On Your Feet! Enhancing Vection in Leaning-Based Interfaces through Multisensory Stimuli

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ABSTRACT

When navigating larger virtual environments and computer games, natural walking is often unfeasible. Here, we investigate how alternatives such as joystick- or leaning-based locomotion interfaces ("human joystick") can be enhanced by adding walking-related cues following a sensory substitution approach. Using a custom-designed foot haptics system and evaluating it in a multi-part study, we show that adding walking related auditory cues (footstep sounds), visual cues (simulating bobbing head-motions from walking), and vibrotactile cues (via vibrotactile transducers and bass-shakers under participants' feet) could all enhance participants' sensation of self-motion (vection) and involvement/presence. These benefits occurred similarly for seated joystick and standing leaning locomotion. Footstep sounds and vibrotactile cues also enhanced participants' self-reported ability to judge self-motion velocities and distances traveled. Compared to seated joystick control, standing leaning enhanced self-motion sensations. Combining standing leaning with a minimal walking-in-place procedure showed no benefits and reduced usability, though. Together, results highlight the potential of incorporating walking-related auditory, visual, and vibrotactile cues for improving user experience and self-motion perception in applications such as virtual reality, gaming, and tele-presence.

CCS Concepts

• Information interfaces and presentation - multimedia information systems, artificial, augmented, and virtual realities;

Keywords

Navigation interface; 3D user interface; leaning; VR; gaming; vibration; bass-shaker; whole-body interface; surface textures.

1. INTRODUCTION

While joysticks and gamepads are widely used methods for navigating games and virtual reality (VR), they offer hardly any of the self-motion cues accompanying real-world locomotion. Allowing for free-space walking while wearing a head-mounted display provides appropriate physical motion cues, but is often unfeasible because of restrictions in the tracked space, concerns of safety, cost, or technical complexity, or fatigue for longer exposures. Leaning-based navigation interfaces using the Wii balance board [20, 21, 57, 61] and other approaches [19, 34, 62] have been proposed and used as an alternative that allows for long-range locomotion without running into limitations of the tracked space. Compared to joystick and gamepad interfaces where the human body is mostly passive and vestibular/proprioceptive cues are largely lacking, leaning-based interfaces can improve navigation performance [21] and provide a more immersive and embodied experience as they allow for at least some full-body involvement and vestibular motion cueing, which can enhance self-motion perception (vection) [31, 40, 44]. Nevertheless, leaning-based interfaces still lack many of the self-motion cues experienced during real-world locomotion, such as full vestibular cues from translations and rotations, proprioceptive cues from walking, air moving by our ears, as well as haptic and auditory cues from our feet touching ground. We designed a multipart study to investigate if and how joystick- and leaning-based locomotion interfaces might be improved by adding different walking-related self-motion cues such as auditory cues (footstep sounds), visual cues (simulating bobbing head-motions from walking), vibrotactile cues (via vibrotactile transducers and shakers under participants' feet) and minimal walking-in-place.

While there is evidence that the visually-induced sensation of illusory self-motion ("vection") can be enhanced by adding matching auditory cues (e.g., dynamic sound fields) and vibrations/subsonics [24, 32, 40], it is largely unknown how they affect active locomotion conditions using seated joystick versus standing leaning interfaces. As self-motion sensations are typically enhanced by multisensory stimulation [32, 43–46], we do expect overall enhancement by providing additional self-motion related cues in the current studies. Similarly, we hypothesized additional benefits including improved speed and distance perception and overall performance and usability, especially in systems that require more precise navigation or wayfinding, or a higher level of user engagement through increased realism.

Some may consider the usage of walking-in-place (WIP) techniques [55] to overcome the caveat of lack of motion cues, as this technique does provide some proprioceptive cues by mimicking physical walking while not physically moving around. However, WIP can be tiring over time, which might lead to reduced usage. In addition, while WIP gestures are fairly natural for forward walking, they can be awkward for walking backwards or strafing,

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which are both common in the real world and computer games [51]. Furthermore, the physical motion rather resembles walking upstairs instead of natural forward motion.

In the approach presented in this paper, we follow a different direction. We present a system that can provide fine-grained multi-sensory cues for standing leaning-based interfaces, extending work by Marchal et al. [33] and Feng et al. [14] who focused on supporting seated users. The system provides audio-visual cues as well as foot-based stimuli ("foot haptics") that partly *substitute* real-world cues. Sensory substitution is a method in which sensory information is transferred from one kind of stimulus to another, both within or across the senses. For example, a popular method of substitution is the translation of kinaesthetic information into vibrotactile cues, being a substitution within the same (haptic) sensory system [29]. In our system, "foot haptics" are deployed by a dense grid of vibrotactors, a bass-shaker, and a loudspeaker under each foot. Cues are physically co-located similar to cues perceived during real-world walking.

The system design is guided by previous studies indicating that navigation techniques for synthetic environments can be enhanced by visual and non-visual cues such as head bobbing, step sounds, or plantar (foot-based) vibrotactile cues [10, 38, 45, 53, 56]. These cues can contribute to both the travel and wayfinding aspects of navigation, and have been reasonably well researched in the domain of physical walking interfaces. Yet, using additional cues for those users who are *not* moving around physically while navigating through an environment is still an open area of research. Exceptions include some studies that explore head bobbing, footsteps sounds, and vibration for seated stationary users [14, 53], and vestibular cues provided through motion platforms [26], showing positive effects on self-motion. Here, we investigate how adding different walking-related auditory, visual, and vibrotactile cues might affect standard joystick situations (with seated users) as well as standing leaning conditions, and if they might be differently affected by the added cues.

2. RELATED WORK

Navigation is one of the key tasks performed in both real and virtual environments, and encompasses both physical and psychological aspects. Physical navigation interfaces have been studied widely and can increase the overall usability and user experience of the system [6, 7, 41], enhance spatial perception and orientation important for a wide range of tasks [7], and reduce motion sickness [4]. In this section, we look more closely at related studies on leaning-based navigation interfaces, as well as feedback to support navigation interfaces.

Leaning-based locomotion interfaces. Our interface development and accompanying studies relate directly to leaning-based interfaces for travel in synthetic environments like games or virtual environments, including the use of the Wii balance board [20, 57, 61] and other types of leaning interfaces [19, 34, 62]. Leaning interfaces to some degree resemble other interfaces that keep the user physically at one location, such as WIP interfaces [51, 55], natural motion interfaces such as those supported by treadmills [12], or navigation systems for seated users. An overview of many techniques can be found in [7], while a focused overview of how in particular feet can be used for interaction purposes is described in [59].

Vection. Embodied self-motion illusions (e.g., vection) have long been studied and can be induced in stationary observers by moving visual flow fields, moving spatialized sounds, and biomechanical cues from walking on circular (but not linear) treadmills (see recent reviews in [24, 32, 44]). Visually-induced vection can be enhanced by adding simulated camera motions that mimic jitter [38] or head bobbing, the vertical and horizontal oscillatory motion of the head during natural walking [10], which can be communicated as a purely visual cue [52], as well as through physical movement of the user [26]. Researchers have also looked into the integration of visual and non-visual cues for self-motion perception [13, 23] and information storage thereof [2]. Some studies showed that minimal provision of vestibular cues can enhance self-motion [22, 27, 49], while also foot step sounds [42,53], wind [14], and tactile patterns associated with walking [44] or leaning in sideways directions [30] showed positive effects. Furthermore, body pitch affects self-motion [5, 8, 9]. Studies on actively tilting the body have shown that while horizontal (sideways left-right) vection was not affected by body tilt, vertical (a.k.a. elevator) vection was reduced for upright posture and increased to the level of horizontal vection as body tilt increased [35]. In contrast, static leaning has also been shown to positively affect self-motion for seated users [31].

Foot-based feedback. Foot-induced feedback for both physically moving and non-moving users has been approached from various directions. Not only the feet themselves, but also the legs have been stimulated [7], for example through moving foot pedals [28]. Furthermore, and a key instigator for our system, plantar cutaneous vibration feedback (the stimulation of the foot sole) can be sufficient to elicit a walking experience [54]. To achieve this, researchers have taken advantage of the high sensitivity of the foot sole [18]. Among others, researchers have looked into pressure distributions associated with heel and toe strike defining roll-off of the feet in natural motion by using a low-frequency loudspeaker [53]. Furthermore, non-directional tactile cues (e.g., floor vibrations) have been shown to provide some self-motion cues [13, 14, 53]. Some studies also looked specifically into navigational cues ("turn right") by deploying a dense grid of vibrotactors under the mid-foot [58]. Vibrotaction can also be used to elicit ground texture cues, partly also in combination with audio [36, 37, 39, 50] and has been shown to positively affect haptic surface compliance [60]. Finally, vibrotaction has been used for providing collision feedback [3]. With regards to auditory feedback, footstep sounds have been used to elicit self-motion sensations [14], as the frequency of steps provides some information about how fast the user is moving. Approaches partly include ground texture information, though it has been shown that perception can be biased through cross-modal effects [16]. Sometimes cues were displayed to the feet by mounting loudspeakers in close vicinity [39]. To some extent, vibration and audio cues have been studied in concert, and shown to improve vection [43]. This integration of audio and tactile cues also relates to recent studies looking specifically into the integration of various multisensory cues for rendering of walking [33], an area our system and user study also targets.

Gait. The physical aspect of locomotion can be defined by *gait*, the bipedal (forward) propulsion caused by the human limbs, which is affected by, for example, velocity and ground surface [15]. Gait is comprised of the different stride phases, in which the legs are moved, and the feet hit the ground (foot strike for each step). Stride phases differ in both frequency and length, depending on how fast the person moves. They include the stance phase (where a foot touches the ground) and swing phase (where the leg is moved and the foot is airborne); combined, they form one gait cycle. Thereby, ground contact of the foot is defined by a roll-off process of the human foot, affected by different force (pressure) phases underneath the foot sole (cf. Fig. 2). Furthermore, the amount of ground contact per roll-off (step) differs with velocity.

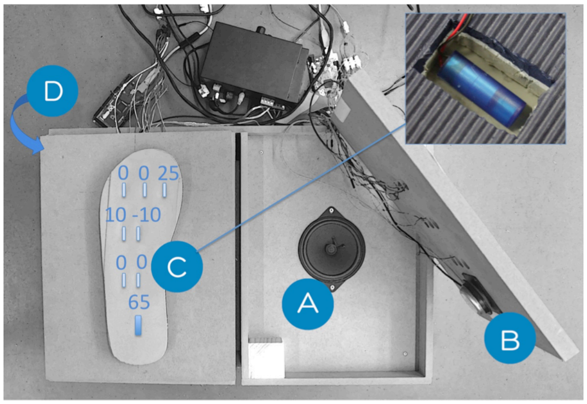

Figure 1. Hardware setup: Feedback to each foot consists of (A) a loudspeaker mounted in a solid case to provide air volume, (B) a bass-shaker, (C) eight vibrotactors mounted underneath the foot (overlaid in blue: seven small, one large vibrotactor, latter shown in close up from below foam sole), with PWM intensity control, and (D) the core frame of a Wii balance board.

Foot strike can differ between different people, as for example runners commonly have either heel or mid-foot strike. In this article we mainly focus at heel strike roll-off patterns. Finally, as an effect of the stride phases and balance shifts, the human body will exhibit horizontal and vertical oscillatory motions, which are partly counterbalanced by the vestibular system [49]. The shift of balance can be noticed by human vision, as the human viewpoint shifts in a process commonly described as *head bobbing*.

3. SYSTEM DESIGN

The main research problem targeted in this paper is *how* to improve self-motion perception, usability, and user engagement in leaning- and joystick-based navigation through synthetic environments. To this end, we designed as system that combines multisensory feedback with sensors to detect the user's weight shifting, thus controlling the navigation.

3.1 System and Cue Overview

The overall system (Fig. 1) consists of various feedback components mounted underneath the feet, placed on top of the Wii balance board load sensors and electronics in a wooden (medium-density fiberboard) case. Cues are provided by actuators mounted underneath each foot: a loudspeaker (Fig. 1, A) mounted in a speaker case, a bass-shaker (exciter, Fig. 1, B), and a grid of vibrotactors (Fig. 1, C). Furthermore, additional visual cues are provided through the head-mounted display connected to the system, an Oculus Rift DK2. Stimuli for each foot are isolated by creating two boxes that are separated by 1cm thick solid foam insulation. As such, the feedback provided to one foot can hardly be noticed by the other foot. As a product of the various devices, the system can provide additional walking-related cues including **visual** (head bobbing), **auditory** (footstep sounds), and **vibrotactile** (foot roll-off pressure and ground impact) cues. The full system runs in real-time on a graphics workstation using Unity3D. The vibrotactors are controlled through pulse-width modulation (PWM) over two Arduino Mega boards triggered over Uniduino, while the loudspeaker and bass-shaker are driven by two amplifiers. The system was designed to be compact and portable, and thus does not allow for full-body rotations or stepping away from the designated foot positions and vibrotactors.

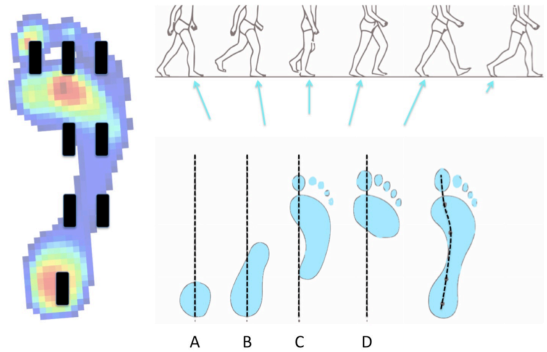

Figure 2. Left: Foot pressure distribution zones of a standing user (image Wikimedia commons) showing the vibrotactors locations. Right: gait analysis of half a gait cycle during normal walking showing (A) heel strike, (B) heel strike to foot flat, (C) foot flat to midstance, and (D) midstance to toe off (redrawn from [15]).

3.2 Navigation Methods

Leaning-based locomotion uses the Wii balance board to allow the user to produce forward, backward, and sideways (strafing) motions, as well as turning during forward motion. We did not allow the user to turn around while not moving. The Wii measured users' leaning via center of pressure (COP) changes, which controlled translation velocities in the direction of the COP change. To allow for smooth control over both slow and faster locomotion speeds, we used an exponential velocity control ($velocity \sim COPdeflection^{2.7}$) based on pilot results. For the seated joystick conditions, we used a Microsoft X-Box gamepad with the same exponential velocity control scheme with a factor of 2.7. Velocities were limited to 3.7m/s for both interfaces.

3.3 Visual Head Movement

Largely following the specification of head bobbing by Grossmann et al. [17], a custom-built head-bobbing algorithm was implemented in Unity3D to simulate the horizontal and vertical oscillatory motion of the head during real-world walking. Iterative design and pretesting with several specialists was used to fine-tune the head-bobbing parameters to create a "flat 8" (infinity) motion pattern, synced with the user's speed of travel. To do so, two sine waves, one for each of the x- and y-axes, are instantiated, while the y-axis wave has double the frequency of the x-axis.

3.4 Audio

The design premise for the audio cues is the delivery of realistic walking sounds, which are presented using two loudspeakers (Visaton FR10 20W) mounted beneath the feet, driven by a single amplifier (Samson Servo 200). Sounds are thus collocated with the feet, similar to [39]. As such, added realism is achieved, as the walking sounds are spatially consistent with where they appear near the feet in real life. Walking sounds are defined by two main characteristics: the speed of walking and the ground surface over which the user walks. Based on the movement velocity, the step-sound duration is compressed to match the stride-phase duration and interrelated airborne phases where the feet do not touch the ground (see next section). Thus the sounds are always synchronized with the ground contact phases affected by the walking speed, starting when the heel hits the surface. We pre-selected a

Table 1. Walking and running phases and actuator / cue characteristics, inspired by literature, refined through iterative design

	Walking 5 km/h		**Slow running** 9 km/h		**Fast running** 13 km/h	
Stride frequency [1], also affecting bobbing frequency	120 strides / min Stride length: 0.7m 500 ms/ stride		128 strides / min Stride length: 1.17 m 470 ms/stride		159 strides / min Stride length: 1.35 m 380 ms/stride	
Foot roll-off: **contact pressure** [11,15,24]	*Vibrotactors*	*Bass-shaker*	*Vibrotactors*	*Bass-shaker*	*Vibrotactors*	*Bass-shaker*
	Base value	Volume 10%	Base value +10%	Volume 25%	Base value +20%	Volume 40%
Foot roll-off: **ground contact** [15]	570 ms ground contact / stride (10% double support period)		330 ms ground contact / stride (30% airborne phase)		220 ms ground contact / stride (40% airborne phase)	

solid (wood) and aggregates (gravel) to be representative of surfaces users normally can distinguish quite well [16].

3.5 Vibrotactile

Inspired by previous systems applying plantar vibration to improve self-motion perception [13, 14, 53] and navigation cues [58], we created a vibration system stimulating different parts of the foot soles. Vibrotactile cues are mainly used to *substitute* for light force cues that humans experience when striking the feet on ground surface, and are closely linked to the footstep sounds introduced in the previous section. As such, we perform sensory substitution within the somatosensory system, translating pressure cues into vibrotactile cues. We mainly focus on simulating the roll-off pressure distribution. The system deploys eight vibrotactors per foot: seven underneath the mid-foot and toes (Precision Microdrives Pico drive 5mm encapsulated vibration motors 304-116, maximum 15,000 RPM), and one underneath the heel (Precision Microdrives 9mm Pico drive 307-103 13,800 RPM) as illustrated in Figures 1 and 2. The vibrotactors are placed so that users with varying foot sizes can still perceive the stimuli. The vibrotactors are glued to a rubber surface, stretched over a solid foam sole, in which small holes are made to hold the vibrotactors. As such, each vibrotactor can vibrate well against the foot sole, instead of receiving a heavy load and dampening when users stand on them. This allows the feedback to be highly similar under different posture conditions, as postures (like standing or sitting) affect pressure on the soles differently. The vibrotactors are arranged to stimulate the key zones underneath the foot (Fig. 1), from heel to mid-foot and toes. The foot is in almost direct contact with the vibrotactors, as the leaning device is used without shoes, which would dampen the feedback unnecessarily. Users wear light socks for hygienic reasons. To strengthen heel impact on the ground surfaces, a bass-shaker (Visaton EX-60) is used. The bass-shaker is mounted on the foot-support plate underneath the heel, stimulating this part of the foot strongest during activation. While vibration cannot be isolated with the current design to solely target the heel, there is a noticeable fall-off of strength towards other parts of the foot, similar to the effect of ground impact during real-world walking. The vibrotactors and bass-shaker are synchronized to simulate the different **gait phases** during natural motion. Gait can be defined by stride phases and length, and differences in plantar pressure and duration (the "ground contact phase") experienced during the different stages of foot roll-off in a gait phase. Different motion speeds affect these characteristics to varying extents, as summarized in Table 1.

To mimic **foot roll-off behavior** during gait [15], we simulate plantar pressure by stimulating different zones of the foot sole over time. Fig. 2 (left) depicts the plantar pressure distribution of a standing user. The pressure distribution of different zones in terms of lower and higher pressure is roughly similar during walking. Yet, which zone receives pressure depends on the stage in the roll-off process. Roll-off can be divided into four phases (Fig. 2, right): namely (A) heel strike, (B) heel strike to foot flat, (C) foot flat to instance, and (D) instance to toe off [15]. Terziman et al. [53] simulated roll-off by using low-frequency loudspeakers mounted underneath the foot, allowing approximated roll-off feedback using contact models. In contrast, we make use of a dense grid of vibrotactors to fully simulate the pressure underneath the foot sole. This is also in contrast to other systems that only stimulate the heel and toes during physical motion [39, 50]. While the system by Velazquez et al. [58] makes use of a denser grid of vibrotactors, these only stimulate the mid-foot, and only provide directional cues for navigation. Notwithstanding, we assume that the roll-off procedure will also provide some motion cues, as the vibration pattern continuously "travels forward" when moving forward.

All vibrotactors are assigned different vibration profiles (Fig. 2) that mimics pressure changes during walking (the zones in Fig. 2, left). These patterns are affected by whether the user is walking, running slowly, or running fast, which defines the ground contact phase and duration. Based on the mentioned gait literature, we define three **walking profiles**. An increase in running speed affects stride parameters differently; either frequency or length [47] or both frequency and length [1] can increase. Within our system, we varied both frequency and length. Each of the three modes has different stride frequencies and lengths that we interpolate between (leaning adjusts speed continuously), while the pressure profile also changes. We based values on the background literature (Table 1), adjusting them accordingly through iterative design. During normal walking, either the left or right foot is always stimulated, with some overlap. With increasing velocity and a different swing phase associated with the motion of the limbs, the airborne phase increases [15], introducing phases in which none of the feet receives (vibrotactile) stimuli. These phases coincide with an increase in stride length, frequency, and ground contact [1], relative to a base PWM value defined by the surface material. Through design iteration and considering maximum PWM values, the base PWM for wood was selected at 156, while it is 130 for gravel. The base value is increased based on the aforementioned pressure profile, depicted in Fig. 2. Additionally, the **ground impact** increases with increasing speed of locomotion, though not equally over all parts of the sole [11, 25]. In particular the pressure under the heel increases more than all other points when the speed increases from walking to running slowly [25]. To adjust for this increase, we linearly increase the vibration with increasing speeds. Running slowly increases the base PWM of the vibrotactors by 10%, running fast by 20%. Thereby, we distribute the pressure simulation of the heel over both the vibrotactor and the bass-shaker mounted underneath the heel. In sync, the audio also gets louder. This is achieved by increasing the base volume; walk-

Table 2 – Procedure and design: overview of sessions of the experiment

	Session 1	Session 2	Session 3	Session 4	Session 5
Interfaces	Leaning, joystick	Leaning	Leaning, joystick	Leaning with/without WIP	Leaning
Cue conditions	[ON]: Audio, Vibrotactors, bass-shaker, head bobbing	[ON or OFF]: audio, vibrotactors, bass-shaker [ON]: head bobbing	[ON]: Either no foot stimuli, audio only or all cues (audio, vibrotactors and bass-shaker) [ON or OFF]: head bobbing	[ON]: Audio, vibrotactors, bass-shaker [OFF]: head-bobbing	[Either all ON or OFF]: Audio, vibrotactors and bass-shaker [ON]: head bobbing
Travel	Follow marker	Follow marker	Follow marker	Free movement	Free movement

ing has 10%, running slowly 25%, and running fast 40%. These values should be seen as relative, as the final loudness was defined at the amplifiers through calibration.

4. EXPERIMENTS

We performed a multipart study to create a better understanding of the potential effects and interaction of different multisensory cues provided by the system.

4.1 Method

Twelve participants (25-48 years old, mean age 29, one female) participated in the user study. Seven participants reported they played games daily or weekly, and the rest less frequently. All users had normal or corrected-to-normal vision. On average, the whole study took about one hour to complete.

4.1.1 Stimuli and Apparatus

For the various sessions of the experiment, we deployed the base system as described in Section 3. Participants were seated during all joystick conditions (cf. Fig. 3) to allow for testing effects of foot haptics on seated users and to match the most common (seated) posture during joystick usage. Participants were also seated when answering questions between studies. Simulated eye height was kept constant across seated and standing conditions to ensure comparable optic flow.

Figure 3. User in standing leaning (left) and seated (middle) pose. Right: Test environment with follow-me object.

4.1.2 Experimental Design and Procedure

The experiment was performed as a within-subjects study and consisted of five sessions as summarized in Table 2. As each session was designed to address different research questions and we did not intend to compare absolute values across sessions, we did not counterbalance the order of sessions between participants but instead used the same order for everyone. Furthermore, the focus of this study was on participants' perception and user experience rather than task performance, so even if there was transfer of learning between the different sessions this should not critically affect observed results. Most sessions compared standing leaning against either seated joystick or standing leaning with added walking-in-place (WIP), deploying various combinations of cues provided through the feedback device. Before the first session, participants received oral instructions, signed informed consent, and answered demographics questions. We also checked for correct foot position on the vibrotactor surface by playing a test sequence over all vibrotactors and asking participants if all vibrotactors could be felt.

During the experiment, participants were asked to rate questions using a 11-Point Likert (0-10) scale, with 10 being in full agreement. After each trial in every session, users rated vection intensity ("I had a strong sensation of self-motion"), their ability to judge speed and travelled distance ("I could judge my velocity/distance travelled well"), the level of involvement (item INV2 from the IPQ questionnaire [48] "I was not aware of my real environment", also as a partial indicator of presence and user engagement), and level of motion sickness ("I feel sick or nauseous", only in Session 3). These questions where displayed within the HMD, rated orally, and noted down by the experimenter. After each session, the HMD was removed and participants answered post-session questions displayed in an online form on a desktop PC screen. Questions encompassed user comfort, the ability to concentrate on the task, perceived navigation performance, ease of learning, fun, the ability to use the interface for longer durations, vection intensity, and usability as detailed in Figure 6. After the first session, participants also rated the level of convincingness of walking on the two ground textures. We allowed participants to take a short break by removing the HMD when motion sickness was an issue. Before and After all the whole study participants reported if they were fresh and relaxed, as well as their level of motion sickness. In light of a previously performed study [31], we also asked if they thought leaning itself had positively affected self-motion.

The main task in all sessions was to navigate over a clearly visible curved path. We created six paths through a natural environment populated with trees at the border of each path (Fig. 3, right). All paths had the same curvature profile, as curves were basically mirrored. The trees were chosen to provide some motion cues in the peripheral visual field. The gravel path had the various non-visual cues adapted accordingly. To ensure similar velocity profiles despite active navigation, participants in Sessions 1-3 had to follow a marker (a clearly visible blue sphere, see Fig. 3 right) that was moving in front of them. In Sessions 4 and 5 participants were asked to move freely along the path and vary their speed dynamically. The marker was moved at different speeds starting with walking, followed by slow/fast or fast/slow running, changing every three seconds. The speeds were chosen to match walking, slow and fast running profiles (Table 1). Trials lasted about 10s. Pilot studies indicated that 10s is sufficient to experience vection and be able to experience and rate the different interfaces and cue combinations.

Before the main experiment, we performed a pilot study with three specialists. In this pilot, we calibrated the head bobbing to avoid motion sickness, and the strength of the vibrotactors and bass-shakers, resulting in the values shown in Table 1. Before starting a given session, the subject went through a vection calibration phase, in which they would lean forward and move through a star field simulation, providing strong vection cues. This served the purpose of providing the user with a sense of strong self-motion, forming the reference for the vection intensity rating requested after each trial. Thereafter, we performed the following five sessions.

Session 1: How well can different cues be associated with different ground surfaces? In this session, participants could practice the navigation interface, following the sphere marker for two trials each for both leaning and joystick interfaces, resulting in four trials. During navigation, we enabled all cues (vibrotactile, bass-shaker, audio, and head-bobbing). In contrast to Sessions 2-5, we separated the path into two zones (wooden planks and gravel) to get a first impression about how well users would rate the convincingness of walking on wood versus gravel.

Session 2: How do different audio-tactile cue combinations affect self-motion perception while leaning? In the second session**,** we focused specifically on the effects of different cues on the subjective rating of self-motion and involvement, employing a 2×2×2 factorial design. Each participant completed 16 trials, consisting of the factorial combination of two audio conditions (audio on, off), two bass-shaker conditions (bass-shaker on, off), and two vibrotactor conditions (vibrotactors on, off), and two repetitions per condition. Repetitions were blocked for all sessions, meaning that all cue conditions were finished before being repeated. Head bobbing was used during all conditions.

Session 3: What is the influence of leaning, head bobbing, and foot haptics when comparing joystick and leaning? In the next session, we focused on assessing the effect of the implemented cues on self-motion perception and involvement by comparing leaning (while standing) to the joystick (seated) interface, employing a 2×2×3 factorial design, using slightly different cue combinations from Session 2. Each participant completed 24 trials, consisting of the factorial combination of two navigation interfaces (leaning, joystick), two visual cue conditions (head bobbing on, off) and three foot-based stimuli conditions (no foot stimulation, audio only, and all audio, vibrotactor, and bass-shaker cues combined), with two repetitions per condition. Joystick and leaning conditions were grouped in counterbalanced order.

Session 4: **Does minimal WIP enhance leaning locomotion?** In this session, we explored the potential of adding minimal WIP while leaning to move forward. To prevent foot position from shifting away from the vibrotactors and to ensure that the vibrotactile stimuli could be continuously applied to the whole foot, we instructed participants to perform a "minimal" WIP where they moved the legs as when walking in place, yet without lifting the heel up from the foot interface. Pilot studies showed that this minimal WIP method only slightly affected leaning compared to normal WIP (where heels/feet may lift off the ground) where leaning could no longer have been used effectively. Participants were asked to freely move over the predefined path by leaning, either with or without added minimal WIP, repeated twice, totaling four trials. We allowed the participants to practice WIP once before starting the actual trials. Participants were encouraged to synchronize their WIP with the foot haptics and head bobbing stimuli.

Session 5: Does foot haptics affect perception during free locomotion? Finally, we specifically looked into the effect of multisensory cues during free exploration. We allowed the participants to freely move over a path, instructing them to vary their speed dynamically. The session only had two conditions, namely the presence or absence of all cues (vibrotactor, bass-shaker, and audio), repeated twice. As such, participants completed four trials. Although exploration time was not limited in Session 4 and 5, participants generally did not take more than 20s.

4.2 Results and Discussion

Generally, participants reported very positively on the overall usability and quality of stimuli, with an average of 7.25 (7.6 when excluding outliers in Session 4) on a 0-10 scale. Post-experiment questions showed average motion sickness scores of 3.92 on a 0-10 scale (SD: 2.64), with four of the 12 participants experiencing high levels (>5). Furthermore, confirming to some extent the results reported in [31], participants reported that leaning overall supported self-motion: eight users reported very positive (scores 8-10), and all but one reported scores of 4 or higher, leading to an average of 6.5 (SD = 2.40).

Session 1: How well can different cues be associated with different ground surfaces? Session 1 focused on allowing the participants to practice with the leaning and gamepad navigation techniques, while also looking into the perceptibility of different ground surfaces. The rated convincingness of walking on wood and gravel was overall fairly high (6.54 on a 0-10 scale) and showed no significant effects of surface type or locomotion mode (standing-leaning versus seated gamepad), although there was a trend towards higher ratings for the standing-leaning condition scores (wood M = 7.08, SD = 1.55, gravel M = 6.42, SD = 1.89) than the seated gamepad conditions (wood M = 6.75, SD = 1.01, gravel M = 5.92, SD = 2.04). Further per-trial analysis revealed no significant effects of surface or locomotion type on self-motion perception, speed and distance estimation, or involvement. In the post-session debriefing, participants stated that compared to the leaning interface, the joystick was easier to learn ($t(11) = 3.26$, $p = 0.008$), and allowed them to more easily concentrate on the task ($t(11) = 2.24$, $p = 0.046$) and more easily navigate and follow the guide object ($t(11) = 3.94$, $p = 0.002$), see Figure 4 (left). Joystick and leaning were rated similarly in terms of comfort (M = 8.21 on a 0-10 scale), enjoyment (8.63), self-motion sensation (8.08), overall usability (8.04) and long-term usage (8.25). This shows the potential and quality of foot haptics and leaning interfaces, even for prolonged usage, as gamepads are the quasi standard for travel in at least game environments.

Session 2: How do different audio-tactile cue combinations affect self-motion perception while leaning? ANOVA results showed increased sensations of self-motion (vection) both for adding audio ($F(1,11) = 16.89$, $p = 0.002$, $\eta^2 = 0.61$) and vibrations ($F(1,11) = 4.96$, $p = 0.048$, $\eta^2 = 0.311$), as depicted in Figure 4. Participants stated that they were better able to judge self-motion velocities with added audio ($F(1,11) = 10.01$, $p = 0.009$, $\eta^2 = 0.48$), vibrations ($F(1,11) = 5.13$, $p = 0.045$, $\eta^2 = 0.32$), and bass-shaker ($F(1,11) = 7.76$, $p = 0.018$, $\eta^2 = 0.41$). Participants further reported that they could judge traveled distances better with added auditory cues, $F(1,11) = 9.47$, $p = 0.011$, $\eta^2 = 0.46$. Finally, participants reported being less aware of the real envi-

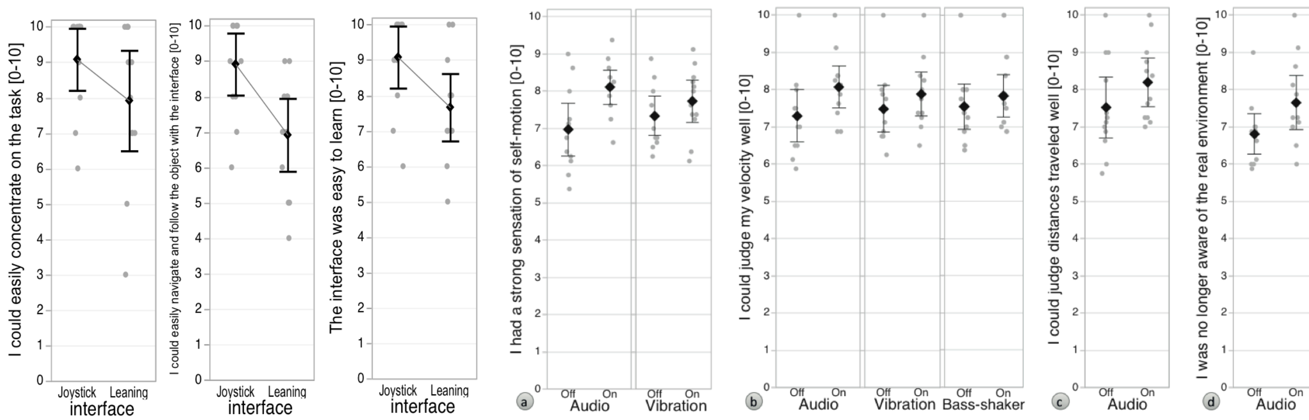

Figure 4: Data plots illustrating significant effects for Session 1 (left three plots) and Session 2. Diamonds and whiskers depict means and 95% confidence intervals; smaller dots depict mean individual participants' data.

ronment and thus more involved and present when auditory cues were added $F(1,11) = 5.87$, $p = 0.034$, $\eta^2 = 0.35$. None of the other main effect or interactions reached significance.

Session 3: What is the influence of leaning, head bobbing and foot haptics when comparing joystick and leaning? In Session 3, which took the longest, post-session ratings showed higher scores for the joystick versus leaning interface for comfort, concentration, ease of navigation, learnability, prolonged usage, and overall usability (see last six plots in Figure 5). While all ratings for the leaning interface were still fairly high (all above 6, most above 7), there is a clear need for improvement to bring them close to the joystick level. The per-trial ratings showed significant effects of the type of foot stimulation on participants' rating on vection ($F(1.15, 12.64) = 16.33$, $p = 0.001$, $\eta^2 = 0.60$), their stated ability to judge both self-motion velocities ($F(1.23, 13.55) = 8.93$, $p = 0.001$, $\eta^2 = 0.45$) and traveled distances ($F(1.13, 12.44) = 7.70$, $p = 0.003$ $\eta^2 = 0.41$) as well as involvement ($F(1.13, 12.44) = 7.98$, $p = 0.002$ $\eta^2 = 0.42$). As illustrated in Figure 5 (top), estimates were highest for the full stimulation using audio, vibrotactor, and bass-shaker cues combined, intermediate for the audio-only condition, and lowest for the condition without any foot or audio stimulation. Furthermore, vection was enhanced when adding head bobbing ($F(1,11) = 8.62$, $p = 0.014$ $\eta^2 = 0.44$) and when replacing the seated joystick interface with a leaning-based interface ($F(1,11) = 7.92$, $p = 0.017$, $\eta^2 = 0.42$). In particular, the significant effect of interface is interesting, as standing leaning improved the sensation of self-motion (M = 7.11, SD = 1.48) compared to the seated joystick usage (M = 6.60, SD = 1.71). This confirms and extends previous findings that found a positive effect of leaning while seated [31]. Finally, involvement ratings were increased when head bobbing was added, $F(1,11) = 5.92$, $p = 0.033$ $\eta^2 = 0.35$. Motion sickness was relatively low overall (M = 2.43, SD = 2.05 on a 0-10 scale) and did not show any significant effects of any of the independent measures.

Session 4: **Does minimal WIP enhance leaning locomotion?** Even though we were successfully able to use WIP during internal testing, all except two participants had major problems with WIP. This is reflected in significantly reduced scores for all measures including user comfort, the ability to concentrate on the task, perceived navigation ability, learnability, enjoyment, long-term-usage, vection, and usability as illustrated in Figure 6. As such, we conclude that combining leaning with the minimal WIP used (moving legs while keeping feet on the floor) is not a promising approach. A more pronounced WIP in which the heels could be lifted might have led to other results, but would have disturbed the delivery of foot haptics to that part of the foot. Due to the low scores, we did not further analyze the per-trial results.

Session 5: Does foot haptics affect perception during free

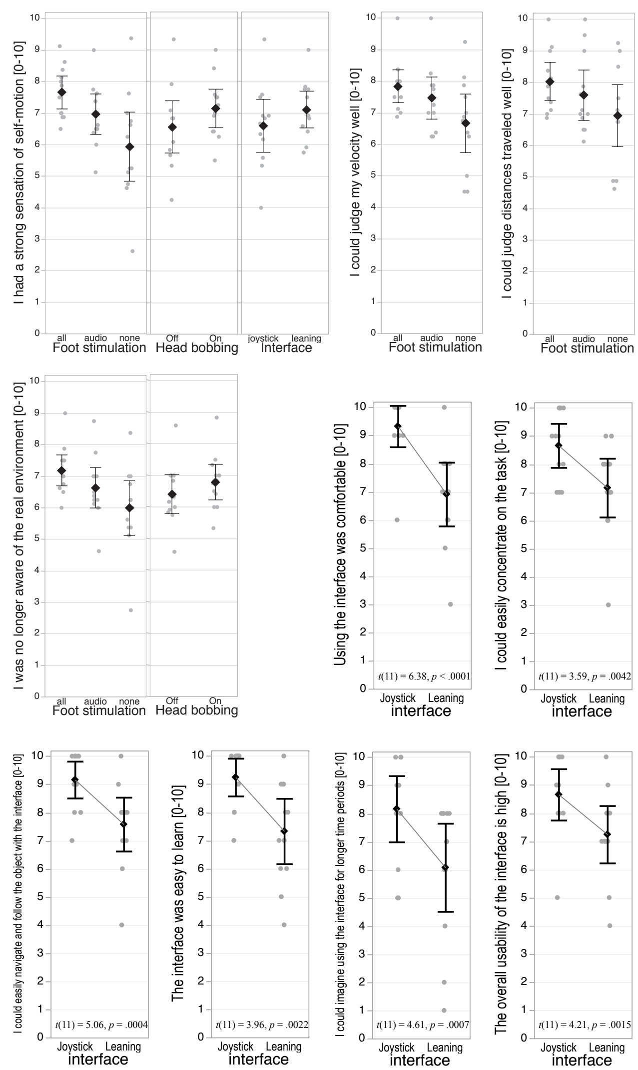

Figure 5: Data plots of significant effects in Session 3.

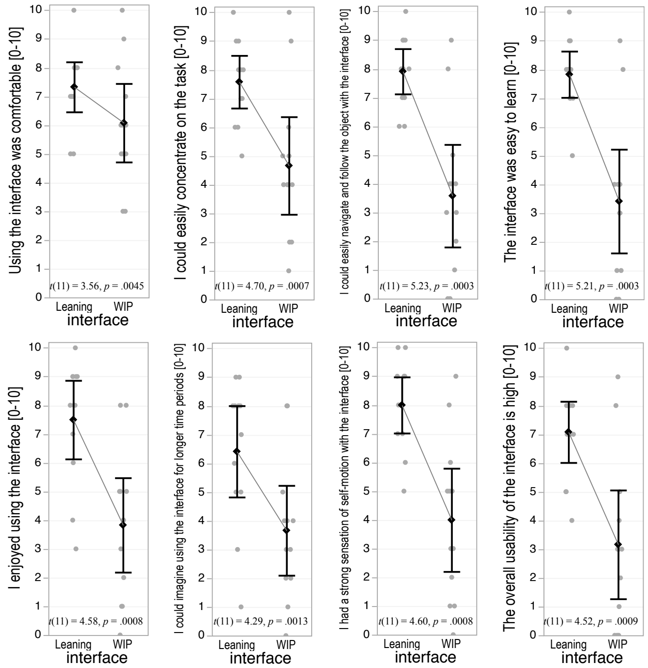

Figure 6: Data plots of significant effects in Session 4.

locomotion? The results were in line with the previous sessions: Adding combined audio, vibrotactor, and bass-shaker cues significantly enhanced all per-trial dependent measures (See Fig. 7). That is, when participants were provided with auditory and vibrotactile cues ("ON") compared to no such cues at all ("OFF") they reported significantly enhanced sensation of self-motion (vection: $t(11) = 3.88$, $p = 0.003$, OFF: M = 6.54, SD = 1.74, ON: M = 8.54, SD = 0.99), reported being better able to judge self-motion velocities ($t(11) = 2.96$, $p = 0.013$, OFF: M = 6.75, SD = 1.36, ON: M = 8.04, SD = 1.27), and travelled distances ($Z = -2.37$, $p = 0.018$, OFF: M = 7.20, SD = 1.53, ON: M = 8.33, SD = 1.29) and reported higher involvement ($Z = -2.67$, $p = 0.007$, OFF: M = 6.29, SD = 0.62, ON: M = 7.88, SD = 1.26). Overall, ratings were slightly higher than in the previous sessions. This is in alignment with participants' reporting in the post-session interview that they could better focus on the effects of the cues when they did not have to follow the moving object.

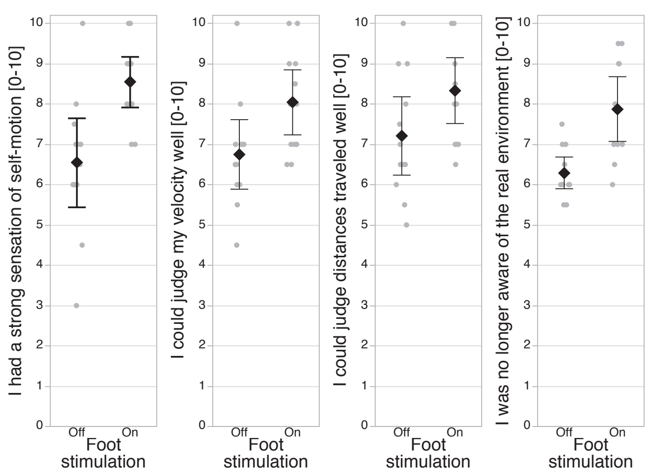

Figure 7: Data plots illustrating significant effects in Session 5.

5. CONCLUSIONS

In this article, we presented a novel system coupling leaning-based travel with foot-haptics mechanisms. Results showed that both self-motion perception (vection) and involvement/presence could be significantly enhanced by adding walking-related vibrotactile cues (via vibrotactile transducers and bass-shakers under participants' feet), auditory cues (footstep sounds), as well as visual cues (simulating bobbing head-motions from walking). Moreover, participants' self-reported ability to judge self-motion velocities and distances traveled was enhanced by adding footstep sounds and vibrotactile cues. Interestingly, all these observed benefits of adding walking-related cues occurred independently of whether participants controlled self-motion via joystick while seated or via leaning while standing. This suggests a more general benefit of adding walking-related cues that might generalize to further locomotion paradigms and interfaces, with many potential application areas.

Together, the outcomes support the assumption that haptic and proprioceptive cues experienced during natural walking can at least to some degree be substituted for by other feedback channels such as vibrotactile feedback, and can be further supported by audio-visual cues. This outcome is in line with previous studies, such as the system and study by Terziman et al. [53], showing similar effects for seated users.

A key finding in this paper is that leaning while standing improved self-motion perception significantly compared to seated users using a joystick, even though participants had extensive experience using joysticks but no experience using leaning-based interfaces. This extends prior work showing that passive (but not active) seated leaning on a manual gaming chair could enhance self-motion sensations [42].

Motion sickness was an issue for some users. While this might at least in part be attributed to the long duration of the experiment inside a head-mounted display, as even with breaks it took around one hour, further research is needed to investigate which factors might have contributed and how motion sickness could be reduced. Because of the marker-following procedure, we could only ask participants to introspectively rate their ability to judge velocities and distanced travelled. Future work is planned to investigate if this self-assessment also translates to improved behavioral measures of distance/velocity and more complex navigation behavior. Pilot data suggests that seated leaning can indeed reduce distance underestimation for VR locomotion. However, the current results suggest that compared to seated joystick usage, standing leaning interfaces, in particular when combined with minimal WIP might require additional cognitive/attentional resources, and would benefit from additional practice and further interface improvements.

In the future, we intend to extend the base system by looking into the potential of including limited haptic feedback to the feet, for example to provide collision feedback. We are also interested in the addition of other motion cues, such as wind and barely perceptible wind sounds that occur when someone is moving through the physical world. Furthermore, we will investigate how we can generalize the system to better include rotations, for example by using torso-directed locomotion [6].

Despite the need for further system improvements, the current results already highlight the potential of sensory substitution and incorporating walking-related auditory, visual, and vibrotactile cues for improving user experience and self-motion perception in applications ranging from virtual reality and gaming to telepresence and architectural walk-throughs.

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