"Human Joystick": Enhancing Self-Motion Perception (Linear Vection) by using Upper Body Leaning for Gaming and Virtual Reality

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ABSTRACT

Locomotion in virtual environments is a crucial area of research, as it enables and supports many of the tasks we perform in gaming and virtual reality systems. Yet, creating intuitive and well performing locomotion interfaces is a challenge, especially when users cannot move around freely. However, body-centered self-motion cues are often preferential because they may improve orientation, spatial judgments and engagement, and reduce motion sickness. While gamepads or joysticks may often be good enough to navigate around, these devices do not support our natural experience of self-motion in our real world. However, it is not well understood how body-centered self-motion cues can be introduced without the user physically moving around. Previous work has shown positive effects on self-motion perception, and in this article we look into the potential of upper-body tilt while users are seated as a cost-effective, easy to establish and well-maintainable method. We report on a study that uses both linear and exponential velocity mapping to investigate the effects of dynamic upper body leaning versus joystick control on self-motion perception (vection), perceived distances traveled, and various usability and user experience measures.

Joystick control was rated higher than leaning control in terms of comfort of posture and muscle relaxation. However, there were no significant differences in terms of overall usability, learnability, overall comfort, preference, precise locomotion, problems using the interface, or motion sickness. Moreover, seated leaning yielded not only significantly enhanced self-motion perception (forward linear vection) compared to joystick locomotion, but also higher levels of engagement, involvement, attentional capture, enjoyment, as well as reduced distance overshooting. These results are promising given that participants were all highly familiar with joystick but not leaning for VR/gaming navigation. They also illustrate the potential of seated leaning-based interfaces, which might also be more suitable for longer-term usage due to reduced fatigue compared to standing interfaces. Our results suggest that replacing traditional interfaces with more embodied minimal-motion-cueing interfaces might be a technically simple and cost-effective way of enhancing user experience and usability in situations ranging from gaming to VR and teleoperation/telepresence. However, further experimentation is needed to extend current findings to more general and complex navigation.

Keywords: Navigation; virtual environments; 3D user interface; body-centric cues; leaning, self-motion perception; vection; embodied interfaces.

1 INTRODUCTION AND MOTIVATION

While common input devices for gaming and VR locomotion like joysticks and gamepads are often quite affordable, reliable, well-tested and allow for fairly precise locomotion, they provide only very limited proprioceptive and none of the vestibular cues that would accompany corresponding real-world travel. This lack of physical motion cues creates a strong cross-modal inconsistency or even conflict, where visual cues and joystick motion indicate self-motion, whereas non-visual cues like the proprioceptive and especially vestibular cues indicate stationarity (Harris, Jenkin, & Zikovitz, 1999; St George & Fitzpatrick, 2011). Such cross-modal inconsistency and reduced embodiment might be related to motion sickness (Keshavarz, Hecht, & Lawson, 2014; Keshavarz, Riecke, Hettinger, & Campos, 2015; Lawson, 2014), as well as reduced spatial orientation (Ruddle, 2013) and presence (Hartmann et al., 2015). Furthermore, having to use one or both hands for locomotion control, as in the case for most vehicle interfaces but not natural walking, reduces our ability to use our hands for important tasks and natural interactions (such as pointing, grasping, interacting with instruments) and communication (such as gesturing while talking) (Beckhaus, Blom, & Haringer, 2005; Kitson, Riecke, & Neustaedter, 2015; LaViola, Feliz, Keefe, & Zeleznik, 2001; Zielasko, Horn, Freitag, Weyers, & Kuhlen, 2016).

Here, we present a study investigating if and how we might be able to use upper body leaning to control simulated self-motions, and if this can be used to enhance self-motion perception. Much like a "human joystick" we track the seated users' torso leaning, which controls the simulated movement in the leaning direction, similar to a joystick. However, unlike a joystick, the "human joystick" locomotion interface metaphor readily provides users with minimal self-generated motion cueing. That is, the user perceives vestibular and proprioceptive "forward" cues for simulated self-motion by forward leaning. In addition, it frees up our hands so they can be used for other tasks like interaction or communication (Beckhaus et al., 2005; Kitson et al., 2015; LaViola et al., 2001; Zielasko et al., 2016).

A recent study showed that the sensation of self-motion in a virtual environment presented via HMD could be enhanced when standing participants leaned in the direction of intended self-motion, as compared to using a joystick to control self-motion (Kruijff et al., 2016). However, most VR and gaming applications are designed for sitting users, and asking users to stand for an extended period of time is often unfeasible and too exhausting (Chester, Rys, & Konz, 2002). So, could we obtain similar leaning

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benefits in sitting users if they simply lean with their upper body, a motion metaphor often referred to as "human joystick" (Harris, Nguyen, Wilson, Jackoski, & Williams, 2014; Khan, Pekelharing, & Desle, 2012; Marchal, Pettre, & Lecuyer, 2011)?

Another recent study compared static versus dynamic forward and backward leaning in seated observers while asking them to use a joystick to travel instructed distances in a simple optic-flow based virtual environment (Kruijff, Riecke, Trepkowski, & Kitson, 2015a). While both static and dynamic leaning affected distance production, neither static nor dynamic leaning affected self-motion perception (vection). However, this might have been due to methodological specifics in that study: simulated self-motion was always controlled by a joystick and not directly by upper body leaning, as that study was intended to independently vary joystick and leaning. The question now is if this decoupling of leaning and motion control could explain the lack of an observed effect of leaning on vection, or if seated leaning indeed does not benefit vection at all.

In the current study, we used a similar distance production task as in (Kruijff et al., 2015a) but directly used participants' upper body leaning as an input to control their locomotion speed in VR, as if their upper body acted as a human joystick. While motion cueing and leaning in the direction of intended travel has been shown to enhance vection for standing users and active leaning (Kruijff et al., 2016) and sitting users and passive motion cueing/leaning (Groen & Bles, 2004; Riecke & Feuereissen, 2012), there is no evidence as to whether active upper body leaning can enhance vection in seated users (Kruijff et al., 2015a). If so, this would not only be theoretically interesting but could also be of considerable interest for designing more affordable, usable, and effective self-motion simulation and navigation paradigms for VR and gaming that do not require costly actuated methods or free-space walking.

The current study was designed to address this gap in the literature by comparing joystick control versus upper-body leaning controlled locomotion in seated participants performing a distance production task.

In this paper, we show that positive benefits can actually be achieved. In due course, we provide contributions by showing the following:

- seated forward leaning yielded significantly enhanced self-motion perception (forward linear vection) compared to joystick locomotion;
- seated leaning resulted in higher levels of engagement, involvement, attentional capture, and enjoyment, but lower ratings of comfort of posture and muscle relaxation;
- leaning reduces distance overshooting.

2 Related work

Navigation and self-motion. Navigation is one of the main tasks we perform in our real world. Not surprisingly, it is also one of the main actions while interacting with virtual environments or games, and includes both physical and psychological aspects. Physical aspects of navigation interfaces have been widely studied and affect usability and user experience (Bowman, Koller, & Hodges, n.d.; Bowman, Kruijff, LaViola, & Poupyrev, 2005; Riecke et al., 2010), as well as motion sickness (Bos, Bles, & Groen, 2008). Moreover, physical locomotion, an important aspect of navigation, can enhance spatial perception and orientation, important for most tasks within a virtual environment or game (Bowman et al., 2005). Navigation interfaces are highly affected by self-motion perception issues, a topic that has found much attention in psychology studies, but also specifically in virtual reality experiments. Thereby, researchers have not only looked into visual but also non-visual cues (DeAngelis & Angelaki, 2012; Harris, Jenkin, & Zikovitz, 2000) and interrelated information storage issues (Berthoz, Israël, Georges-François, Grasso, & Tsuzuku, 1995). Some researchers focused specifically on vestibular cues (Ivanenko, Grasso, Israël, & Berthoz, 1997) and vestibular stimulation (Harris et al., 1999; St George & Fitzpatrick, 2011), auditory cues (Riecke, Väljamäe, & Schulte-Pelkum, 2009; Väljamäe, Larsson, Västfjäll, & Kleiner, 2006) and tactile/biomechanical cues (Rupert & Kolev, 2008). Still, our understanding of self-motion perception remains limited.

Body tilt and posture. Already in 1993, Fairchild and colleagues reported that "Lean-based navigation seems stunningly effective as a navigation paradigm for reasonably complex physical spaces" (p. 49), although they did not present a formal user study (Fairchild, Lee, Loo, Ng, & Serra, 1993). The studies reported in this paper were motivated by several previous experiments that investigated how static or dynamic body tilt might affect perceived self-motion. Prior work showed that passive whole-body tilt can enhance self-motion in a moving-base motion simulator (Groen & Bles, 2004) while leaning with a modified gaming chair could enhance vection for linear and curvilinear forward vection, compared to passive motion without motion cueing or active joystick control (Riecke & Feuereissen, 2012). Researchers have also shown that static body tilt could affect various aspects of our visual and non-visual perception. Bringoux and colleagues showed that estimation of an earth-referenced horizon was affected by their body tilt, while body pitch can affect our perceived self-motion direction (Bourrelly, Vercher, & Bringoux, 2010).

One's posture can also affect self-motion sensations, with upright seated postures resulting in stronger self-motion sensations than lying postures (Guterman, Allison, Palmisano, & Zacher, 2012). Furthermore, Nakamura and Shimojo compared linear vection induced in observers sitting either upright or tilted backward and showed that while vertical vection was reduced for upright posture and increased to the level of horizontal vection as body tilt increased, horizontal vection was not affected by body tilt (Nakamura & Shimojo, 1998). However, they did not study forward linear vection. In addition, more extreme leaning angles are often not sensible for navigation interfaces as they often require complex constructions and can reduce usability.

Kruijff and colleagues reported on two studies that investigated the effects of static and dynamic upper body leaning on perceived distances traveled and self-motion perception while seated. They showed that static leaning (i.e., keeping a constant forward torso inclination) had a positive effect on self-motion (but not vection), while dynamic torso leaning showed mixed results (Kruijff, Riecke, Trepkowski, & Kitson, 2015b).

On the other hand, in motion simulators, dynamically tilting users or the whole motion simulator during simulated accelerations is standard practice and has been shown to improve the realism of linear self-motion as well as embodied illusions of self-motion (linear vection) (Berger, Schulte-Pelkum, & Bülthoff, 2010; Groen & Bles, 2004). However, dynamically tilting users is often expensive and requires considerable space and technical expertise. Moreover, the optimum level of dynamic body tilt depends on a number of factors including the type, velocity, and acceleration of the visual stimulus and the amount of physical translation, which can make it challenging to optimize a system (Groen & Bles, 2004; Stratulat, Roussarie, Vercher, & Bourdin, 2011). Finally, some researchers have started to investigate the usefulness of leaning interfaces on applications requiring hands-free interaction.

Zielasko and colleagues compared five hands-free seated locomotion interfaces (Zielasko et al., 2016). Body leaning and accelerator pedal metaphor-based system outperformed a walking-in-place and shake-your-head metaphor, although there was not comparison to a standard joystick condition.

Embodied locomotion interfaces. As an alternative for expensive and technically complex installations, researchers have looked into low-cost solutions that can still support the human body to be actively involved in navigation. For example, Beckhaus and Riecke removed external actuation and instead let users actuate, thus actively providing their own motion cueing while seated (Beckhaus et al., 2005; Kitson, Hashemian, Stepanova, Kruijff, & Riecke, 2017; Kitson et al., 2015; Riecke, 2006; Riecke & Feuereissen, 2012). Walking-in-place interfaces (Templeman, Denbrook, & Sibert, 1999; Usoh et al., 1999) form another alternative where standing users mimic natural walking motions. Our study relates to various physical leaning-based interfaces for navigation in virtual environments, including the usage of the Wii balance board (de Haan, Griffith, & Post, 2008; Valkov, Steinicke, Bruder, & Hinrichs, 2010; Wang & Lindeman, 2012) and other kinds of leaning interfaces (Guy, Punpongsanon, Iwai, Sato, & Boubekeur, 2015; Marchal et al., 2011; Wang & Lindeman, 2011). The results of our study can inform the design of this type of interface, which we will discuss later in this article.

Beyond state of the art. To the best of our knowledge, there is no prior evidence that dynamic upper body leaning can enhance self-motion perception in seated observers. (Kruijff et al., 2015b) showed that statically leaning forward while seated can increase the speed of visually-simulated forward self-motion, but showed no effect on vection. In a follow-up study, the same participants were asked to dynamically lean while using a joystick to control VR locomotion. Results showed no significant vection benefit of leaning, although a pilot study where participants experimented with torso leaning suggested possible benefit on vection and realism. The authors pointed out methodological limitations that might have contributed to the lack of a clear effect of dynamic leaning, including that participants' locomotion through the VE was only controlled by a joystick and not directly affected by the users' leaning.

Furthermore, apart from allowing for hands-free locomotion, leaning-based interfaces also provide at least some vestibular motion cueing and full-body involvement, which can provide more compelling sensations of self-motion (vection) (Riecke, 2011; Riecke & Schulte-Pelkum, 2013). However, few of the above studies investigating leaning-based interfaces directly assessed vection. Recent evidence showed, though, that standing leaning ("human joystick") tracked by a Wii balance board enhances self-motion perception compared to joystick locomotion (Kruijff et al., 2016). Vection was further enhanced by adding walking-related cues including visually-simulated head bobbing, footstep sounds, and vibrotactile cues mimicking pressure changes on the users' feet.

The current study was designed to investigate if this leaning-benefit for standing leaning would extend to seated observers leaning their upper body, because sitting is known to be more comfortable and less fatiguing, and thus more suitable for extended usage in many applications (Chester et al., 2002). We addressed previous methodological limitations by providing a more extensive vection explanation and demonstration phase, and directly controlling simulated self-motions through upper body leaning using a backpack-mounted tilt sensor. We also varied mapping methods, studying both linear and exponential mapping and different leaning angles, as a previous study by Kruijff and colleagues indicated linear mapping might have affected results (Kruijff et al., 2015b). For example, exponential velocity mapping can potentially be beneficial for short-distance travel, as slow velocities can be more easily controlled than using a linear mapping algorithm matching a full velocity range when the angle of leaning forward is (biomechanically) limited. Finally, we included a more extensive set of questions about different aspects of user experience and usability.

3 Hypotheses and Research Questions

In this section, we illustrate the motivation for the study and the research questions that informed the study design.

RQ1: How does leaning versus joystick locomotion control affect self-motion perception?

(a) We hypothesized dynamic upper body leaning to enhance vection because leaning provides minimal motion cueing and, in particular, vestibular and proprioceptive self-motion cues that are known to enhance vection (Berger et al., 2010; Kruijff et al., 2016; Nakamura & Shimojo, 1998; Riecke, 2006; Riecke & Feuereissen, 2012; Schulte-Pelkum, 2007), but have not been shown effective for seated leaning interfaces.

(b) We hypothesized higher learnability, ease of use, and usability for the joystick interface, as we expected participants to be highly familiar with joystick but not leaning interfaces. Furthermore, we predicted joystick control to result in higher ratings of overall comfort, posture, muscle relaxation, long-term usability, and precise locomotion control because the leaning might become fatiguing over time (Wang & Lindeman, 2011). Conversely, we hypothesized leaning to not only yield enhanced vection but also higher engagement, involvement, and enjoyment due to the more embodied locomotion control. These predictions were in part motivated by Marchal and colleague's finding that their Joyman whole-body leaning interface yielded higher ratings of fun, presence, and rotation realism than joystick control.

(c) Finally, based on prior findings (Kruijff et al., 2015b) we predicted that leaning forward might enhance velocity perception when compared to the joystick condition. Hence we predict leaning to reduce distance overshooting and reduce overall travel velocities.

RQ2: How does linear versus exponential velocity mapping affect vection and usability?

Most velocity control interfaces like joysticks use a linear mapping between deflection and resulting simulated velocity. This linear mapping can make it challenging to both finely control small movements and reach high enough velocities to cover large distances quickly. To this end, we compared a linear velocity mapping with an exponential mapping that was hypothesized to allow for smooth control over both small movements and large distances ($velocity \sim deflection^{1.58}$). We did not use a dead-zone for the mapping. On the one hand, we predicted enhanced vection for the exponential versus linear velocity control for the torso leaning interfaces, as it yields stronger motion cueing for small velocities. On the other hand, we predicted higher learnability and usability for linear transfer function as it is more "standard" and might be easier to learn and predict how deflection affects self-motion.

RQ3: How does instructed distance affect self-motion perception?

To investigate how the other factors might be qualified by the travel speed and distance, participants were instructed to travel distances of one of 2m, 10m, or 50m. We predicted that the longer to-be-travelled distances should yield higher vection intensity ratings, as vection does not occur immediately but only after an onset latency and then takes time to build up until it is fully saturated (Riecke & Schulte-Pelkum, 2013).

4 METHODS

4.1 Participants

Sixteen participants (all males) completed the experiment, all being students. The experiment was run in accordance with the declaration of Helsinki and participants signed informed consent.

4.2 Stimuli and apparatus

Visual stimuli were presented stereoscopically thorough a low-cost head-mounted display (HMD), the Oculus RIFT DK2 providing a per-eye resolution of 960×1080 pixel per eye and a binocular FOV of about 100° diagonally. Stimuli were generated in real time at 75Hz using a test environment developed in the game engine Unity3D$_{tm}$. The head tracking embedded in the HMD was enabled, and participants were instructed to keep the cross-hair (and thus their head) levelled throughout the trial (see Figure 1).

As depicted in Figure 1, the VE was designed to be simplistic and consisted of a grass-like textured ground plane and several layers of white blobs, designed to provide strong optic flow during simulated self-motion but no absolute size cues, distance cues, or landmarks that could have biased results. No auditory or other cues were provided in the VE.

Throughout the experiment, participants were seated at a normal chair and used either a joystick (Sony Dualshock® 3) or upper body leaning to control forward linear self-motion through the virtual environment (VE). Motion was limited to forward-only throughout the study. Within the study, we deployed both linear and exponential mapping of the leaning degree to simulated forward motion (velocity). The exponential mapping was a simple exponential function, with an exponent of 1.58. Speed increased until 30 degrees leaning forward, while for more than 30 degrees, speed was held constant. The exponential mapping is characterized by a slow increase of velocity while leaning slightly forward, allowing for more precise motion control of lower velocity than linear mapping. At higher degrees of leaning, the difference between linear and exponential mapping decreases. A pilot study suggested that forward leaning becomes increasingly uncomfortable for leaning angles of more than 30 degrees. Participants wore a light custom-built backpack frame (cf. Figure 1, left) equipped with a high-resolution inclination sensor (PhidgetSpatial 1042). This sensor was used to measure their torso leaning angle that was used to control simulated self-motions in the leaning conditions.

4.3 Experimental design

The experiment was conducted as a within-subject study, employing a 2×2×3 factorial design with 3 repetitions per condition, leading to a total of 36 trials per participant. Trials were characterized by the factors interface (joystick versus leaning), velocity mapping (exponential versus linear) and instructed distance to-be-traveled (2 versus 10 versus 50 meters).

The four possible combinations of interface (joystick versus leaning) and velocity mapping (exponential versus linear) were run in separate blocks of 9 trials in balanced order across participants. Half of the participants completed all joystick trials first followed by leaning trials, whereas the order of the interfaces was reversed for the other half of the participants. For each interface, half of the participants completed the linear mapping first and the other half completed the exponential mapping first. Thus each participant completed four blocks with the four different combinations of interfaces and velocity mapping. There were three repetitions of each of the three distances instructed within a block. Distances instructed were then randomized in triplets to deal with potential learning or carry-over effects.

4.4 Procedure

After receiving written and oral instructions and signing an informed consent form, participants were asked about demographics and computer gaming experience, and rated their level of mental and bodily fitness (on a 0-10 Likert scale) to measure possible motion sickness effects of the experiment. Participants were then seated and donned the backpack and HMD, which were both kept on throughout the experiment. Compared to most studies using leaning-based interfaces, we decided to use sitting as compared to standing position or high stools to reduce fatigue and enhance comfort (Chester et al., 2002).

Before the actual experiment participants were provided with oral vection instructions to familiarize them with the sensation of self-motion and how to rate it. The vection experience was anchored in everyday experience as the instructions contained examples of where participants might have experienced a vection illusion before, for example the train illusion.

At the beginning of each of the four experimental blocks, participants completed a 1-minute practice trial to try out the given interface (joystick or leaning) and to get an impression of the velocity mapping (linear or exponential). Furthermore, participants were asked to travel at full forward velocity for an extended period of time to provide them with a strong vection experience they can use as a reference in the later experimental conditions. Thereafter, we verified again if the principles behind vection rating were clearly understood. At the beginning of each trial, the to-be-traveled distance was displayed via a pop-up message in the HMD. Participants were also reminded to look and face forwards while keeping their eyes open, and to fixate the crosshair that was displayed centrally on the screen as indicated in Figure 1.

Depending on the block, participants used either joystick or upper body leaning to move the instructed distance forwards through the environment. After each trial, participants rated perceived vection intensity on a scale from 0 to 100% using a visual analog scale displayed in the HMD. Participants were instructed that a rating of “0%” indicated a completely stationary feeling the

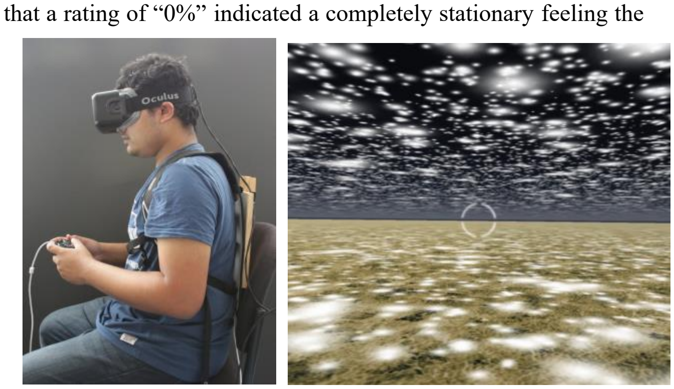

Figure 1: Left: Participants wore a HMD (Oculus Rift DK2) and custom-made backpack carrying the inclination sensor (PhidgetSpatial 1042). Right: Visual stimuli of the virtual environment designed to provide strong optic flow but no landmarks.

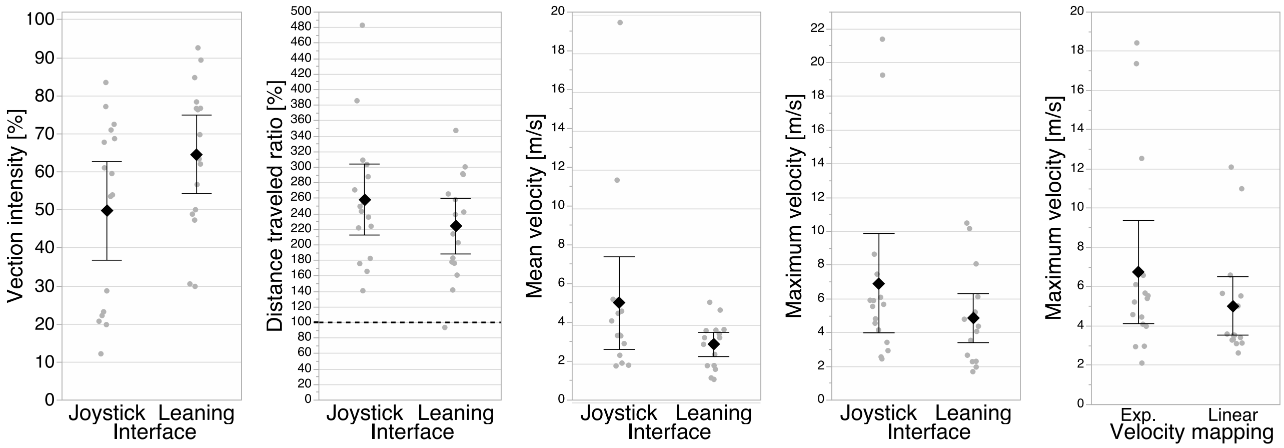

Figure 2: Plots of significant main effects of interface (left 4 plots) and velocity mapping (right plot). Solid diamonds indicate arithmetic means, error bars indicate 95% confidence intervals, and light gray dots indicate individual participants' data. Note: Maximum velocity reached only marginal significance (p = .067)

whole time (i.e., pure object motion with no self-motion) whereas "100%" indicated a feeling of compelling sensation of self-motion which was almost indistinguishable from actual self-motion, and values in between according to the respective intensity of the experienced self-motion.

Participants were instructed to focus primarily on their sensation of self-motion while also producing the instructed distances. Participants were advised not to aim for finishing as fast as possible but to move as naturally as possible, in reflection of generating a natural feeling of self-motion.

We used introspective vection measures as customary the vection research, as the experience of self-motion is by definition introspective, and there are not yet any reliable alternative physiological or behavioral indicators of vection. We refrained from asking participants to judge vection onset latencies during the trials because they were already busy controlling their self-motion with the joystick or leaning, and we wanted to avoid a dual-task paradigm with potential unknown consequences.

After the experiment participants rated each of the four combinations of interface (joystick vs. leaning) and velocity mapping (linear vs. exponential) on a 0-10 Likert-like scale in terms of user comfort, ergonomics and overall experience of self-motion as detailed in subsection 5.2.

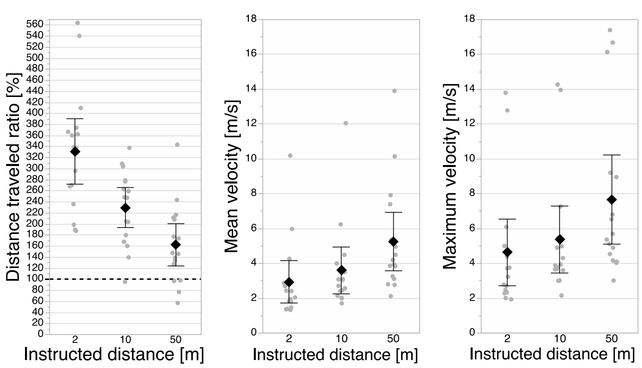

Figure 3: Plots of significant main effects of instructed distance. Solid diamonds indicate means, error bars indicate 95% confidence intervals, and light gray dots indicate individual participants' data.

5 Results

5.1 Experiment data

Data were analyzed using repeated-measures ANOVAs for each of the dependent measures. Within-subject independent variables were interface {joystick, leaning interface}, velocity mapping {exponential, linear}, instructed distance to be traveled {2m, 10m, 50m}, and repetition {1, 2, 3}. Greenhouse-Geisser correction was applied whenever the assumption of sphericity was violated. Only significant or marginally significant main effects and interactions are reported in the text, and plotted in Figure 2 - Figure 4.

5.1.1 Effects of interface

Vection intensity ratings were higher for the leaning interface (M = 64.6, SD = 21.9) compared to the joystick (M = 49.7, SD = 26.4, $F(1,15)$ = 10.406, p = .006, η_2 = .410), see also Figure 2 left. The effect size of η_2 = .410 indicates that 41% of the variability can be attributed to the factor interface, which is considered a large effect size (Cohen, 1988). The type of interface showed also a significant main effect on the ratio between actually travelled and instructed distance, with the joystick showing a larger distance overshoot (M = 258.4, SD = 145.1) than the leaning interface (M = 224.2, SD = 121.0, $F(1,15)$ = 5.783, p = .030, η_2 = .278). The joystick interface also yielded faster average travel velocities (M = 5.0, SD = 5.0) than the leaning interface (M = 2.9, SD = 2.0, $F(1,15)$ = 4.536, p = .050, η_2 = .232), see Figure 2 middle. The maximum velocity showed a similar trend, but only reached marginal significance, $F(1,15)$ = 3.890, p = .067, η_2 = .206.

5.1.2 Effects of velocity mapping

The velocity mapping showed only a significant main effect on the maximum travel velocity, with the exponential mapping yielding faster maximum velocities (M = 6.8, SD = 7.0) than the linear mapping (M = 5.0, SD = 3.5, $F(1,15)$ = 7.790, p = .014, η_2 = .342, see Figure 2 right).

5.1.3 Effects of distance

Instructed distances showed a significant main effect on the ratio between produced and instructed distances $F(2,30)$ = 34.476, p = <.001, η_2 = .697). As illustrated in Figure 3 (left), smaller instructed

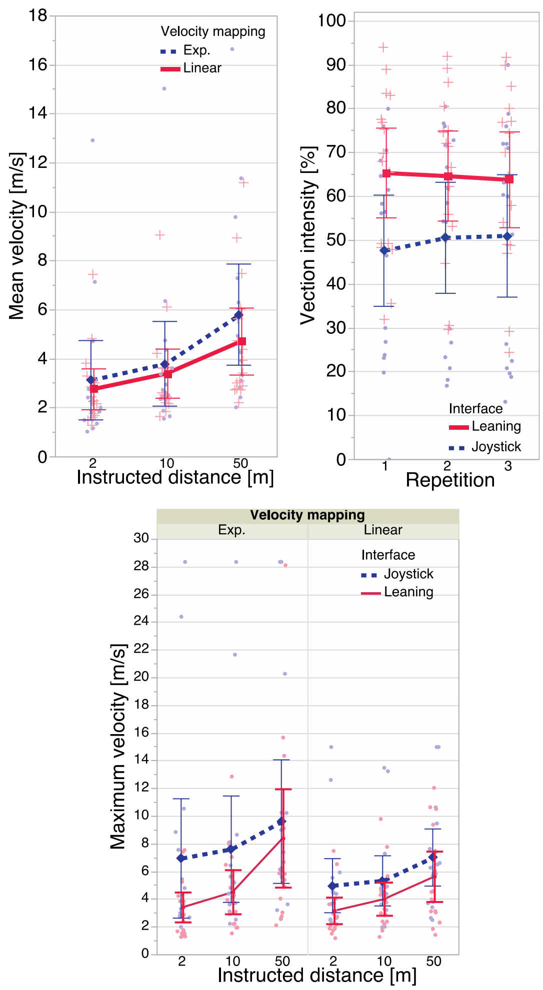

Figure 4: Plots illustrating significant interactions. Solid diamonds indicate means, error bars indicate 95% confidence intervals, light dots and plus signs indicate individual participants' data.

distance lead to larger distance overshooting, suggesting a more pronounced velocity underestimation. Both average and maximum travel velocity showed significant main effects of instructed distance, $F(2,30) = 34.024$, $p < .0001$, $\eta^2 = .694$ and $F(2,30) = 14.804$, $p = .0011$, $\eta^2 = .497$, respectively. As depicted in Figure 3, maximum and average travel velocities steadily increased for increasing instructed distances.

Unexpectedly, larger instructed distances did not result in higher vection intensity ratings ($F(2,30) = 1.725$, $p = .195$, $\eta^2 = .103$, even though larger to-be-traveled distances lead to longer optic flow exposure which one might expect to enhance vection. Directly correlating vection intensities with absolute distances traveled (instead of instructed distances) on a single trial basis showed a similar lack of any significant effect, $r(547) = .0083$, $p = .843$, $r^2 < .0001$.

5.1.4 Interactions

The ANOVA indicated three significant interactions that qualify the observed main effects. Mean travel velocity showed a significant 2-way interaction between velocity mapping and instructed distance, $F(2,30) = 3.979$, $p = .029$, $\eta^2 = .210$). As indicated in Figure 4 (top left), the exponential velocity mapping resulted in a more pronounced increase in mean travel velocities for increasing to-be-travelled distances than the linear velocity mapping. Planned contrasts indicate that the exponential velocity mapping led to higher mean velocities than the linear velocity mapping for the largest instructed distance of 50m, $F(1, 20.7) = 6.635$, $p = .0177$, while mean velocities did not differ significantly for instructed distances of 10m ($F(1, 20.7) = .888$, $p = .357$) or 2m ($F(1, 20.7) = .758$, $p = 394$).

Vection intensities showed a significant 2-way interaction between interface and repetition $F(2,30) = 3.940$, $p = .030$, $\eta^2 = .208$). As indicated in Figure 4 (top right), there was a trend towards increased vection intensities for later trials (repetition 2 and 3) for the joystick but not the leaning interface. Stated differently, the vection benefit of the leaning over the joystick interface was slightly reduced for later trials. Nevertheless, planned contrasts show that leaning still showed significantly higher vection intensity ratings than the joystick for repetition 1, $F(1, 16.58) = 14.055$, $p = .0017$, repetition 2, $F(1, 16.58) = 8.879$, $p = .0086$, and repetition 3, $F(1, 16.58) = 7.325$, $p = .015$.

Finally, there was a significant 3-way interaction between interface, velocity mapping, and distance, $F(2,30) = 3.805$, $p = .043$, $\eta^2 = .202$. While 3-way interactions should be interpreted with caution, a careful inspection of the plotted data in Figure 4 (bottom), suggests that the increase in maximum velocity for increasing to-be-traveled distances was most pronounced for the exponential velocity mapping and the leaning interface. Note that the effect sizes η^2 of all significant main effects and interactions are considered large (Cohen, 1988).

5.2 Post-experimental questionnaire data

The post-experimental questionnaire data were analyzed using 2 × 2 repeated-measures ANOVAs with the factors interface {joystick, leaning} and velocity mapping {exponential, linear}. Significant effects are plotted in Figure 5, marginally significant ($p < .1$) effects and the remaining data are plotted in Figure 6.

5.2.1 Effects of interface

We will first report the measures where the joystick interface outperformed the leaning interface (top three plots in Figure 5), followed by the five measures that showed a benefit of the leaning interface over the joystick. Participants reported that their muscles were more relaxed for the joystick (M = 7.7, SD = 2.1) than the leaning interface (M = 6.1, SD = 2.4, $F(1,15) = 4.709$, $p = .046$, $\eta_2 = .239$). The effect size η_2 indicates that 23.9% of the variability in the data can be attributed to the factor interface. Similarly, the comfort of posture was rated higher for the joystick (M = 8.1, SD = 1.7) than the leaning interface (M = 6.4, SD = 2.1, $F(1,15) = 9.098$, $p = .009$, $\eta_2 = .378$). There was also a marginal trend that participant could imagine using the interface for longer periods of time for the joystick (M = 7.3, SD = 2.9) than leaning (M = 5.9, SD = 2.9, $F(1,15) = 3.235$, $p = .092$, $\eta_2 = .177$).

On the other hand, participants' perception of being no longer aware of their real environment was rater as higher for the leaning interface (M = 5.1, SD = 3.3) than the joystick (M = 4.0, SD = 3.4, $F(1,15) = 7.049$, $p = .018$, $\eta_2 = .320$). This questions measures participant's involvement in the virtual scene (item INV2 from the IPQ questionnaire (Schubert, Friedmann, & Regenbrecht, 2001), and is also a partial indicator of presence and user engagement, suggesting that participants were more involved when using the leaning interface over the joystick. Similarly, their attention was more captured by the virtual environment when using the leaning interface (M = 5.8, SD = 2.6) over the joystick (M = 4.3, SD = 2.9, $F(1,15) = 15.123$, $p = .0015$, $\eta_2 = .502$). Participants also reported a stronger sensation of self-motion (vection) when using the leaning interface (M = 7.1, SD = 2.9) compared to the joystick (M = 4.8, SD = 3.0, $F(1,15) = 16.875$, $p = .0009$, $\eta_2 = .529$). Enjoyment was also rated higher for the leaning interface (M = 7.9, SD = 1.7) as compared to the joystick (M = 6.1, SD = 2.7, $F(1,15) = 7.185$, $p = .017$, $\eta_2 = .324$). There was a similar effect of increased engagement when using the leaning interface (M = 7.6, SD = 2.2) as compared to the joystick (M = 5.9, SD = 2.8, $F(1,15) = 4.738$, $p = .046$, $\eta_2 = .240$).

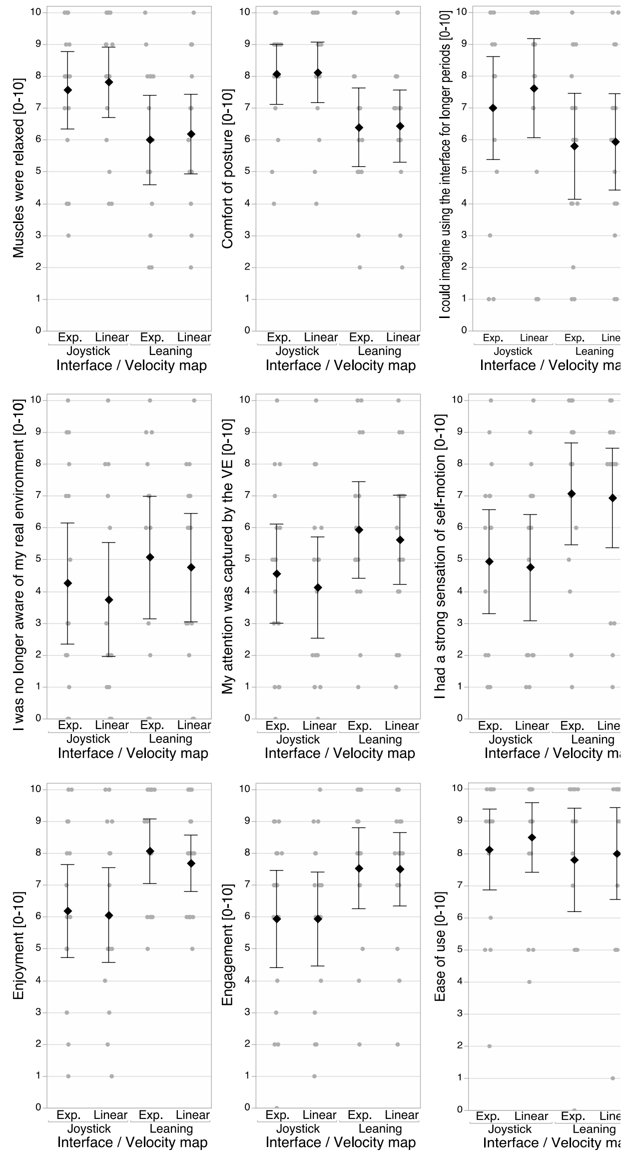

Figure 5: Plots of significant and marginally significant main effects of interface (first eight plots) and velocity mapping (last plot). Solid diamonds indicate means, error bars indicate 95% confidence intervals, and light gray dots indicate individual participants' data.

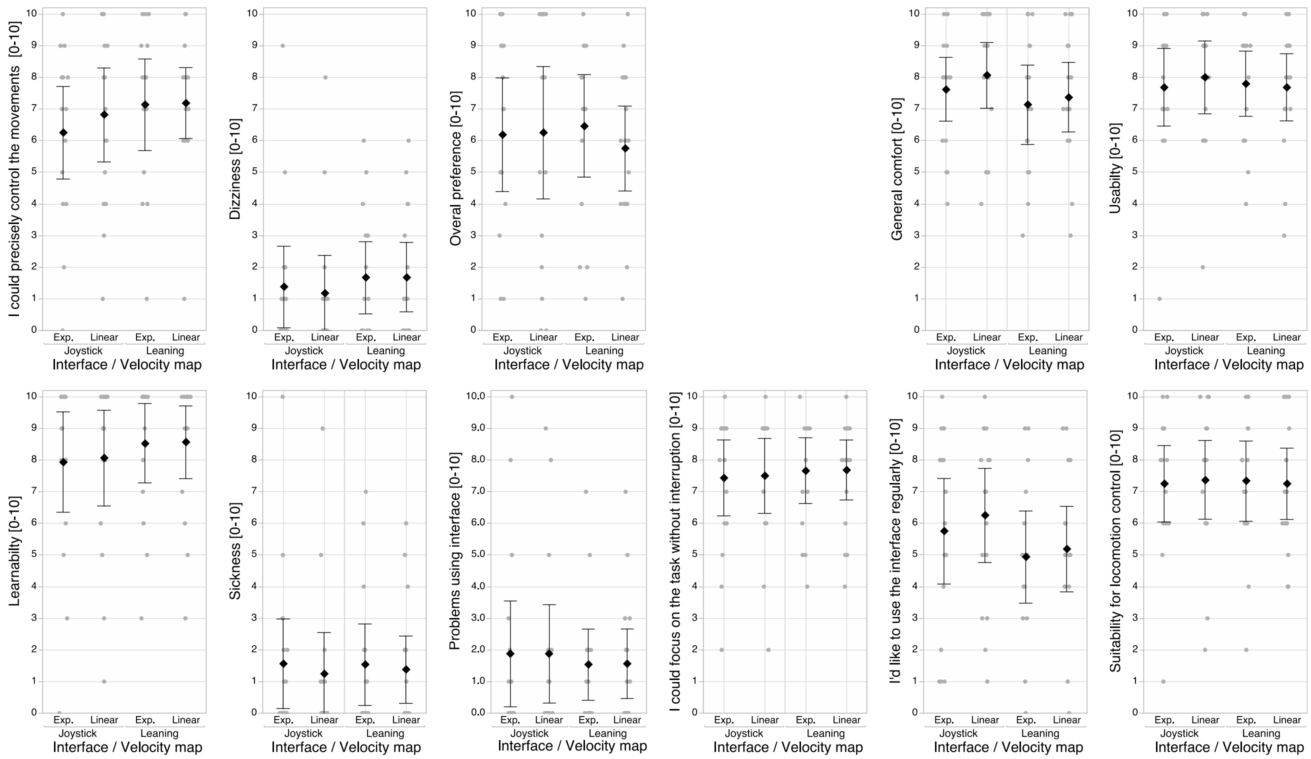

Figure 6: Plots of marginally significant interactions between interface and velocity mapping (first three plots). Remaining plots show non-significant results illustrating the overall high comfort, usability, learnability, and suitability of both the joystick and leaning interface. Solid diamonds indicate means, error bars indicate 95% confidence intervals, and light gray dots indicate individual participants' data.

5.2.2 Effects of velocity mapping

Velocity mapping showed a significant main effect only on the dependent measure ease of use (cf. bottom right plot in Figure 5), with the linear velocity mapping showing slightly higher ease of use ratings (M = 8.3, SD = 2.4) than the exponential mapping (M = 8.0, SD = 2.6, $F(1,15) = 4.623$, $p = .048$, $\eta^2 = .236$).

5.2.3 Interactions between interface and velocity mapping

There were no significant interactions. There were, however several marginally significant interactions ($0.05 < p < .1$) for ratings of how precisely participants could control the movements ($F(1,15) = 3.378$, $p = .086$, $\eta^2 = .184$), dizziness ($F(1,15) = 4.310$, $p = .055$, $\eta^2 = .223$), and overall preference ($F(1,15) = 3.429$, $p = .084$, $\eta^2 =$ 186). As illustrated in Figure 5, these trends suggest a slightly more precise joystick control and reduced dizziness for the linear over the exponential mapping for the joystick. For the leaning interface, the interaction suggests a slight preference for the exponential over the linear velocity mapping.

5.2.4 Overall ratings for non-significant results

To provide a complete picture of the results of the post-experimental questionnaire and to provide a sense of the absolute level of the different ratings, Figure 6 depicts the results of the remaining questionnaire items that showed no significant main effects or interactions.

Overall comfort was rated as fairly high (mean = 7.55 on a 0-10 scale, standard deviation = 2.01). Overall usability (M = 7.81, SD = 2.03) and learnability (M = 8.28, SD = 2.52) was rated similarly high. Sickness was rated fairly low (M = 1.41, SD = 2.30), and as illustrated in Figure 6 only two participants (for the joystick) and 3 (for the leaning interface) reported sickness levels larger than 2. Participants overall reported few problems using the interfaces (M = 1.69, SD = 2.53), although there were a few responses of 5 and higher that indicate room for improvement, even for the joystick interface. Participants overall stated that they could well focus on the task without interruption (M = 7.59, SD = 1.99). Participants showed mixed responses, though, when ask if they would like to use the interface regularly (M = 5.59, SD = 2.78). Nevertheless, they rated the suitability of all interfaces relatively high (M = 7.33, SD = 2.19). As shown in Figure 5, overall ease of use was rated as high (M = 8.14, SD = 2.46) irrespective of using the joystick or leaning.

6 Discussion

RQ1 (a): Forward leaning enhances self-motion perception. Per-trial ratings showed that controlling simulated forward motions in VR with upper-body leaning instead of a standard joystick significantly enhanced user's sensation of self-motion (forward linear vection), even though our participants had extensive experience with using joysticks but not leaning-based interfaces. This vection-enhancing effect of leaning in the direction of intended travel was confirmed by post-experimental vection ratings. To the best of our knowledge, this is the first study showing a clear vection benefit when seated users lean to control self-motion. This complements and extends recent findings that vection can also be enhanced in *standing* users through leaning (Kruijff et al., 2016) or in *seated* users when using self-powered motion cueing in a manual force-feedback wheelchair (Riecke, 2006) or whole-body passive (but not active) leaning in a modified gaming chair (Riecke & Feuereissen, 2012). Note that we did not include corroborative vection measures like vection onset latency or vection duration to avoid introducing a secondary task while controlling self-motion. Future studies are needed and planned to investigate if leaning not only increases vection intensity but also leads to earlier vection onset and longer vection durations.

RQ1 (b): Leaning is less comfortable but more engaging and enjoyable than joystick control.

As predicted, the joystick was rated higher in terms of comfort of posture and muscle relaxation, and showed a trend towards better long-term usability due to potential fatigue effects of the leaning interface for longer durations, an issue previously noted by Wang et al [46]. However, we did not observe the predicted higher overall comfort and more precise locomotion control for the joystick. Moreover, although all participants were highly familiar with joystick but not leaning interfaces, this did not lead to the hypothesized reduction in learnability, ease of use, and usability for the leaning interface. Given the high familiarity of the joystick but not leaning interface, these results underline the potential of leaning-based interfaces, especially when users are seated, which is known to more comfortable and less fatiguing than standing or using a sit/stand stool (Chester et al., 2002). Indeed, these results are much more favourable for leaning-based interfaces than the result by Kruijff and colleagues (Kruijff et al., 2016) who used *standing* leaning to control self-motion. Whereas (Kruijff et al., 2016) showed a significant reduction in overall comfort, ease of concentrating on task, navigation, learnability, and overall usability for standing leaning as compared to joystick control, we observed none of these detrimental effects for *seated* leaning in the current study. Future studies are planned to directly compare seated versus standing leaning interfaces using otherwise identical procedures to further investigate this. As predicted, seated leaning yielded not only enhanced vection but also higher engagement, involvement, and enjoyment, which might be related to the more embodied locomotion control. These findings corroborate and extend Marchal et al.'s finding that their Joyman whole-body leaning interface yielded higher ratings of fun, presence, and rotation realism than joystick control (Marchal et al., 2011).

RQ1 (c): Leaning reduced distance overshooting.

Leaning instead of joystick control also improved behavioral measures by reducing distance overshooting, which might also be related to the enhanced physical motion cues and self-motion sensation when leaning. Furthermore, dynamic leaning reduced travel speeds, and users were less likely to use maximum travel speed as compared to using the joystick, confirming earlier results using static leaning (Kruijff et al., 2015b). Although further experimentation is needed, these findings suggest that using a more embodied interface might be a way towards more veridical perception in simulated environments.

RQ2: How does linear versus exponential velocity mapping affect vection and usability?

Using exponential versus linear velocity mapping did not improve vection for the leaning interface, even though we had hypothesized that the exponential mapping might yield stronger motion cueing for small velocities. While we predicted improved ratings of learnability and usability for the linear velocity mapping as it is more common and more easily predictable, we only observed a small benefit in terms of ease of use, but no significant benefits in terms of learnability or overall usability or any other of the usability and user experience measures used. This suggests that velocity mapping in VR and gaming applications can be adjusted within reasonable limits to fit application-specific needs without critically impacting usability or user experience. Still, these results should be seen in context of forward motion: other types of motion like leaning sideways to travel through a curve may yield different results.

RQ3: Larger travelled distances did not enhance vection.

We predicted that longer distances travelled should yield higher vection intensity ratings, as vection does not occur immediately but only after an onset latency and then takes time to build up until saturation (Riecke & Schulte-Pelkum, 2013). Unexpectedly, we observed no such effect. This might be caused by a very early vection onset and rapid vection saturation, although further experiments that include an explicit vection onset latency measure would be needed to test this hypothesis.

7 Conclusion

In sum, the seated leaning-based interface performed surprisingly well and outperformed the joystick not only in terms of vection but also yielded higher rated levels of involvement, engagement, attentional capture, enjoyment, and also led to reduced distance overshooting. As users were highly familiar with using joystick navigation but not leaning to navigate through the virtual scenes, these results are promising and illustrate the potential of seated leaning-based interfaces. As such, it can be a powerful method to support tasks in VR environments that for example require more exact spatial judgements, in which an improved sense of self-motion can be beneficial. Yet, gaming environments also can highly benefit, as the increased self-motion can not only increase usability but also user engagement, for example in racing games where motion plays an important role. Even more so, while the method is self-actuated, highly affordable solutions are in reach, while even combinations of self-actuation and minimal mechanical actuation could be envisioned.

There are limitations, however, and further studies are needed to investigate how the observed benefits of leaning-based interfaces might generalize to more complex tasks with different scenarios, longer durations, different user populations, and more complex trajectories including other motion direction such as rotations, curvilinear paths, or sideways (strafing) motions. Still, leaning is a natural interaction in many real-life navigation methods, like leaning into a curve while riding a motorcycle or leaning forwards before taking the next step. Therefore, we are reasonably confident that at least some of the results will generalize.

A recent exploratory study showed trends that motion cueing interfaces like leaning chairs similar to the ChairIO (Beckhaus et al., 2005) or the NaviChair (Kitson et al., 2015) can enhance self-motion (Kitson et al., 2017), but significant vection benefits were so far only observed for leaning in standing users (Kruijff et al., 2016), manual motion cueing while sitting on a manual wheel chair (Riecke, 2006), passive motion cueing on a gaming chair (Riecke & Feuereissen, 2012; Schulte-Pelkum, 2007), but not active leaning in seated users. The current results close this gap and corroborate the potential of affordable, easy to use seat-based interfaces that solely make use of leaning to induce a strong sensation of self-motion. Self-motion heavily affects navigation and, as such, is important for a wide range of tasks in both virtual-reality and gaming. In particular, it shows the potential for the design of more ergonomic, enjoyable and engaging interfaces. Previous work such as (Marchal et al., 2011; Wang & Lindeman, 2011) reported that leaning interfaces, in particular their elastic tilt board, performed well in ratings of intuitiveness, realism, fun, and sense of presence, but that users also noted fatigue to be a major issue while standing for extended periods of time. Seating might overcome this caveat (Chester et al., 2002), offering more convenient and ergonomic leaning than for standing users, while still offering many of the advantages (including self-motion cues) users normally receive during leaning in a standing posture. Moreover, seating reduces potential dangers of standing or walking while wearing a head-mounted display, and allows for more space-efficient setups. Seated leaning might also integrate more easily into existing work or gaming setups. For example, architects working on a design walkthrough or gamers sitting comfortably would not need to stand up to use a more embodied leaning-based interface.

Together with related work on leaning-based interfaces (Beckhaus et al., 2005; Fairchild et al., 1993; Guy et al., 2015; de Haan et al., 2008; Harris et al., 2014; LaViola et al., 2001; Marchal et al., 2011; Zielasko et al., 2016), our results suggest that replacing standard locomotion interfaces like joystick or keyboard/mouse with more embodied locomotion interfaces that provide minimal motion cueing and vestibular cues through user-initiated leaning in the intended motion direction can be a promising, cost-effective and technically simple method for enhancing user experience, presence/involvement, and self-motion perception. This could have a wide range of applications including gaming, VR, tele-presence/tele-operation, entertainment, and architecture walk-throughs.

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