Upper Body Leaning can affect Forward Self-Motion Perception in Virtual Environments

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ABSTRACT

The study of locomotion in virtual environments is a diverse and rewarding research area. Yet, creating effective and intuitive locomotion techniques is challenging, especially when users cannot move around freely. While using handheld input devices for navigation may often be good enough, it does not match our natural experience of motion in the real world. Frequently, there are strong arguments for supporting body-centered self-motion cues as they may improve orientation and spatial judgments, and reduce motion sickness. Yet, how these cues can be introduced while the user is not moving around physically is not well understood. Actuated solutions such as motion platforms can be an option, but they are expensive and difficult to maintain. Alternatively, within this article we focus on the effect of upper-body tilt while users are seated, as previous work has indicated positive effects on self-motion perception. We report on two studies that investigated the effects of static and dynamic upper body leaning on perceived distances traveled and self-motion perception (vection). Static leaning (i.e., keeping a constant forward torso inclination) had a positive effect on self-motion, while dynamic torso leaning showed mixed results. We discuss these results and identify further steps necessary to design improved embodied locomotion control techniques that do not require actuated motion platforms.

Categories and Subject Descriptors

H.5.1. [**Information Interfaces and Presentation**]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2. [**Information Interfaces and Presentation**]: Information Interfaces and Presentation: User Interfaces—Ergonomics.

General Terms

Measurement, Performance, Experimentation, Human Factors

Keywords

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

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1. INTRODUCTION

Enabling effective yet intuitive spatial orientation and locomotion in 3D environments is a timely and highly relevant research problem. In particular with the rapid advent of head mounted display (HMD) systems such as the Oculus Rift^{tm} or Valve VIVE^{tm}, research on natural locomotion metaphors and techniques is stimulated as users are increasingly interested in highly engaging, immersive interfaces. However, these HMDs come with a series of new challenges and opportunities as they are head-worn and providing a much larger field of view (FOV) than traditional gaming displays. Well-designed locomotion interfaces can improve the experience and performance in virtual environments (VE) [22]. Yet, despite recent advances in virtual reality (VR) technology, supporting effective spatial orientation and providing a compelling sensation of self-motion through the VE remains challenging [27]. While modern VR systems allow for photorealistic graphics, users typically perceive simulated self-motions not as actual and embodied self-motion, but rather as camera motion [26]. Even more so, when HMDs are combined with traditional input methods like gamepad or joystick they can quickly lead to motion sickness and disorientation, reducing overall usability and user experience [32]. As such, there is a clear need for improved techniques to support spatial orientation and self-motion perception for HMD-based systems.

Freely moving around through a physical environment while navigating through virtual content still provides an unsurpassed self-motion experience [32]. Real-world viewpoint changes normally involve upper body and head movements that provide a rich set of cues. However, in many VR applications users cannot move around freely. While some systems are designed for standing [34,35] or leaning while standing [14,20,39], most users of HMD applications, in particular game-driven, are still seated. Despite a few notable developments [1,14,15,25,29], most existing 3D navigation interfaces for seated users do not take advantage of body-centric physical cues, nor is it well understood how these cues work for seated user interfaces [6]. Rather, most interfaces rely on using our hands – mostly deploying mouse, joystick or even gestures – which may reduce usability, especially because we cannot use our hands for other purposes like natural gesturing. This situation introduces an interesting design requirement: how can we design novel navigation techniques that provide suitable self-motion cues while users are seated?

The starting point for the studies reported in this article was the analysis of what cues, besides visual information, we may introduce to users to enhance self-motion perception. Different motion behavior patterns in real life seem to affect our sensation of movement through a real environment at first glance. For example, people tend to lean forward further when running or bicycling faster. In contrast, other motions force users to lean backward – think about accelerating quickly in a fast vehicle, being pressed into a chair. Previous work, as we will show in the next section, informed us that upper body tilt could have a positive effect on self-motion perception [9,13,21]. As a result, we were interested in investigating if and to what degree we could provide useful body-centered cues by simply employing upper body tilt in seated users, where leaning forward and backward is straightforward and requires little personal or technical effort.

Inspired by previous work, we designed two studies in which users wore a HMD while being seated. We looked closely at how upper body tilt can affect self-motion perception, while also briefly exploring differences with leaning in a standing posture. In particular, we studied the effects of **static leaning** (asking participants to keep a tilted posture throughout a trial) versus **dynamic leaning** (changing the upper-body inclination dynamically throughout a trial) because these introduce different kinds of cues to the user, cues that previously have been shown to positively affect self-motion. Through the studies, we aimed at identifying possible effects of different kinds of leaning and potential needs for further studies. In addition, based on study results we targeted the formulation of initial design guidelines for novel and more embodied navigation interfaces. Throughout the paper, we will show that static leaning indeed does have a positive effect on self-motion perception in that it enhanced perceived self-motion velocity. Yet, to our surprise, the dynamic tilting produced mixed results. Informed by previous work, we expected the additional cues of dynamically tilting would strengthen self-motion perception. However, we could not find such a positive effect. In the study reflection, we will unravel the results, identifying how the outcomes of are useful for interface designers. We believe that specific physical devices may be designed that may adapt to specific velocities that in return can improve the user's experience of speed in a specific environment. We will also show that more research is needed, to understand better the differences between static and dynamic leaning.

2. RELATED WORK

Navigation is one of the key tasks performed in both our real world 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 [5,6,23], enhance spatial perception and orientation, which is important for a wide range of tasks [6], and reduce motion sickness [3]. Self-motion, affecting navigation to a large extent, spans various research areas and has been studied extensively too, although there are still large gaps in our understanding. Among others, researchers have looked into the integration of visual and non-visual cues for self-motion perception [11,17] and information storage thereof [2]. Some studies focused specifically on vestibular cues [18], auditory cues [28,36] and tactile/biomechanical cues [30]. Many researchers have also experimented with vestibular stimulation to induce self-motion [16,31]. Our studies were motivated by several previous experiments that investigated how static or dynamic body tilt might affect perceived self-motion. For example, several prior studies indicated that static body tilt could affect various aspects of our visual and non-visual perception. Bringoux et al. showed that blindfolded participants' estimation of earth-referenced horizon (i.e., horizontal with respect to gravity) was systematically affected by their body tilt [9]. Tilting their chair forward yielded lower horizon estimates, and backwards body tilt resulted in elevated estimates. Similar effects of body tilt have been shown when judging the elevation of a visually presented object and one's judged ability to pass under it [8]. Body pitch has also been shown to affect our perceived self-motion direction [4]. When judging one's perceived direction of self-motion in an expanding optic flow field simulating forward translation with or without some upward/downward component, forward/backwards body tilt (pitch) resulted in systematic downward/upward bias.

With respect to seating postures, an upright posture has been shown to yield stronger illusory self-motion (linear forward vection induced by an optic flow field) than lying postures [13]. However, it is largely unknown if merely statically leaning forward or backwards might be sufficient for affecting our self-motion perception. From an applied standpoint, it is often unfeasible to have users completely lie down, whereas forward/backwards leaning can be easily accomplished in most natural user settings without additional cost or simulation effort.

In a small study with four participants, Nakamura and Shimojo compared linear vection induced in observers sitting either upright or tilted backward 30, 45, or 60° [21]. While horizontal (sideways left-right) vection was not affected by body tilt, vertical (aka elevator) vection was reduced for upright posture and increased to the level of horizontal vection as body tilt increased. However, they did not investigate forward linear vection, and it remains an open question how static body tilt might affect forward linear vection. If there was any effect, this could provide a simple and affordable means of enhancing (or reducing) self-motion perception without the need for expensive equipment. Our study was designed to address this gap.

Dynamically tilting users or the whole motion simulator during simulated accelerations is standard practice in moving-base motion simulators such as high-end driving or flight simulators, and has been shown to improve the realism of linear self-motion as well as the percentage of users experiencing embodied illusions of self-motion (linear vection) [12]. However, dynamically tilting users comes with considerable cost and technical complexity. 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 tune a system [12,33].

As a step towards reducing technical complexity and cost, Beckhaus, Riecke, and others proposed to remove all external actuation and instead let users actuate actively providing their own motion cueing while seated [1,19,25,29]. By using a modified manual wheelchair [29] or a leaning gaming chair [25], they demonstrated that user-powered full-body translational or translational and tilting motion cueing could enhance both forward linear and curvilinear vection [29]. However, to the best of our knowledge there is no prior research investigating if upper body leaning by itself could also affect perceived self-motion. If so, this could 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.

With respect to spatial navigation interfaces, some connection exists to walking-in-place interfaces [34,35], as well as natural motion interfaces such as supported through treadmills [10]. Yet, these studies focus on standing poses, whereas our study looks at seated users. Moreover, these studies were not focused on navigation. Finally, our study relates directly to various physical leaning-based interfaces for navigation in virtual environments, including the usage of the Wii balance board [15,37,38]and other types of leaning interfaces [14,20,39]. The results of our study can inform the design of such interfaces, as we will discuss later in this article.

3. Research questions

In an attempt to address some of the above-mentioned gaps and challenges, we wanted to investigate if self-motion perception and realism could be enhanced by simpler means than a moving-base simulator or other means to move the whole user. We also asked whether forward or backward leaning of the upper body might by itself enhance our sensation of forward motion, and how the velocity of the simulated self-motion might mediate this. Furthermore, as supported through self-motion literature [18], we were interested in the effect vestibular cues (in particular acceleration cues) would have when a body is moved dynamically. That is, what are the differences between keeping a fixed leaned posture and dynamically leaning (moving the upper body forward or backward) on self-motion perception? Furthermore, how can the results inform the design of novel navigation interfaces? And, what further steps may be needed to refine design requirements and improve interfaces?

To this end, we designed two studies in which we investigated whether static (Study 1) or dynamic (Study 2) tilting of just one's upper body might provide at least some of the benefits of full-scale dynamic motion cueing.

Figure 1: Experiment setup showing a participant in the upright (0°) condition wearing the HMD and backpack (left). Visual stimuli of the optic flow environment (right).

4. STUDY 1 – STATIC LEANING

4.1 Methods

4.1.1 Stimuli and apparatus

In both studies, visual stimuli were presented through a head-mounted display (HMD), the Oculus RIFT^{tm} DK2. This low-cost HMD provides stereo graphics at a resolution of 960×1080 pixel per eye and a binocular FOV of about 100 degrees. The experiments were programmed in Unity3D^{tm} and rendered at 60Hz. The head tracking embedded in the RIFT was enabled, and participants were instructed to to keep the cross-hair (and thus their head) leveled during all leaning conditions (see Figure 1, right). Participants were asked to use a joystick to control forward linear self-motion through a simulated 3D optic flow field. The virtual environment consisted of a particle field of white blobs on a black background, designed to provide strong optic flow when moving through it but no absolute size cues, distance cues, landmarks, or a horizon that could have biased results. No auditory or other cues were provided in the VE. Participants were asked to use a Sony Dualshock® 3 gamepad to control movement through the environment and travel the instructed distance while motion was constrained to forward-only. To measure participants' torso leaning angle (posture), they wore a lightweight backpack frame on which a high-resolution inclination sensor was mounted (PhidgetSpatial 1042), as illustrated in Figure 1. Before the experiment, the fit of the backpack was adjusted such that the inclination sensor readings for sitting upright were similar between all users. Participants were seated on an office chair with armrests to enable the user to keep a constant angle of leaning forward. For the backward leaning condition, participants could lean comfortably against the backrest. In the second study, we also added extra padding in the lower back to enable steeper leaning angles. The participants' leaning angle was displayed on a control monitor, was closely monitored by the experimenter, and corrected during the experiment when necessary. All experiments were logged automatically; variables included the condition, the travelled distance and time, velocity parameters, and the answers to ratings. All experiments were videotaped for further analysis.

4.1.2 Experimental design and procedure

The first study was designed as a two-stage study. Experiment 1 was conducted as a within-subject study, employing a 3×3×3 factorial design. Each participant completed 54 trials in randomized order, consisting of a factorial combination of 3 leaning angles {forward 10°, upright (0°), backward 10°}, 3 instructed distances {10, 15 and 20 meters}, 3 speed mappings {half, normal and double speed} and 2 repetitions per condition. Note that due to the lack of absolute size cues there is no obvious mapping of virtual environments units to meters. From the data we can calculate a mean perceived speed of about 3.5m/s for the normal speed mapping, though. In order to discourage participants from simply counting seconds as a means to estimate traveled distance, we modified the maximum movement velocity per trial by using the three speed mappings between the joystick deflection and the resulting simulated velocity. After signing informed consent and receiving written and oral instructions, participants were seated and donned the backpack and HMD. Before the experiment started, participants were asked about demographics and computer gaming experience, and rated their level of mental and bodily fitness (on a 1-11 Likert scale) to measure possible motion sickness effects after the experiments. Before each trial, participants were instructed about the desired posture and to-be-traveled distance via a pop-up in the immersive environment. The leaning (posture) was static in this experiment and participants were asked to adopt the respective posture before starting a trial and keep it throughout the trial. Participants used the joystick to move the desired distance through the environment. After each trial, participants rated perceived vection intensity and vection realism on a scale of 1 (low) to 11 (high) using a simple rating mechanism in the Unity application. We use introspective vection measures as customary the vection research, as the experience of self-motion is by definition introspective, and there are no reliable alternative physiological or behavioral indicators of vection. As participants were engaged in controlling the velocity with their joystick during a trial to produce instructed distances, we refrained from asking them to also report vection onset latencies, as this would have resulted in a dual-task paradigm with potential unknown consequences. Participants could keep the HMD on throughout the experiment. The second experiment was of a more explorative nature and designed to get further insights into what kinds of body movements participants would naturally choose, and guide the design of study 2 (experiment 3 and 4). To this end, participants completed three trials where they were asked to try out and experiment what kind of dynamic, static leaning or whole-body movements might be most conducive in enhancing their self-motion sensation. While standing or sitting as they preferred, they were asked to freely adjust their body posture and motion to produce the most compelling self-motion while at the same time using the joystick to move freely through the environment (forward only). Each participant completed three trials using the same half, normal and double speed mappings. After the experiments participants answered 13 questions about user comfort and ergonomics, and described further possibilities for improving natural motion cues in an open-ended questionnaire. The answers were expected to help us in designing study 2 as well as devise design guidelines for leaning interfaces.

4.1.3 Participants and demographics

Explorative data analysis identified that one participant produced notable outliers, for which reason their data were excluded. Data from 15 participants (5 females / 10 males, aged from 19 to 55; mean age: 25.67) were analyzed, producing a total of 810 trials. 80% (12/15) of the participants stated they played games daily or weekly, 20% (3/15) played monthly or more rarely. The preferred medium for playing was online (9/15, 60%) followed by playing offline on their computer (2/15, 13.3%), game consoles (13.3%), handheld devices (6.7%) and cell phones (6.7%). The majority of participants had no prior experience with HMDs like the Oculus RIFT (8/15, 53.3%) or used it just once (5/15, 33.3%). Only two participants had used HMDs several times in the past (13.3%).

4.2 Results and discussion

4.2.1 Experiment 1 – Static leaning

Because the optic flow-based virtual environment was devoid of absolute size cues, participants' velocity perception and distances traveled varied considerably between participants. Thus, we converted distances traveled in from VE units to normalized distances in meters by dividing the traveled distance per trial and participant by the mean distance per participant, and multiplying it by the mean instructed distance of 15m. This way, mean normalized distances per participant are by definition 15m. This reduced between-subject variability, and allowed us to focus more on the effect of self-motion cues. Data were analyzed using repeated-measures 3×3×3×2 ANOVAs for the independent variables learning angle, instructed distance, velocity mapping, and repetition for the dependent measures relative distance traveled, vection intensity, and vection realism. Significant main effects and interactions are presented below and summarized in Figure 2. Bonferroni correction was applied as needed.

4.2.1.1 Effect of leaning

Our main focus of the study, the effect of **leaning** on self-motion perception, showed a significant main effect on normalized distance traveled ($F(2, 28) = 3.33$, $p = .05$, $\eta_p^2 = .192$). As can be seen in Figure 2 (right) and confirmed by planned contrasts, participants travelled significantly less far when leaning forward (M = 14.34, SD = 5.40) compared to upright (M = 15.31, SD = 6.34), $p = .039$, or backward postures (M = 15.35, SD = 6.63), $p = .023$. This suggests that merely leaning forward can significantly increase our perceived speed of forward self-motion, without any need for external actuation or motion cueing. Unexpectedly, however, leaning did not show any significant main effects on vection intensity ($F(2, 28) =1.26$, $p = .300$, $\eta_p^2 = .83$) or vection realism ($F(2, 28) = .577$, $p = .568$, $\eta_p^2 = .040$).

4.2.1.2 Interaction effects

We found a significant three-way interaction between **leaning, velocity mapping, and repetition** ($F(4, 56)= 2.596$, $p = .046$, $\eta_p^2 = .156$). As can be seen in Figure 3, the second iteration shows a clearer fall-off of relative distance traveled for increasing speeds and forward leaning, whereas first repetition does not show such a consistent tendency. This suggests that potential effects of movement velocity and leaning become more consistent with increasing practice on the task.

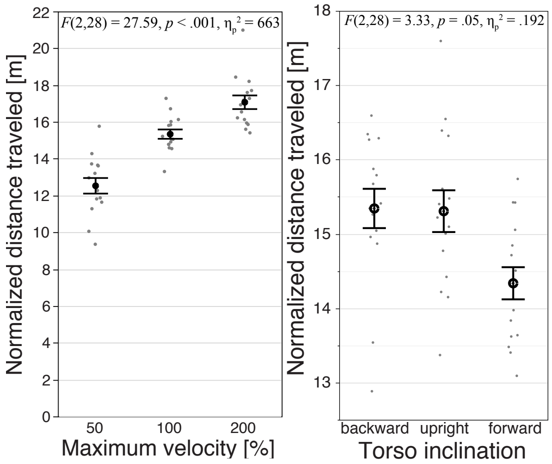

Figure 2: Mean normalized distances traveled for different speed mappings (left), torso inclinations (right). Whiskers depict standard errors, gray dots depict mean individual participants' data. Top insets show ANOVA main effects.

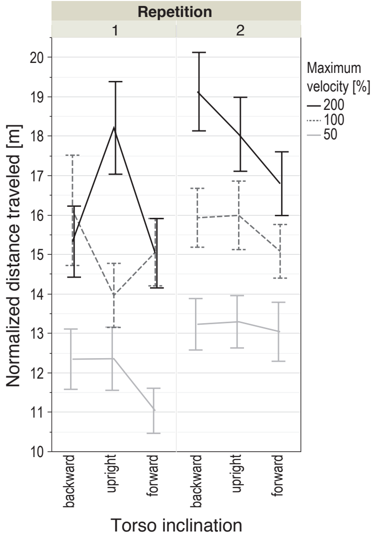

Figure 3: Three-way interaction between leaning, speed and repetition.

4.2.1.3 Effect of speed mapping

Traveled distances also showed a significant main effect of the **speed mappings**, $F(2, 28)= 27.587$, $p < .001$, $\eta_p^2 = .663$, with higher speed mappings resulting in further traveled distances (cf. Figure 2). Planned contrasts showed that distances traveled were significantly higher for the 200% speed mapping (M = 17.09, SD = 4.74) than for the 100% mapping (M = 15.36, SD = 6.18), which in turn was higher than for the 50% condition (M = 12.55, SD = 4.74). That is, participants could not fully compensate for the different maximum travel speeds, and might to some degree have used timing to estimate distance traveled. Note, however, that merely using travel time to estimate distances would have resulted in distanced traveled of 7.5m, 15m, and 30m for the speed mappings of 50%, 100%, and 200%, respectively, indicating that participants predominately could to a large degree compensate for the different motion speeds.

4.2.1.4 *Effect of instructed distance*

Instructed distances showed significant main effects on the dependent measures normalized distance traveled ($F(2,28) = 134.09$ $p < .001$, $\eta_p^2 = .905$), vection intensity ($F(2,28)= 5.86$, $p = .007$, $\eta_p^2 = .295$) and vection realism ($F(2,28)= 4.50$, $p = .020$, $\eta_p^2 = .243$). As illustrated in Figure 4 (left), the normalized distance traveled was very close to the predicted distances as indicated by the dashed gray line, for 10m instructed distances (M = 10.98, SD = 3.61), 15m (M = 14.97, SD = 5.44), and 20m (M = 19.04, SD = 6.22). That is, participants were overall quite sensitive to the to-be-instructed distance and could reproduce different distances based on the various motion cues received, and showed very little regression toward mean responses. The effect size of $\eta_p^2 = .905$ indicates that 90.5% of the variability in the distances traveled could be accounted for by the instructed distance.

As vection generally has an onset latency of several seconds and gradually builds up, one would expect the largest to-be-produced distance to yield the highest vection ratings. However, this was not the case: Post-hoc comparisons showed that vection intensities were significantly higher for the 15m condition (M = 58.3%, SD = 16.4%) than for both the 20m (M = 56.2%, SD = 17.2%), $p = .022$ and 10m condition (M = 55.8%, SD = 26.9%), $p = .017$. Similarly, vection realism ratings were higher for the 15m condition (M = 54.9%, SD = 18.9%) than for 10m (M = 51.7%, SD = 18.7%), $p = .020$ condition, but not significantly higher than for the 20m condition (M = 53.3%, SD = 19.3%), $p = .167$. Some users noted they had difficulties in reliably judging vection. For this reason, we included a vection familiarization procedure in study 2. Further studies would be needed to confirm this unexpected finding and potential underlying reasons. Given that vection ratings only differed by about 3% between these conditions, this finding might not be as important as the other observed effects.

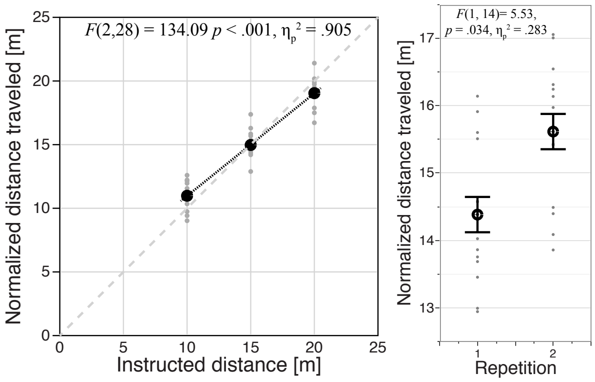

Figure 4: Mean normalized distances travels for the different instructed distances (left) and repetitions (right).

4.2.1.5 *Effect of repetition of conditions*

As depicted in Figure 4 (right), participants travelled significantly further for the second repetition as compared to the first repetition ($F(1, 14)= 5.53$, $p = .034$, $\eta_p^2 = .283$). While further studies are needed to better understand this effect, it might be related to participants getting slightly desensitized to the motion simulation over time, in the sense that longer exposure leads to reducing self-motion velocity estimates.

4.2.2 *Experiment 2 – Free exploration*

In the second experiment, participants tried out and experimented with what kind of dynamic or static leaning and whole-body movements might be most conducive in enhancing their self-motion sensation for the different velocity mappings (half, normal, double speed), and stated which one felt most intense with regard to the feeling of self-motion. Users were allowed to take any position and perform any kind of motion. When asked to state their preferred posture (see Figure 5), participants' response patterns were fairly similar for the half-speed and normal-speed conditions, where the upright posture was the most common preference (5/15 participants). For the double-speed condition, however, participants tended to prefer forward leaning (6/15) and slight forward leaning (5/15), as well as backward leaning (3/15), whereas only one participant preferred upright posture. Together with verbal reports from the post-experimental debriefing, this suggests that leaning might be a sensible method especially for faster simulated self-motions in VR. For example, one participant stated "leaning forward makes it a bit more realistic when the motion speed is set to high". Three more explicitly noted that leaning forward was the best fit for the fast movement velocity, and that this lead to the strongest sensation of self-motion.

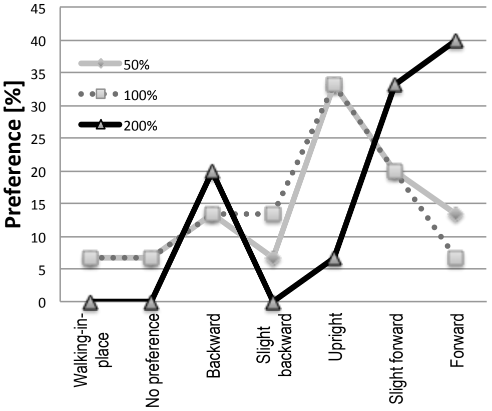

Figure 5: Leaning and motion preferences depending on velocity mapping.

Finally, one participant preferred walking-in-place for the slow and medium velocity, but not the fast velocity, whereas another participant stated that body position did not influence their perception of self-motion for the slow and medium velocity mappings. Note that all but two participants clearly preferred seating to standing postures for the slow and medium velocities, and none preferred standing postures for the fast velocity.

In sum, with increasing speed the rather heterogeneous valuation in the half and normal speed mode became more consistent as participants tended to prefer a forward or at least a slightly forward leaning position in the double speed mode.

The participants' choices are in line with what we found in the statistical analysis in phase 1, with direct statement of the positive effect of forward leaning on self-motion perception especially for the faster motions. At this point, it is unclear if the choice for leaning is due to the fact most users tend to sit while working and playing games. Most users did not have experience with the Oculus RIFT or similar head-mounted display devices. Even though participants were invited to stand up and experiment walking around, it may be that they were not accustomed to moving and walking around with the HMD (and constrained by the cables) to mimic natural motion.

4.2.3 *Pre/post questionnaires*

Questionnaire data are summarized in Table 1. Overall, participants stated they felt comfortable and relaxed, meaning the leaning or other experimental procedures did not seem to discomfort them. Also, no motion sickness was reported. Participants noted low excitement, which is not surprising due to the abstract nature of the experiment. Participants were somewhat aware of the real environment while, similarly, the user's attention was somewhat caught by the virtual reality, showing medium immersion. Additionally, the graphics were rated as sufficient to perform the experiment task, while they could concentrate well on the task and had no problems with using the interface. Subjectively, participants noted the body position (posture) had some influence on the perception of self-motion.

	mean	SD
General comfort	8.07	2.22
Posture comfort	7.27	2.02
Motion sickness	1.87	1.69
Dizziness	2.40	2.67
Muscle relaxation	7.20	3.14
Excitement	3.33	1.40
Awareness real environment	5.40	2.20
Immersion	5.33	2.80
Graphics task suitability	6.53	2.50
Concentrate on task	8.20	2.20
Problems with interface	2.07	2.02
Fresh and relaxed – before exp.	5.67	1.05
Fresh and relaxed – after exp.	7.87	2.00
Effect of posture on self-motion	6.60	2.92

Table 1 – Pre and post questionnaire ratings on an 11-point Likert scale from 1 = strongly disagree to 11 = strongly agree.

Yet, while opinions varied quite widely, this also shows there is room for improvement. The variation in opinion on the effect of leaning on self-motion was also reflected in the open questions at the end of the questionnaire. Some participants reported that leaning forward felt best for movement, especially for moving fast. Some participants specifically reported that the faster you moved forward the more you should lean forward to maximize the feeling of self-motion. In the open questions, there were also some contradicting expressions of the effect of forward versus backward leaning to match faster speeds, an effect which we also saw in the leaning and motion preferences reported in Figure 5. Interestingly, only a few participants experimented with dynamic leaning motions, likely because they had extensive exposure to static leaning before. Those who did experiment with dynamic leaning, however, stated that this helped to render the self-motion experience more intense and realistic. This was one motivation for use of investigating user-controlled dynamic leaning motions in the second study. Further motivation comes from the promising results of dynamic leaning in prior studies (see Section 2). Unfortunately, these studies did not directly assess vection or velocity/distance perception, so it remains an open research question to determine what kind of leaning or other self-motions might be most suitable to enhance the user's sensation of self-motion in immersive media. To this end, we designed the second study to investigate how dynamic leaning motions might affect self-motion perception and produced distances, using an experimental paradigm similar to study 1.

5. STUDY 2 – DYNAMIC LEANING

5.1 Methods

5.1.1 Procedure and design

The second study was also designed as a two-stage study, deploying similar procedures as study 1. Once again, in phase 1 each participant completed 54 trials, consisting of a factorial combination of 3 leaning angles {forward 10°, upright (0°), backward 10°}, 3 instructed distances {10, 15 and 20 meters}, 3 speed mappings {half, normal and double speed} and 2 repetitions per condition. Below we only describe those aspects of the methods and procedures that differ from study 1. Motivated by the effect of repetition on performance in study 1, the randomization of conditions was now performed within each of the repetitions. Users first went through all conditions in randomized order in repetition one before repeating all conditions again. Furthermore, instead of adopting and keeping a static posture before the each trial started as instructed in experiment 1, users were now asked to only start leaning forward as they tilted their joystick forward and started the simulated self-motion through the VR. As such, each trial included an initial dynamic stage (dynamically tilting the body forward or backward as instructed) followed by a fairly static stage (keeping the posture during the constant-velocity simulated motion). Because some participants in experiment 1 mentioned that judging vection was difficult without a clear reference of what vection intensity refers to, e.g., 50% or 100%, we added a familiarization phase - participants were asked users to move through the environment backwards at double speed for about 15 seconds - before the experiment designed to give them a strong sensation of vection that could later act as a reference point of what strong vection should feel like [24]. While the maximum leaning angle in phase 1 was only 10° and chosen to match the static leaning angles in experiment 1, it is possible that this leaning might not be extensive enough to show any clear effects. To investigate how not only the direction but also the amount of leaning might affect self-motion perception, phase 2 employed three different maximum leaning angles. That is, each participant performed 7 trials in randomized order, with maximum leaning angles of 0° as well as 5°, 15° and 30° both forward and backward. As participants needed feedback to be able to match these different leaning angles, the experimenter gave them verbal feedback once they reached the desired leaning angle for each trial. For each trial, participants were requested to travel 10 meters with normal speed and no repetitions per condition. In both experiments, participants were asked to report on their background, as well as fill out a questionnaire with 21 questions about general comfort and ergonomic issues.

5.1.2 Demographics and user background

16 users participated in experiment 3 and 4 (4 female/12 male, aged 20-30 years, mean: 24.19 years). Each participant performed 54+7 trials, adding to a total of 976 trials. 25% (4/16) played games daily, 31.3% (5/16) weekly, 25% (4/16) monthly, 12.5% (2/16) every half a year, and 6.7% (1/16) every year. The most favored platforms were online PC games (50%, 8/16), 25% (4/16) played cellphone games, while offline PC and console both received 12.5% (2/16). 68.8% (11/16) of participants never used an Oculus RIFT before, 18.8% (3/16) used it once, and 12.5% (2/16) used it a few times before.

5.2 Results and Discussion

5.2.1 Experiment 3 – limited dynamic leaning

In line with our first experiment, participants were able to reproduce instructed distances fairly consistently (Figure 6). The instructed distance had a significant main effect on the normalized traveled distance ($F(2, 30) = 156.79$, $p < .001$, $\eta_p^2 = .913$), with $\eta_p^2 = 91.3\%$ of the variability in the distances traveled being accounted for by the instructed distance. In contrast to experiment 1, the normalized traveled distance did not show any significant main effects of repetition, velocity, or leaning. In comparison to the first experiment where vection was not influenced by any of the independent variables, experiment 3 showed several effects, potentially due to the added vection familiarization phase: the maximum velocity had a significant effect on vection intensity (F(1.11, 16.71) = 12.82, p = .002, η_p^2 = .461), with higher velocities yielding more intense vection (Figure 7 (left). This is in agreement with the vection literature, where at least up to a certain "optimal velocity" vection tends to increase with stimulus velocity[7]. Furthermore, there was a two-way interaction between torso inclination and repetition on vection intensity (F(2, 30) = 4.679, p = .017, η_p^2 = .238), see Figure 7 (right).While there was a tendency for more intense vection for the second repetitions in the upright posture, the forward and backward leaning conditions showed no such trend.

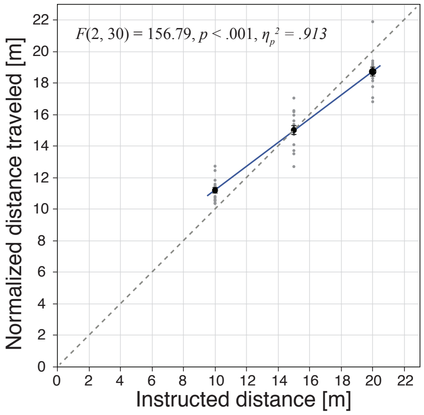

Figure 6. Traveled normalized distance versus instructed distance

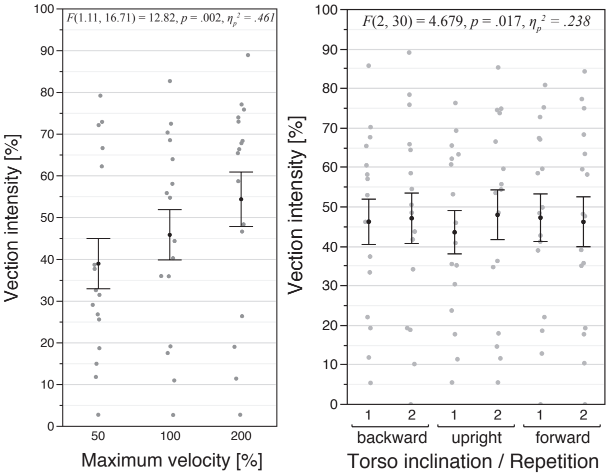

Figure 7: Effects on vection intensity

While these findings are interesting and novel, further research is needed to corroborate them and better understand underlying reasons. We also found a two-way interaction between torso inclination and maximum velocity on vection realism (F(1.90, 28.50) = 3.473, p = .047, η_p^2 = .188), see Figure 8. While vection in the backward and forward leaning conditions were rated more realistic with larger movement velocity, the upright conditions showed the opposite effect. Similar to the results found in experiment 2, this suggests that leaning is particularly effective in enhancing self-motion perception for faster movement velocities, whereas it provides little benefit for slower movements. Although the ratings of vection intensity and realism indicate some effect of leaning on self-motion perception, in contrast to our first study, leaning did not have any significant effect on the produced distance, F(2, 30) = .332, p = .720, η_p^2 = .022. This did surprise us, since we assumed the additional body-centric acceleration and dynamic motion cues provided by physically leaning forward or backward would have a stronger effect than merely statically leaning. Moreover, tilting users during simulated accelerations and decelerations is commonly used in moving-based motion simulators [12,33] as well as simpler human-powered leaning methods have often been shown to improve self-motion perception [14,15,18,20,37,39]

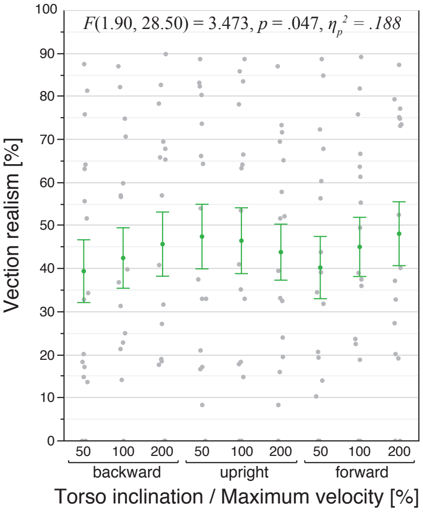

Figure 8: Effects on vection realism

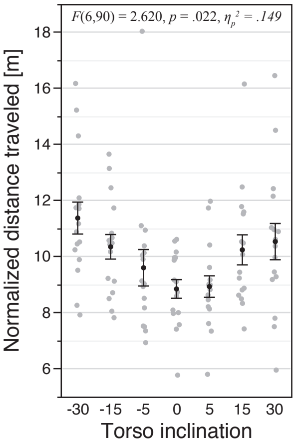

Figure 9 Effects of leaning on traveled distances

5.2.2 *Experiment 4 - extended dynamic leaning*

In contrast to experiment 3, analysis of experiment 4 where participants dynamically leaned 0°, 5°, 15° and 30° forwards and backwards showed no significant effects of leaning on vection intensity and realism. Instead, we found a significant effect of torso inclination on normalized traveled distance (F(6, 90) = 2.620, p = .022, η_p^2 = .149): As indicated in Figure 9, the further users leaned forwards or backwards, the longer the traveled distance. It is important to note that the direction of the effect was actually the opposite of what would be expected based on the literature and experiment 1, which would have predicted an increased perceived speed and thus a reduction (not increase) in distanced traveled the further the user leaned. We will further discuss this issue in the reflection section 6.

5.3 Pre/post questionnaires

The analysis of the pre and post questionnaires (Table 2 and Figure 10) provided some insights in addition to our findings of the distance distribution. As in the first study, a 11-point Likert scale was used. Generally, the comfort in all leaning conditions seemed good – in all postures, users provided medium-high ratings (about 7-8 for all postures) for the comfort and muscle relaxation metrics. Also similar to study 1, the user-excitement was low, while users could nicely concentrate on the task and noted medium immersion. The interaction itself posed no problems, and the graphics were useable for performing the task.

Yet, many users wished for more cues. While we intentionally used a simple and abstract environment in the current studies to reduce potential confounds, it would be interesting to see how users would perform with additional cues such as landmarks and absolute size cues. Motion sickness and dizziness was not an issue, with the exception of one user who had to take a short break. In general, participants were fresh and relaxed before and after the experiment and, hence, we do not expect any negative performance effects of potential posture discomfort or motion sickness. As indicated in Table 2, participants rated that their muscles were more relaxed for the upright as compared to the forward or backward conditions. There was also a non-significant tendency towards higher general comfort and posture-specific comfort ratings for the upright posture compared to forward and backward leaning. At the same time, there was a non-significant trend towards higher self-motion sensations for the forward and backward leaning conditions compared to the upright condition.

	mean	**SD**
Motion sickness	1.69	2.50
Excitement	2.31	1.66
Dizziness	2.12	2.58
Awareness real environment	4.56	2.27
Immersion	6.25	3.36
Graphics task suitability	6.81	3.06
Concentrate on task	7.88	3.10
Interaction problems	2.69	2.27
Fresh and relaxed – before exp.	8.81	1.72
Fresh and relaxed – after exp.	7.75	2.84

Table 2. Pre/post questionnaire results

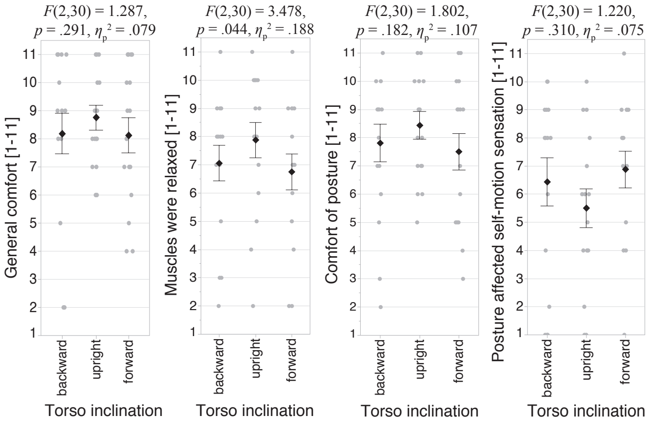

Figure 10. Effects of leaning on questionnaire ratings.

This trend was confirmed in the open questions: while 4/16 users noted no effect of posture on self-motion perception, the remaining 12/16 users (75%) reported at least some benefit of leaning on self-motion perception, with 3/16 participants (19%) only stating a minimal benefit. Participants, however, did not agree on whether forward or backward leaning was more instrumental: while 5/16 (31%) reported a stronger benefit of forward leaning, 3/16 (19%) mentioned a larger benefit for backward leaning. This suggests considerable individual differences in the preferred leaning type, which might be important to consider in the design of leaning-based motion interfaces. For example, it might be sensible to give users an option to choose their preferred leaning direction. Overall, only 4/16 users (25%) commented on the amount of leaning, and those agreed that a medium amount of leaning was most effective (15° here). Still, while these ratings are in line with the subjective ratings of vection realism and intensity, the distance distribution did not reflect these statements directly.

6. REFLECTION AND CONCLUSION

Both studies showed that leaning has an effect on self-motion perception. However, a comparison between the two studies reveals there are quite a few differences and surprising results.

6.1 Effects on self-motion perception

Leaning forward can positively affect self-motion perception: Within our first experiment, we showed that statically leaning forward did significantly affect self-motion perception by reducing distances traveled, likely because of an increase in perceived speed of self-motion. The results are in line with and extending previous body tilt studies we discussed in section 2 [9,13,21]. This suggests that even a simple manipulation such as statically leaning forward while sitting can enhance our self-motion perception in VR, thus providing an extremely simple and affordable approach. However, statically leaning forward reduced traveled distances by only about 6% and, thus, might by itself only have limited applied benefit. In addition, statically leaning forward might not be ergonomically feasible for longer durations.

Leaning subjectively enhances self-motion perception and is preferred especially for higher speeds: In experiment 2, participants experimented with different static and dynamic leaning motions and either reported no clear preference or remarked that leaning can enhance their sensation of self-motion and overall realism, especially for faster simulated self-motions. In the debriefing after experiment 4, 75% of participants stated that dynamic leaning enhanced self-motion perception at least somewhat. However, they disagreed as to whether forward leaning (31%) or backward leaning (19%) was more suitable, although they seemed to agree that a moderate amount of leaning (less than the maximum of 30° used in experiment 4) was most instrumental and that the faster motions are best accompanied by more extensive leaning. These findings are overall in alignment with results from experiment 2, where users showed a stronger preference for leaning compared to upright postures for the fastest simulated self-motion.

Vection unaffected by leaning, at least for current procedure: It was surprising that vection measures showed no clear main effect of either static leaning (experiment 1) or dynamic leaning (experiment 3 and 4), even though prior work, using somewhat different procedures, did report such benefits [12,21,25]. Post-experimental debriefing suggests that this lack of a vection-facilitating effect, especially in experiment 1, might have been related to participants' difficulty in reliably judging their self-motion sensation without a clear reference stimulus and anchored response scale. For experiment 3, we tried to address this by including a vection familiarization phase, and we observed somewhat higher sensitivity to experimental manipulations and larger variations in vection responses, although a more extensive vection demonstration and practice phase might have yielded clearer effects in all experiments reported here. This highlights the importance of careful experimentation and providing a reference experience to sufficiently ground any introspective scale.

Exposure/learning effects: Experiment 1 suggests that longer exposure might lead to lower perceived self-motion velocities. In terms of guidelines for experimentation, this highlights the importance of carefully designing studies in order to take exposure effects into account, for example by counter-balancing different conditions. The 3-way interaction observed in experiment 1 further emphasizes the importance of taking exposure effects into consideration, in that effects of experimental parameters can become more clear and consistent with exposure.

Dynamic leaning shows unexpected results: In experiment 3, where participants dynamically leaned up to 10° forward and backward, we observed no significant main effects of leaning on either distance traveled or vection ratings. When the amount of dynamic leaning was varied in experiment 4 (5°, 15° and 30°), we actually observed the opposite of what we would have predicted based on experiment 1 and 2 and the literature [9,13,21]: That is, for steeper leaning inclinations, participants actually traveled further, not less as predicted. While this result was puzzling, the qualitative data from the exit interviews and the video analysis could provide us with some pointers towards a potential explanation. It seemed like users often tended to first concentrate on dynamically leaning forward to reach the desired posture, with steeper postures taking slightly longer to adopt, before concentrating on judging how far to move forward. This leads to the assumption of a two-stage process in the action selection and planning phase in human information processing [40], and matches observations from the video analysis. If participants employed such a 2-stage strategy and did not fully incorporate the distance travelled during the dynamic leaning phase before reaching the maximum leaning extent, this would predict longer distances traveled especially for the most extreme leaning angles, which is exactly what we observed in experiment 4. In contrast, experiment 3 only used leaning angles of 10° and showed no effect of leaning on produced distances. In retrospect, this could be related to the potential effects of leaning being compensated for by the above-mentioned 2-stage approach of first leaning before starting to fully concentrate on the to-be-travelled distance. Further experiments are needed and planned to investigate this.

6.2 Conclusions and outlook

Although many questions await further research, designing leaning-based and, thus, more embodied locomotion interfaces seems overall like a promising avenue for further research and might ultimately help to enhance self-motion perception, user experience and engagement, as is also suggested by prior work [1,12,14,20,21,25,29,39]. Generally, we did not see any negative effects of static or dynamic leaning on user comfort, and most ratings were positive. However, it should be noted that participants only had to keep the leaning postures for a short time. Supporting leaning, especially forward leaning, for extended durations will likely require ergonomic supports.

In general, there are a number of potential usability issues that can counteract potential benefits of more embodied locomotion interfaces. For example, in the current study, locomotion through VR was only controlled by a joystick and not directly affected by users' leaning. While this was necessary for experiment 1 and 2, multiple users commented that they would like to directly control the simulated self-motion with their body inclination, using a "human-as-a-joystick" metaphor. This would likely also help to address the two-stage control issue described above. As we discussed in section 2, such leaning-control approaches have been employed by a number of studies ranging from standing-leaning interfaces to sitting-leaning interfaces using a modified gaming chair or leaning stool interface [1,14,15,19,20,25,37,39].

In conclusion, our study provide first indications that upper body leaning can improve self-motion perception and user experience, which could inspire the design of improved user interfaces that are more embodied yet affordable as the do not require external motor actuation. At the same time, it suggests that decoupling torso leaning from the VE velocity control (by using a joystick in the current study) might be problematic and conceals potential benefits of dynamic torso leaning. On reason might be the lack of direct visual feedback from torso leaning, which might have added cognitive load and resulted in participants in dynamic leaning conditions to first concentrate on the leaning before fully engaging on the distance production task as discussed earlier. Together, this highlights the importance of providing direction action-perception coupling – while separating different parameters can be valuable in fundamental research to disambiguate influences of different factors, immediate and intuitive coupling of user actions to observable effects is essential for designing user interfaces that are both effective and intuitive.

Based on and inspired by our findings and participant feedback, we are currently designing a study using the human-as-a-joystick direct input metaphor using different inclination/speed mappings and incorporating rotations and translations in both forward/backward and left/right direction, as well as comparing upper-body-only motion like in the current experiment to a leaning chair stool paradigm inspired by [1,19,25].

7. REFERENCES

[1] Beckhaus, S., Blom, K., and Haringer, M. 2005.Intuitive, Hands-free Travel Interfaces for Virtual Environments. Proceedings of the 3D user interface workshop, IEEE Virtual Reality Conference.

[2] Berthoz, A., Israël, I., Georges-François, P., Grasso, R., and Tsuzuku, T.1995. Spatial memory of body linear displacement: what is being stored? Science , 269, 5220, 95–8.

[3] Bos, J., Bles, W., and Groen, E. 2008. A theory on visually induced motion sickness. Displays 29, 2, 47–57.

[4] Bourrelly, A., Vercher, J.-L., and Bringoux, L. 2010. Pitch body orientation influences the perception of self-motion direction induced by optic flow. Neuroscience letters 482, 3, 193–7.

[5] Bowman, D., Koller, D., and Hodges, L.1998. A Methodology for the Evaluation of Travel Techniques for Immersive Virtual Environments. Virtual Reality: Research, Development, and Applications 3, , 120–131.

[6] Bowman, D., Kruijff, E., LaViola, J., and Poupyrev, I. 2005. 3D user interfaces : theory and practice. Addison-Wesley.

[7] Brandt, T., Dichgans, J., and Koenig, E. 1973. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Experimental Brain Research 16, 5.

[8] Bringoux, L., Robic, G., Gauthier, G., and Vercher, J. 2008. Judging beforehand the possibility of passing under obstacles without motion: the influence of egocentric and geocentric frames of reference. Experimental brain research 185, 4, 673–80.

[9] Bringoux, L., Tamura, K., Faldon, M., Gresty, M., and Bronstein, A. 2004. Influence of whole-body pitch tilt and

kinesthetic cues on the perceived gravity-referenced eye level. Experimental brain research 155, 3, 385–92.

[10] Darken, R., Cockayne, W., and Carmein, D. 1997. The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds. Proceedings of the ACM Symposium on User Interface Software and Technology, 213–221.

[11] DeAngelis, G. and Angelaki, D.2012. Visual–Vestibular Integration for Self-Motion Perception.

[12] Groen, E.L. and Bles, W. 2004. How to use body tilt for the simulation of linear self motion. Journal of vestibular research : equilibrium & orientation 14, 5, 375–85.

[13] Guterman, P., Allison, R., Palmisano, S., and Zacher, J.. 2012. Postural and viewpoint oscillation effects on the perception of self-motion. Journal of Vision 12, 9, 576–576.

[14] Guy, E., Punpongsanon, P., Iwai, D., Sato, K., and Boubekeur, T. 2015. .LazyNav: 3D Ground Navigation with Non-Critical Body Parts. Proceedings of the IEEE Symposium on 3D User Interfaces.

[15] De Haan, G., Griffith, E., and Post, F. 2008. Using the Wii Balance Board as a low-cost VR interaction device. Proceedings of the ACM symposium on Virtual reality software and technology, 289.

[16] Harris, L., Jenkin, M., and Zikovitz, D. 1999. Vestibular Cues and Virtual environments: Choosing the Magnitude of the Vestibular Cue. Proceedings of IEEE Virtual Reality'99, 229–236.

[17] Harris, L., Jenkin, M., and Zikovitz, D. 2000. Visual and Non-Visual Cues in the Perception of Linear Self Motion. Experimental Brain Research 135.

[18] Ivanenko, Y.P., Grasso, R., Israël, I., and Berthoz, A.1997. The contribution of otoliths and semicircular canals to the perception of two-dimensional passive whole-body motion in humans. The Journal of physiology 502,Pt 1, 223–33.

[19] Kitson, A., Riecke, B., and Neustaedter, C. 2015. NaviChair: an embodied interface to navigate virtual reality. Proceedings of the ACM Symposium on Spatial User Interaction.

[20] Marchal, M., Pettre, J., and Lecuyer, A. 2011. Joyman: A human-scale joystick for navigating in virtual worlds. 2011 IEEE Symposium on 3D User Interfaces, 19–26.

[21] Nakamura, S. and Shimojo, S. 1998. Orientation of selective effects of body tilt on visually induced perception of self-motion. Perceptual and motor skills 87, 2, 667–72.

[22] Peterson, B., Wells, M., Furness, T., and Hunt, E. 1998. The Effects of the Interface on Navigation in Virtual Environments. in Proceedings of Human Factors and Ergonomics Society 1998 Annual Meeting.

[23] Riecke, B., Bodenheimer, B., McNamara, T., Williams, B., Peng, P., and Feuereissen, D. 2010. Do we need to walk for effective virtual reality navigation? physical rotations alone may suffice, 234–247.

[24] Riecke, B., Feuereissen, D., and Rieser, J. 2009. Auditory self-motion simulation is facilitated by haptic and vibrational cues suggesting the possibility of actual motion. ACM Transactions on Applied Perception 6, 3, 1–22.

[25] Riecke, B. and Feuereissen, D.2012. To move or not to move: can active control and user-driven motion cueing enhance self-motion perception ("vection") in virtual reality? Proceedings of the ACM Symposium on Applied Perception..

[26] Riecke, B.and Schulte-Pelkum, J. 2013. Perceptual and Cognitive Factors for Self-Motion Simulation in Virtual Environments: How Can Self-Motion Illusions ("Vection") Be Utilized? In F. Steinicke, Y. Visell, J. Campos and A. Lécuyer, eds., Human Walking in Virtual Environments. Springer New York, New York, NY, 27–54.

[27] Riecke, B. and Schulte-Pelkum, J.2014. An integrative approach to presence and self-motion perception research.

[28] Riecke, B.E., Väljamäe, A., and Schulte-Pelkum, J. 2009. Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. ACM Transactions on Applied Perception 6, 2, 1–27.

[29] Riecke, B. 2006. Simple user-generated motion cueing can enhance self-motion perception (Vection) in virtual reality. Proceedings of the ACM symposium on Virtual reality software and technology, 104.

[30] Rupert, A. and Kolev, O. 2008. The Use of Tactile Cues to Modify the Perception of Self-Motion.

[31] St George, R.. and Fitzpatrick, R.2011. The sense of self-motion, orientation and balance explored by vestibular stimulation. The Journal of physiology 589, Pt 4, 807–13.

[32] Steinicke, F., Visell, Y., Campos, J., and Lecuyer, A., eds. 2013. Human Walking in Virtual Environments. Springer Verlag.

[33] Stratulat, A.M., Roussarie, V., Vercher, J.-L., and Bourdin, C. 2011. Does tilt/translation ratio affect perception of deceleration in driving simulators? Journal of vestibular research : equilibrium & orientation 21, 3, 127–39.

[34] Templeman, J.N., Denbrook, P.S., and Sibert, L.E.2009. Virtual Locomotion: Walking in Place through Virtual Environments. Presence: Teleoperators and Virtual Environments 8, 6, 598–617.

[35] Usoh, M., Arthur, K., Whitton, M.C., et al.1999. Walking > Walking-in-Place > Flying in Virtual Environments. Proceedings of ACM SIGGRAPH '99, 359–364.

[36] Väljamäe, A., Larsson, P., Västfjäll, D., and Kleiner, M.2006. Vibrotactile Enhancement of Auditory-Induced Self-Motion and Spatial Presence. Journal of the Audio Engineering Society 54, 10, 954–963.

[37] Valkov, D., Steinicke, F., Bruder, G., and Hinrichs, K.2010. Traveling in 3D Virtual Environments with Foot Gestures and a Multi-Touch enabled WIM. Proceedings of Virtual Reality International Conference, 171–180.

[38] Wang, J. and Lindeman, R. 2012.Leaning-based travel interfaces revisited: frontal versus sidewise stances for flying in 3D virtual spaces. Proceedings of the ACM symposium on Virtual reality software and technology, 121.

[39] Wang, J. and Lindeman, R.W.2011. Silver Surfer: A system to compare isometric and elastic board interfaces for locomotion in VR, 121–122.

[40] Wickens, C. and Carswell, C. 1997. Information processing. In G. Salvendy, ed., Handbook of Human Factors and Ergonomics. Wiley & Sons., New York, 130–149.