumption. The statistics column reports the t-statistic for parametric cases and W for nonparametric cases. An asterisk indicates significant results at $p < 0.05$

knee flexion at stance, and maximum hip flexion at stance for the right leg, and for the left leg at maximum knee flexion at stance as well as swing, and maximum hip flexion at stance as well as swing. We observed medium effect sizes for the right hip flexion at heel strike, and the left hip flexion at heel strike as well as toe off. Finally, we measured large effect sizes for stride length, right knee flexion at heel strike, right hip flexion at toe-off, and left knee flexion at heel strike. Table 3 provides an overview of the effect sizes.

5.3 Simulator sickness

According to Shapiro–Wilk tests, the measurements could be assumed to be normally distributed. Therefore, paired *t* tests were calculated for analysis. Simulator sickness increased significantly between the two measurements before and after the experiment, as shown in Table 4. Investigating the subscales shows that nausea and disorientation were rated significantly more negatively. According to Stanney et al.

Table 4 Study 2: we evaluated the SSQ by computing paired *t* tests

Factor	Pre	Post	t	p	d
Nausea	12.10 (22.70)	21.60 (27.10)	– 2.74	0.016*	– 0.71
Oculomotor	13.60 (16.30)	16.70 (15.70)	– 0.88	0.395	– 0.23
Disorientation	11.10 (21.80)	27.80 (29.80)	– 2.17	0.048*	– 0.69
Total score	14.50 (21.10)	24.20 (23.20)	– 2.29	0.038*	– 0.71

Descriptive data are presented in *M*(*SD*) format. An asterisk indicates significant results at $p < 0.05$

(1997), the pre-values of all subcategories are already very high, indicating significant symptoms. The symptoms even increased in the post-values.

5.4 Qualitative reports

Eight of the subjects would have chosen the flat pair in the virtual shoe store because they like to wear flat shoes in general, but also because it provided them with a more secure walking impression. They also felt more comfortable and realistic. Five participants chose the high-heels, mainly because they look prettier. Two subjects had no preference. The assessment of the future viability of the shoe store corresponded to those of the first study.

5.5 Discussion

When trying on the virtual shoes with the frontal mirror being disabled during the walking phases, the participants changed their gait cycle more prominently when walking in virtual high-heels in contrast to walking in flat shoes while wearing the same shoes or socks in reality. In particular, the participants made smaller steps as well as bent their knees and hips more at heel strike when wearing the virtual high-heels. Note that the right hip flexion just missed significance and only shows a strong trend. Also, we found a significantly greater hip flexion at toe off and a trend for a greater maximal hip flexion during stance for the right leg in the high-heels condition. Moreover, we observed a trend for the maximum right hip flexion at stance. Finally, we found large effect sizes for stride length, right knee flexion at heel strike, right hip flexion at toe-off, and left knee flexion at heel strike. In addition, we observed several medium effect sizes when comparing the individual phases in the gait between the two shoes at the right hip flexion at heel strike, and the left hip flexion at heel strike as well as toe off. Also, we measured small effect sizes for stride duration, pelvic tilt, knee flexion at toe off, maximum knee flexion at stance, and maximum hip flexion at stance for the right leg, and for the left leg at maximum knee flexion at stance as well as swing, and maximum hip flexion at stance as well as swing. Taken together, our second study confirms that participants in the first study were already adjusting their gait cycle despite the potential influence of the frontal mirror reference frame. Figure 5 left illustrates the changes in the gait. The intermodal integration also was reflected in the qualitative statements of the participants. Half of the participants reported a more comfortable walking in the flat shoes compared to the high-heels. The participants again produced a perceptual illusion based on the visual information of wearing high-heels, thus leading to an intermodal integration (Biocca et al. 2001). These results confirm our discussion of the first study's results and support that intermodal integrations can even affect the gait of the users.

However, while the shorter stride length is consistent with our hypothesis, all other differences remain to be contrary to our assumption. The participant showed increased hip and knee angles when walking in the virtual high-heels. Besides the difference in right hip flexion at toe off, the heel strike phase primarily changed between the two pairs of shoes. In this phase of the gait cycle, a physical higher heel would cause the first impact when making a step. In alignment with our discussion of the first study, the lack of a real physical higher heel might have caused these changes in the gait. While the participants accounted for the physical impact at heel-strike, their real shoes caused not the expected constraints on their body, thus leading to the observed overcompensation.

Our results also indicate a strong influence of seeing oneself in a mirror on movement patterns. In the first and second study, participants qualitatively reported to walk better in virtual sneakers than in virtual high-heels. However, we only observed prominent changes in the gait cycle when no mirror was present. As long as the mirror was present, participants might have assumed to already walk differently as shown by their mirror image. This suggests that they used the mirror as a reference frame to confirm their movements by their visual appearance instead of by their other senses. If this assumption is true, it might be an important insight for VR applications of physical training and physiotherapy (Bartl et al. 2022). The mirrored representation of a user's movement must be coherent with the real movements to enable successful movement correction.

Our measurements thus support the first evidence of an effect of bodily affordance. The participants produced perceptual illusions and adjusted their gait cycle to compensate for the affordance caused by the constraints of wearing virtual high-heels. This is backed by their statements of a more comfortable walking in the flat shoes.

The SSQ measurements provide several insights. First, our measurements confirm the discussed issue of the assumed zero baseline on the SSQ (Brown et al. 2022). The participants even started the experiment with a total score above the post-SSQ total score of the first study. This supports the approach of analyzing total score changes instead of concrete values to allow for an interpretability. Our measurements revealed an increase of less than 10 points of the total score which is still in an acceptable range. Second, as we counterbalanced the order of the conditions and measured significant differences, our results rule out that the measured gait changes are evoked or influenced by neither an effect of cybersickness nor the different treadmill model. Third, the stronger increase in the SSQ ratings compared to the first study can be an effect of the lack of the frontal mirror. The participants no longer had a visual clue about their position on the treadmill in their direct line of sight and had to fully rely on the elastic safety belt as well as glancing downward to the virtual treadmill. This might have caused a higher level of anxiety and hence higher SSQ values. To potentially reduce this issue, we decided to provide new visual cues to the participants when evaluating the walking behavior of men in virtual high-heels.

6 Results—study 3

We used the same system and study design as in study 2 but added visual aids to the system to facilitate walking on the treadmill. In particular, we added a Chaperone system around the treadmill providing participants with visual guidance about their position on the treadmill as displayed in Fig. 6. To adjust the setup to the male participants, we exchanged the generic female avatar with a generic male avatar. Since the o3n asset did not provide high-heels for male avatars, we modeled a new pair as displayed in Fig. 7. In addition, the flat sneaker-like shoe changed to a different model. Finally, we decided to further gauge the participants' subjective perception of wearing different virtual shoes. We added the following question to the qualitative measures: *"How did you feel about trying on the virtual high-heel shoes?"*

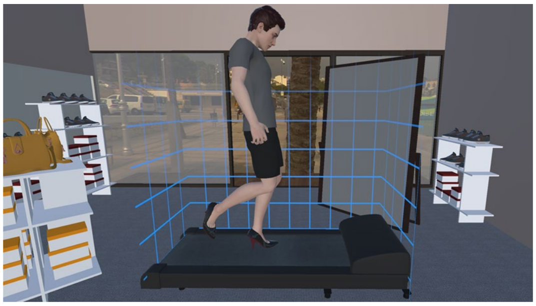

Fig. 6 We used male participants in study 3 and added a Chaperone system to provide visual guidance when walking

Fig. 7 The male avatar received two new pair of shoes that followed the overall style of the shoes used for the female avatar

6.1 Participants

We recruited 16 male undergraduate students using our internal participant recruitment system again. One participant showed strong effects of anxiety while walking on the treadmill and kept his hands on the handrails for the entire duration of the experiment. Since this might have strongly influenced the participant’s gait, we excluded him from the sample. The remaining 15 participants were on average 21.13 years old ($SD = 2.10$) and 183.73 cm tall ($SD = 5.80$). Three of them were left-handed and no one participated with limited vision. Only one subject had not experienced VR before. No participant owned high-heeled shoes themselves. However, four participants have ever worn some and two even wear high-heels annually.

6.2 Gait analysis

Again, five consecutive gait cycles at the end of the walking interval were averaged. Because of the lack of normality indicated by Shapiro–Wilk tests for some measurements, we calculated paired sample t tests in cases where a normal distribution could be assumed, and Wilcoxon’s signed rank tests for measurement pairs where a normal distribution could not be assumed, as indicated in Table 5.

The results show that stride length was significantly shorter in high-heels. In addition, right knee flexion at toe-off, maximum right knee flexion at stance, left knee flexion at heel strike, and left hip flexion at heel strike as well as toe-off were significantly greater in high-heels. Lastly, we observed a trend for a greater right knee flexion at heel strike.

Calculating Cohen’s d, we found a small effect size for stride duration, stride length, pelvic tilt, knee flexion at

Table 5 Study 3: differences in gait pattern between virtual flat and high-heeled shoes with male participants

Factor	Flat shoes	High-heels	Statistics	*p*	*d*
Stride duration	1.22 s (0.12)	1.27 s (0.09)	− 1.28	0.220	− 0.33
Stride length†	1.13 m (1.27)	0.72 m (0.13)	115	< 0.001*	0.35
Pelvic tilt†	6.74° (11.90)	3.91° (1.45)	47	0.489	− 0.25
Pelvic rotation	7.04° (2.56)	7.06° (2.84)	− 0.06	0.956	− 0.01
Right					
Knee flexion (Heel strike)	10.94° (7.12)	14.33° (6.50)	− 1.82	0.090	− 0.47
Knee flexion (Toe-off)	21.13° (12.09)	32.41° (16.67)	− 2.71	0.017*	− 0.70
Max. Knee flexion (Stance)	25.04° (10.36)	33.95° (11.07)	− 2.94	0.011*	− 0.76
Max. Knee flexion (Swing)†	62.01° (7.42)	63.97°° (6.93)	42	0.330	− 0.32
Hip flexion (Heel strike)	37.67° (3.99)	38.13 (3.77)	− 1.08	0.300	− 0.28
Hip flexion (Toe-off)	22.86° (7.20)	26.03° (6.67)	− 1.55	0.143	− 0.40
Max. Hip flexion (Stance)†	37.81° (3.69)	38.16° (4.34)	46	0.454	− 0.11
Max. Hip flexion (Swing)†	39.14° (6.29)	40.04° (4.63)	50	0.599	− 0.25
Left					
Knee flexion (Heel strike)†	14.29° (8.15)	17.83° (6.65)	17	0.012*	− 0.43
Knee flexion (Toe-off)	23.40° (14.83)	25.13° (17.98)	− 0.39	0.705	− 0.10
Max. Knee flexion (Stance)	27.22° (12.88)	29.72° (11.81)	− 0.69	0.503	− 0.18
Max. Knee flexion (Swing)†	61.98° (6.43)	63.65° (5.75)	50	0.599	− 0.33
Hip flexion (Heel strike)†	35.17° (3.92)	36.24° (3.15)	19	0.018*	− 0.55
Hip flexion (Toe-off)	24.54° (8.28)	29.26° (5.69)	− 2.31	0.037*	− 0.60
Max. Hip flexion (Stance)†	35.94° (3.52)	36.03° (4.27)	39	0.252	− 0.05
Max. Hip flexion (Swing)†	39.25° (8.19)	37.41° (3.29)	64	0.847	0.25

The participants could not watch themselves in a mirror while walking. Descriptive data are presented in *M*(*SD*) format. †indicates nonparametric analysis due to violation of the normality assumption. The statistics column reports the t-statistic for parametric cases and W for nonparametric cases. An asterisk indicates significant results at $p < 0.05$

heel strike, maximum knee flexion at swing, hip flexion at heel strike as well as toe off, and maximum hip flexion at swing for the right leg, and for the left leg at knee flexion at heel strike, maximum knee flexion at swing, and maximum hip flexion at swing. We observed medium effect sizes for the right knee flexion at toe off, maximum knee flexion at stance, and the left hip flexion at heel strike as well as toe off. Table 5 provides an overview of the effect sizes.

6.3 Simulator sickness

Since a Shapiro–Wilk test indicated that the measurements could not be assumed to be normally distributed, we computed Wilcoxon's signed rank tests for analysis. Simulator sickness did not increase significantly between the two measurement time points before and after the experiment, as shown in Table 6. Investigating the subscales shows that nausea was rated significantly more negatively. According to Stanney et al. (1997), the post-values of oculomotor and disorientation indicate negligible symptoms. For nausea and the total score the post-values indicate minimal symptoms.

Table 6 Study 3: we evaluated the SSQ computing by Wilcoxon's signed rank tests, as the assumption of normality is violated

Factor	Pre	Post	*W*	*p*	*d*
Nausea	7.00 (5.66)	12.08 (8.43)	4.5	0.025*	− 0.72
Oculomotor	4.04 (6.94)	3.54 (5.63)	3	1.000	0.08
Disorientation	1.86 (7.19)	2.78 (7.80)	2.5	1.000	− 0.08
Total score	5.24 (6.13)	7.23 (5.19)	17	0.077	− 0.28

Descriptive data are presented in *M*(*SD*) format. An asterisk indicates significant results at $p < 0.05$

6.4 Qualitative reports

One participant would have chosen the high-heels, because he would have the confidence to wear the shoes due to the anonymity in VR. One subject had no preference. All other participants would choose the flat pair of shoes. Reasons for this are, on the one hand, personal preference, but also that these shoes felt more real and the avatar with flat shoes more closely matches their own body. One person mentioned the safer feeling when walking in the flat pair of shoes.

When asked how the subjects felt about trying on the virtual high-heels, seven out of 15 (46.7%) said they felt a difference between the pairs of shoes. They felt more elegant in the high-heels but also more wobbly as well as insecure. They felt walking with them more unnatural and difficult than with the virtual flat shoes and suspected they had adapted their gait to the shoes.

6.5 Discussion

In this study, we measured again significant differences in stride length, left knee flexion at heel strike, and left hip flexion at heel strike. Also, right knee flexion at toe off, right knee maximum flexion at stance, and left hip flexion at toe off differed significantly between the two conditions. Right knee flexion at heel strike showed a trend. Similar to the women, men showed no difference in the stereotypical hip tilt and rotation. Lastly, we found medium effect sizes for the right knee flexion at toe off, maximum knee flexion at stance, and the left hip flexion at heel strike as well as toe off. In addition, we observed several small effect size for stride duration, stride length, pelvic tilt, knee flexion at heel strike, maximum knee flexion at swing, hip flexion at heel strike as well as toe off, and maximum hip flexion at swing for the right leg, and for the left leg at knee flexion at heel strike, maximum knee flexion at swing, and maximum hip flexion at swing. In line with the previous study with female participants, men also adapted their walking behavior depending on the virtual shoe worn. The more pronounced behavioral change at toe-off compared to the female participants could be explained by the low experience in walking in high-heels. Without much previous knowledge, the male participants might have assumed a much stronger physical influence when walking in high-heels. This ultimately led to a more exaggerated behavioral change.

Supporting the discussions of the two studies with female participants, the male participants might have experienced an effect of bodily affordance. Our male participants experienced intermodal integration by producing perceptual sensations and adjusted their gait cycle to compensate for the expected affordances of walking in a high-heeled shoe. This is backed by their qualitative statements about their walking experience. Seven of the 15 participants subjectively noticed an influence of the virtual high-heels on their gait behavior. The reported unnatural and difficult walking experience further supports the assumption of an overly strong behavioral change when wearing the high-heels. This again is in line with previous findings (Biocca et al. 2001; Lederman and Jones 2011). Our results of this third study further suggest that the intermodal integration and hence bodily affordance are independent of previous knowledge. The male participants experienced the same physical illusions.

The results of the SSQ support our assumption in the previous two discussions and our changes made to the system. The Chaperone system potentially provided the participants with a better sense for their position on the treadmill and hence lowered their anxiety of falling off. While future work is needed to confirm the positive aspects of such a lightweight Chaperone system, adding it to treadmill-assisted VR walking applications potentially improves the overall perceived quality and safety. This can be an important insight for researchers and developers who target VR walking applications on a treadmill such as rehabilitation systems (Winter et al. 2021).

7 Overall discussion

We conducted a series of three studies to investigate whether an effect of bodily affordance changes a user's behavior in an embodied VE. In particular, we selected virtual shoes as our stimulus and evaluated the gait cycle of women and men walking in virtual flat and high-heeled shoes while constantly wearing flat shoes or socks in reality. In study 2 and 3, when no mirror providing a self-reference was present, we observed a significantly shorter stride length and significant changes in the gait cycle for phases with ground contact. These phases would be affected by the constraints of walking in physical high-heels, thus explaining the behavior of the participants. When looking at the calculated effect sizes, we found several medium and small effect sizes in every study and large effect sizes in the second study. This is further evidence of an influence of the physical constraints of the two types of shoes tested on the gait pattern of the participants. The participants produced perceptual illusions based on the visual appearance of the virtual shoes by experiencing intermodal integrations (Biocca et al. 2001) and accounted for the expected impact of the high-heels on their natural gait pattern. Male participants elicited more changes than female participants which is explainable by the lack of experience with walking in physical high-heels. Additionally, participants in every study reported to walk more comfortably when wearing the flat shoes in contrast to the high-heels. This supports the acceptance of the virtual shoes as their real shoes, an occurrence of intermodal integration, and hence a potential effect of bodily affordance.

However, despite finding several significant differences between the two conditions, we must reject our hypothesis. Although the participants took smaller steps, they showed no pronounced hip rotation and tilt when wearing the high-heels. This can be explained by the lack of a physical impact on their gait cycle otherwise forcing the hip to tilt and rotate more (Simonsen et al. 2012). Also, the direction of the significant changes at heel strike, stance and toe-off was opposite to the expected direction. Similarly, this can be contributed to the lack of a physical impact of real high-heels.

Although we had to reject the hypothesis, our results are novel and have several implications. The change in the gait cycle and the acceptance of the shoes show that even small changes of an avatar can lead to a big difference when noticed. Similar to the increased bodily thoughts when being embodied in a sexualized avatar (Fox et al. 2013), the acceptance of wearing high-heels might result in a stronger identification as a woman. In the case of a VR learning environment for math or natural sciences, it might evoke a stereotype threat resulting in a potential lower performance of female learners (Spencer et al. 1999). Hence, it is important to test for potential side effects of the provided avatars when designing embodied VR learning environments. Future work is needed to investigate whether wearing different virtual shoes also evokes further behavioral changes beyond a potential influence on the gait cycle. In addition, our results indicate the existence of a bodily affordance besides the Proteus Effect. A bodily affordance causes a behavioral change in accordance with the expected constraints of the avatar a user is embodied with. The Proteus Effect, in contrast, describes a conformation of an individual's behavior to their digital self-representation (Yee and Bailenson 2007). Since we only focused on biomechanical behavior changes, the Proteus Effect could not explain the measured differences in our three studies. This hypothesis is further backed by the lack of differences in the participants' hip rotation and hip tilt. These movement patterns are stereotypical for walking in high-heels. According to the Proteus Effect, the participants should have elicited such a behavior. The participants, however, showed only changes that would account for the physical affordance caused by physical high-heels. Hence, the concept of a bodily affordance based on intermodal integrations fills this gap and allows for an explanation of behavioral changes that are not evoked by conforming to a stereotypical behavior. However, it is also likely that our proposed concept of bodily affordance is a sub-component or prerequisite of the Proteus Effect. Our three studies are just the starting point of a scientific investigation and discussion of the proposed concept. Future research shall continue the investigation of bodily affordances by testing other constraints on avatars as well as by replicating our experiment with personalized avatars. In the latter scenario, we hypothesize a similar outcome of a changed gait cycle when wearing virtual high-heels in contrast to wearing virtual sneakers. Besides investigating the influence of personalized avatars, analyzing the changes in the gait over the course of the walking experience is of high interest. In our studies, we only inspected five strides at the end of the walking interval. This, however, leaves out an investigation whether the potential effect of a bodily affordance is immediate or evolves over time. It would similarly be interesting to study if the change in the gait continues for a longer period of walking or whether there is a decline in this effect over time.

There are several limitations of our studies. Each study only had a rather small sample size. Although all three studies resulted in participants to report a perceptual illusion of wearing different types of shoes, our results must be interpreted carefully. It is important to continue this research avenue with a larger sample size to validate our first measurements. Also, we only used young adults as our participants. It is possible that our results are not generalizable to a wider population. A future experiment needs to include a wider population to investigate whether the experience of bodily affordances is not limited to a younger generation. Another potential limitation can stem from our experimental setup. Using a treadmill was necessary as our study required a constant motion of the participants within the tracking space of the motion capture system to clearly detect changes that are not caused by differences in walking speed or sudden changes in direction. Although we slowly introduced our participants to walking on a treadmill while wearing an HMD, it might have caused the participants to walk more carefully than usual. In addition, walking on a treadmill compared to overground walking can cause differences in muscle activation patterns and joint moments and patterns (Lee and Hidler 2008). As a result, their gait might have changed to a certain extent compared to their regular gait. However, this influence would have been present in both shoe conditions and would have similarly affected the participants' gait. Hence, being the only difference between the two conditions, the different types of virtual shoes seem to have caused the differences measured in the gait independent of the task of walking on a treadmill. In addition, our experimental setup of allowing participants to walk in their own shoes is another limitation of our studies. Despite advising the participants to only wear sneakers, each individual pair still potentially resulted in a different walking experience. As a result of this, the experience of the participants might have been affected by the different physical feedback of their real shoes worn during their experimental trail. However, participants wore their shoes throughout the entire experiment, so while there was a potentially constant influence on their experience, the only difference between the conditions was the type of virtual shoe provided.

8 Conclusion

This paper presented and discussed the results of three user studies investigating the existence of a bodily affordance in general and the effects of wearing either virtual flat shoes or high-heels in particular. During a walking task on a treadmill, the participants walked for two minutes in one pair of the virtual shoes before trying on the other pair. In reality, they constantly wore either flat shoes or socks. Using a motion capture system, we analyzed their gait cycles. Also, we asked them for qualitative feedback about their experiences when walking in the virtual shoes. The first and second study targeted women; the third study investigated whether the gait cycle of men is affected when wearing high-heels.

Our measurements revealed several large effect sizes and significant differences in the gait cycle between wearing flat shoes and high-heels. When no mirror provided a potentially influential reference frame, the participants took smaller steps when wearing virtual high-heels. Also, we found significant changes in the flexion of knee and hip for the phases of heel-strike, stance and toe-off. These phases in the gait cycle have ground contact of the foot. Hence, our results suggest that the participants were subconsciously trying to compensate for the typical constraints caused by walking in high-heels. Several participants in every study further reported that they could walk better in virtual sneakers than in virtual high-heels. This indicates a high acceptance of the virtual shoes as their real shoes and might even lead to potential further behavioral changes. This result is notable. It provides first evidence for the existence of a bodily affordance besides or in conjunction with the Proteus Effect, a behavioral change in accordance with the expected constraints of the avatar. Bodily affordances are a result of intermodal integrations (Biocca et al. 2001) with reference to the own body leading to a production of perceptual illusions of missing physical effects on the own virtual bodies.

Future work shall investigate whether wearing different virtual shoes also causes further behavioral changes beyond a potential influence of the gait cycle like inducing the Proteus Effect or a stereotype threat. A different research direction is the evaluation of the influence of other constraints of an avatar's movement capabilities on a user's behavior to continue the discussion of the Proteus Effect and bodily affordances. Also, it is of high interest to investigate whether the effect occurs instantaneously or is built up over time. Lastly, it is important to extend the sample size and the population to validate our findings.

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Author contributions [SO] and [BS] helped in conceptualization, investigation, writing—original draft preparation and methodology; [BS] was involved in VR simulation and data analysis; [SO], [BS] and [ML] contributed to writing—review and editing; [SO] and [ML] supervised the study. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability The VR simulation developed for the current study is available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of The Institute of Human-Computer-Media at University of Würzburg (April 25, 2022).

Consent to participate All consents were approved, and physical forms were signed by the participants prior to the experiments.

Consent for publication All the data published in this paper were declared in the consent forms and consented to by the participants.

References

Banakou D, Groten R, Slater M (2013) Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. Proc Natl Acad Sci 110:12846–12851. https://doi.org/10.1073/pnas.1306779110

Banakou D, Hanumanthu PD, Slater M (2016) Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias. Front Hum Neurosci 10:601. https://doi.org/10.3389/fnhum.2016.00601

Bartl A, Merz C, Roth D, Latoschik ME (2022) The effects of avatar and environment design on embodiment, presence, activation, and task load in a virtual reality exercise application. In: 2022 IEEE international symposium on mixed and augmented reality (ISMAR), pp 260–269. https://doi.org/10.1109/ISMAR55827.2022.00041

Biocca F, Kim J, Choi Y (2001) Visual touch in virtual environments: an exploratory study of presence, multimodal interfaces, and cross-modal sensory illusions. Presence Teleoper Virtual Environ 10(3):247–265. https://doi.org/10.1162/105474601300343595

Birnstiel S, Oberdörfer S, Latoschik ME (2022) Stay safe! safety precautions for walking on a conventional treadmill in VR. In: 2022 IEEE Conference on virtual reality and 3D User Interfaces Abstracts and Workshops (VRW), pp 732–733. IEEE. https://doi.org/10.1109/VRW55335.2022.00217

Brown P, Spronck P, Powell WA (2022) The simulator sickness questionnaire (SSQ), and the erroneous zero baseline assumption. Front Virtual Real. https://doi.org/10.3389/frvir.2022.945800

Charbonneau P, Dallaire-Côté M, Côté SSP, Labbe DR, Mezghani N, Shahnewaz S, Arafat I, Irfan T, Samaraweera G, Quarles J (2017) Gaitzilla: exploring the effect of embodying a giant monster on lower limb kinematics and time perception. In: 2017 international conference on virtual rehabilitation (ICVR), pp 1–8. https://doi.org/10.1109/ICVR.2017.8007535. IEEE

Dearborn K, Ross R (2006) Dance learning and the mirror: comparison study of dance phrase learning with and without mirrors. J Dance Educ 6(4):109–115. https://doi.org/10.1080/15290824.2006.10387323

Ebbeling CJ, Hamill J, Crussemeyer JA (1994) Lower extremity mechanics and energy cost of walking in high-heeled shoes. J Orthop Sports Phys Ther 19(4):190–196. https://doi.org/10.2519/jospt.1994.19.4.190

Fox J, Bailenson JN, Tricase L (2013) The embodiment of sexualized virtual selves: the proteus effect and experiences of self-objectification via avatars. Comput Hum Behav 29(3):930–938. https://doi.org/10.1016/j.chb.2012.12.027

Ijsselsteijn WA, Kort YAW, Haans A (2006) Is this my hand i see before me? the rubber hand illusion in reality, virtual reality, and mixed reality. Presence Teleoper Virtual Environ 15(4):455–464. https://doi.org/10.1162/pres.15.4.455

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psychol 3(3):203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kilteni K, Groten R, Slater M (2012) The sense of embodiment in virtual reality. Presence Teleoper Virtual Environ 21(4):373–387. https://doi.org/10.1162/pres_a_00124

Kilteni K, Bergstom I, Slater M (2013) Drumming in immersive virtual reality: the body shapes the way we play. In: 2013 IEEE virtual reality (VR)). https://doi.org/10.1109/VR.2013.6549442

Kocur M, Bogon J, Mayer M, Witte M, Karber A, Henze N, Schwind V (2022) Sweating avatars decrease perceived exertion and increase perceived endurance while cycling in virtual reality. In: Proceedings of the 28th ACM symposium on virtual reality software and technology (VRST '22). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3562939.3565628

Kocur M, Habler F, Schwind V, Woźniak PW, Wolff C, Henze N (2021) Physiological and perceptual responses to athletic avatars while cycling in virtual reality. In: Proceedings of the 2021 CHI conference on human factors in computing systems (CHI '21). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3445160

Kocur M, Kloss M, Schwind V, Wolff C, Henze N (2020) Flexing muscles in virtual reality: effects of avatars' muscular appearance on physical performance. In: Proceedings of the annual symposium on computer-human interaction in play (CHI PLAY '20), pp 193–205. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3410404.3414261

Kushner AM, Brent JL, Schoenfeld BJ, Hugentobler J, Lloyd RS, Vermeil A, Chu DA, Harbin J, McGill SM, Myer GD (2015) The back squat part 2: targeted training techniques to correct functional deficits and technical factors that limit performance. Strength Cond J 37(2):13–60. https://doi.org/10.1519/SSC.0000000000000130

Lakens D (2013) Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol 4:863. https://doi.org/10.3389/fpsyg.2013.00863

Latoschik ME, Lugrin JL, Roth D (2016) FakeMi: a fake mirror system for avatar embodiment studies. In: Proceeding of ACM symposium on virtual reality software and technology

Lécuyer A (2009) Simulating haptic feedback using vision: a survey of research and applications of pseudo-haptic feedback. Presence Teleoper Virtual Environ 18(1):39–53. https://doi.org/10.1162/pres.18.1.39

Lecuyer A, Coquillart S, Kheddar A, Richard P, Coiffet P (2000) Pseudo-haptic feedback: can isometric input devices simulate force feedback? In: Proceedings IEEE virtual reality 2000, pp 83–90. https://doi.org/10.1109/VR.2000.840369

Lederman SJ, Jones LA (2011) Tactile and haptic illusions. IEEE Trans Haptics 4(4):273–294. https://doi.org/10.1109/TOH.2011.2

Lee SJ, Hidler J (2008) Biomechanics of overground vs. treadmill walking in healthy individuals. J Appl Physiol 104(3):747–755. https://doi.org/10.1152/japplphysiol.01380.2006

Linder M, Saltzman CL (1998) A history of medical scientists on high heels. Int J Health Serv 28(2):201–225. https://doi.org/10.2190/ga2m-fla2-17fb-v5pe

Lugrin JL, Ertl M, Krop P, Klüpfel R, Stierstorfer S, Weisz B, Rück M, Schmitt J, Schmidt N, Latoschik ME (2018) Any "body" there? Avatar visibility effects in a virtual reality game. In: 2018 IEEE conference on virtual reality and 3D user interfaces (VR), pp 17–24. IEEE. https://doi.org/10.1109/VR.2018.8446229

Lugrin JL, Latt J, Latoschik ME (2015) Anthropomorphism and illusion of virtual body ownership. In: Imura M, Figueroa P, Mohler B (Eds) ICAT-EGVE 2015-international conference on artificial reality and telexistence and Eurographics symposium on virtual environments. The Eurographics Association, Aire-la-Ville. https://doi.org/10.2312/egve.20151303

Morris PH, White J, Morrison ER, Fisher K (2013) High heels as supernormal stimuli: how wearing high heels affects judgements of female attractiveness. Evol Hum Behav 34(3):176–181. https://doi.org/10.1016/j.evolhumbehav.2012.11.006

o3n Studio: o3n Male and Female UMA Races. available at https://assetstore.unity.com/packages/3d/characters/humanoids/o3n-male-and-female-uma-races-102187 (2020)

Oberdörfer S, Fischbach M, Latoschik ME (2018) Effects of ve transition techniques on presence, ivbo, efficiency, and naturalness. In: Proceedings of the 6th symposium on spatial user interaction (SUI '18), pp 89–99. ACM, Berlin, Germany. https://doi.org/10.1145/3267782.3267787

OptiTrack: OptiTrack. available at https://optitrack.com (2021)

OptiTrack: Unity Plugin. available at https://optitrack.com/software/unity/ (2021)

Peck TC, Seinfeld S, Aglioti SM, Slater M (2013) Putting yourself in the skin of a black avatar reduces implicit racial bias. Conscious Cogn 22(3):779–787. https://doi.org/10.1016/j.concog.2013.04.016

Prokop P, Švancárová J (2020) Wearing high heels as female mating strategy. Personal Individ Differ 152:109558. https://doi.org/10.1016/j.paid.2019.109558

Reinhard R, Shah KG, Faust-Christmann CA, Lachmann T (2020) Acting your avatar's age: effects of virtual reality avatar embodiment on real life walking speed. Media Psychol 23(2):293–315

Roth D, Lugrin JL, Galakhov D, Hofmann A, Bente G, Latoschik ME, Fuhrmann A (2016) Avatar realism and social interaction quality in virtual reality. In: Proceedings of IEEE virtual reality, pp 277–278

Rubin M (2021) When to adjust alpha during multiple testing: a consideration of disjunction, conjunction, and individual testing. Synthese 199(3):10969–11000. https://doi.org/10.1007/s11229-021-03276-4

Schäfer T, Schwarz MA (2019) The meaningfulness of effect sizes in psychological research: differences between sub-disciplines and the impact of potential biases. Front Psychol 10:813. https://doi.org/10.3389/fpsyg.2019.00813

Simonsen EB, Svendsen MB, Nørreslet A, Baldvinsson HK, Heilskov-Hansen T, Larsen PK, Alkjær T, Henriksen M (2012) Walking on high heels changes muscle activity and the dynamics of human walking significantly. J Appl Biomech 28(1):20–28. https://doi.org/10.1123/jab.28.1.20

Skarbez R, Brooks FP Jr, Whitton MC (2017) A survey of presence and related concepts. ACM Comput Surv 50(6):1–39. https://doi.org/10.1145/3134301

Slater M (2009) Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philos Trans Royal Soc B 364:3549–3557. https://doi.org/10.1098/rstb.2009.0138

Slater M, Wilbur S (1997) A framework for immersive virtual environments (five): speculations on the role of presence in virtual environments. Presence 6(6):603–616. https://doi.org/10.1162/pres.1997.6.6.603

Slater M, Linakis V, Usoh M, Kooper R (1996) Immersion, presence, and performance in virtual environments: an experiment with tri-dimensional chess. In: Proceedings of the ACM symposium on virtual reality software and technology (VRST '96), pp 163–172. ACM, Hong Kong. https://doi.org/10.1145/3304181.3304216

Slater M, Spanlang B, Corominas D (2010) Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. In: ACM SIGGRAPH 2010 papers. SIGGRAPH '10, pp 92–1929. ACM, New York, USA. https://doi.org/10.1145/1833349.1778829

Spencer SJ, Steele CM, Quinn DM (1999) Stereotype threat and women's math performance. J Exp Soc Psychol 35(1):4–28. https://doi.org/10.1006/jesp.1998.1373

Stanney KM, Kennedy RS, Drexler JM (1997) Cybersickness is not simulator sickness. In: Proceedings of the human factors and ergonomics society annual meeting, vol 41, No (2), pp 1138–1142. https://doi.org/10.1177/107118139704100292

Steptoe W, Steed A, Slater M (2013) Human tails: ownership and control of extended humanoid avatars. IEEE Trans Visual Comput Graph 19(4):583–590. https://doi.org/10.1109/tvcg.2013.32

Sullivan GM, Feinn R (2012) Using effect size-or why the p value is not enough. J Grad Med Educ 4(3):279–282. https://doi.org/10.4300/JGME-D-12-00156.1

Unity: Unity. available at https://unity.com (2021)

Waltemate T, Gall D, Roth D, Botsch M, Latoschik ME (2018) The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. IEEE Trans Visual Comput Graph 24(4):1643–1652. https://doi.org/10.1109/TVCG.2018.2794629

Winter C, Kern F, Gall D, Latoschik ME, Pauli P, Käthner I (2021) Immersive virtual reality during gait rehabilitation increases walking speed and motivation: a usability evaluation with healthy participants and patients with multiple sclerosis and stroke. J NeuroEng Rehabilit 18:68. https://doi.org/10.1186/s12984-021-00848-w

Witmer BG, Singer MJ (1998) Measuring presence in virtual environments: a presence questionnaire. Presence 7(3):225–240. https://doi.org/10.1162/105474698565686

Wolf E, Merdan N, Dolinger N, Mal D, Wienrich C, Botsch M, Latoschik ME (2021) The embodiment of photorealistic avatars influences female body weight perception in virtual reality. In: 2021 IEEE virtual reality and 3D user interfaces (VR), pp 65–74. IEEE. https://doi.org/10.1109/vr50410.2021.00027

Yee N, Bailenson J (2007) The proteus effect: the effect of transformed self-representation on behavior. Hum Commun Res 33(3):271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x