VRSpinning: Exploring the Design Space of a 1D Rotation Platform to Increase the Perception of Self-Motion in VR

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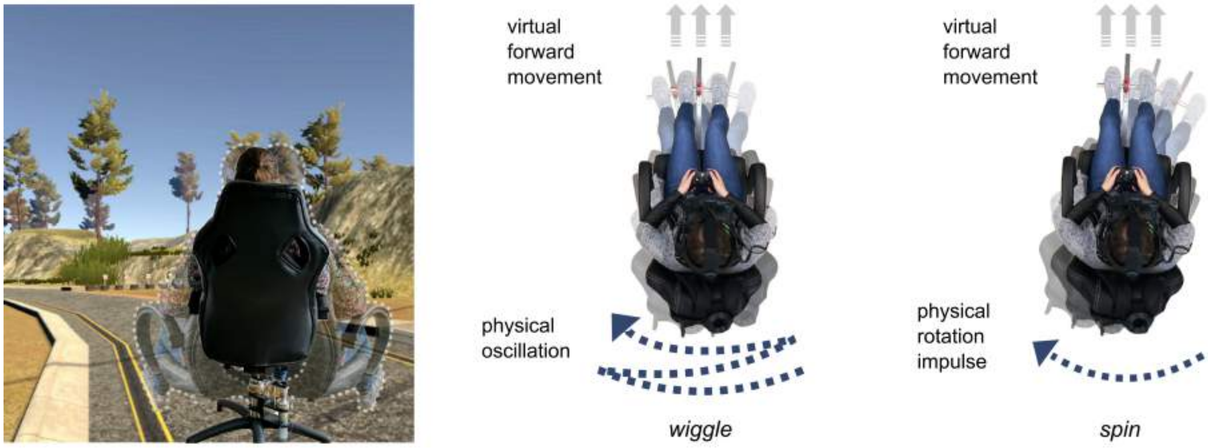

Figure 1. Forward motion approaches of *VRSpinning* to increase vection and reduce simulator sickness: *wiggle* movement to simulate steps or environmental events in VR (left middle), *spin* movement to simulate forward acceleration in VR by applying a short rotational impulse.

ABSTRACT

Current approaches for locomotion in virtual reality are either creating a visual-vestibular conflict, which is assumed to cause simulator sickness, or use metaphors such as teleportation to travel longer distances, lacking the perception of self motion. We propose *VRSpinning*, a seated locomotion approach based around stimulating the user's vestibular system using a rotational impulse to induce the perception of linear self-motion. In a first study we explored the approach of oscillating the chair in different frequencies during visual forward motion and collected user preferences on applying these feedback types. In a second user study we used short bursts of rotational acceleration to match the visual forward acceleration. We found that this rotational stimulus significantly reduced simulator sickness and increased the perception of self-motion in comparison to no physical motion.

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INTRODUCTION

The majority of current locomotion techniques for virtual reality (VR) are focused around standing and short term walking experiences (e.g. HTC Vive or Oculus Rift) using teleportation as a metaphor for traveling longer distances. However, this excludes applications such as driving or flight simulators, where self-motion cannot be solved by teleportation. Additionally, virtual reality requires to be designed to immerse the user for a longer duration than most current short demonstrations (e.g. Fallout 4 VR, Skyrim VR, Doom VR, Gran Tourismo VR) to become a relevant medium for entertainment. All of these recent AAA titles and most likely the upcoming games depend on some kind of locomotion suitable for a longer exposure.

The two currently most dominant forms of locomotion are either physical movement through a tracked space (e.g. HTC Vive) or virtual metaphors such as teleportation (e.g. Fallout 4 VR, Doom VR) and virtual movement (e.g. Resident Evil VR). Since a tracked space is often smaller than the virtual world the user explores, physical movement is often combined with a form of virtual metaphors, when a user reaches the physical limits. Physical movement over time results in high levels of fatigue and will become uncomfortable for longer experiences. Virtual metaphors on the other hand can be used over a longer duration (also while seated) but lack the perception of vection (e.g. teleportation) and can result in higher levels of simulator sickness (e.g. virtual movement) [5]. Therefore, VR requires a (physical) locomotion feedback that creates the feeling of self-motion without causing simulator sickness.

We propose to use physical feedback generated through a motion platform on an actuated swivel chair, which we call *VRSpinning*. We implemented different actuation patterns (*wiggle*, *spin*) and introduce the concept of presenting a visual stimulus (forward acceleration) synchronously with a short and non-matching vestibular stimulus (rotational acceleration), tricking human perception into interpreting the rotational acceleration cue as a forward acceleration (see Figure 1). We found that this approach significantly reduces simulator sickness and increases the perception of self-motion.

To fine tune the stimuli we developed *VRSpinning* using a user centered design approach. We explored two different rotational stimuli to enhance the feeling of forward motion and ran two studies. In the first study we used oscillation for simulating three different movement approaches for forward motion (walking, driving, flying). We ran an exploratory study, exposing the user with the technique and having a think aloud feedback session, collecting calibration values and preferences. We found that users quickly mapped the oscillation to virtual steps but disliked the continuous stimulus when virtually driving or flying. Based on this feedback we redesigned the stimulus to be a short physical rotational acceleration only at the start of a visual forward motion. We countered the physical rotation inside of VR so that users are physically rotated but still keep looking in the same virtual direction. In the second study we measured vection, simulator sickness and presence compared to no physical rotation. We found that the rotational impulse of *VRSpinning* reduced simulator sickness and significantly increased vection as well as the feeling of acceleration compared to no physical motion.

The main contributions of our work are:

- The concept of presenting a visual stimulus (forward acceleration) synchronously with a short and non-matching vestibular stimulus (rotational acceleration), tricking human perception into interpreting the rotational acceleration cue as a forward acceleration.
- Findings from an exploratory user study on an oscillating stimulus for a walking metaphor and resulting user preferences.
- Findings from a second comparative study showing the decrease of simulator sickness and increase of vection using the *VRSpinning* concept for forward motion in virtual reality.

RELATED WORK

Vection

According to [1] and [19] vection can be defined as a *conscious subjective experience of self-motion*, which includes both perceptions and feelings of self-motion. Vection is thereby induced by optokinetic stimulation, but is also influenced by other sensory systems including the vestibular one.

It has been shown that during circular vection, i.e. illusory self-rotation, the perceived direction is opposite to the actual moving direction. This effect is caused by three semi-circular canals of the inner ear that act similar to leaky integrators. Therefore, a constant signal of velocity will decay after less than a minute, which causes that humans are not able to detect rotational movement without visual stimuli [7]. A similar effect can be observed in terms of forward motion. As the vestibular system only detects changes of velocity (accelerations), it will not respond to a constant velocity and also not detect any conflict (since the null signal is expected). This effect is referred to as onset latency, which can vary from a few seconds to half a minute [23]. We leverage this effect by applying a rotational acceleration in order to simulate forward movement in virtual reality. We assume that the direction of a short term acceleration cannot be recognized. However, it should be enough to support the feeling of self-motion induced by the visual stimulus.

Simulator Sickness

The phenomenon of simulator sickness is a well known problem of VR applications. It is commonly considered as a subset of motion sickness, therefore symptoms are related and include eye strain, headache, sweating, vertigo and nausea [15]. The cause of simulator sickness is of polygenic nature [12], however, scientific consent points towards vection as a possible cause of simulator sickness [10]. The two perceptual systems that are mainly involved in perception of self-motion are the vestibular and the visual sensory system. The vestibulo-ocular reflex, which ensures that the eyes are kept in place while the head is moving, elucidates the important relationship between these two senses [15]. Three main theories (sensory conflict theory [21], postural instability theory [22] and poison theory [27]) give an explanation for the phenomenon. The sensory conflict theory is the oldest and most accepted one [15]. It states that the body is not able to handle dissimilar information from different sensory systems. In VR a person usually perceives motion visually, while the vestibular system signals stasis. We counter this by giving a vestibular stimulus (rotational acceleration) synchronously with a visual stimulus. Though conflicting concerning the direction of acceleration, we assume that the short application of physical stimulation is long enough to be perceived as vestibular stimulus, but short enough to prevent the perception of the actual direction. Combined with the fact that the visual stimulus is considered more dominant lead to our assumption that using a rotational impulse combined with visual motion could increase vection and reduce simulator sickness.

Vection During Sensory Conflicts

The human central nervous system integrates visual and vestibular information to get a compelling perception of motion. According to the sensory conflict theory, conflicts arise when merging sensory information does not lead to a coherent and robust perception. One way to constitute a solution is the dominance of one sense over the others.

Although the visual sense is able to dominate the perception of motion, it is not clear how vestibular information integrates with visual information. Wright [28] tested horizontal and vertical visual motions on seated participants during forward motion. For both horizontal and vertical motion, participants' reported perception of self-motion coincided with the visual phase (not the inertial one). Even when the actual forward inertial motion was orthogonal to the visual one. Additionally, the perceived feeling of self-motion increased correspondingly to the amplitude of the inertial feedback. Berthoz et al. [3] tested the perception of forward self-motion induced by peripheral vision and also found that vision dominated in conflicting situations in which visual cues contradicted vestibular ones. According to these findings the feeling of vection increases with the amplitude of vestibular feedback, but does not primarily depend on its direction. We build up on these findings by using a physical, rotational acceleration to increase the feeling of self-motion during a visual forward motion scenario.

Motion Feedback

To solve conflicts arising from visual and vestibular perceptual information in terms of using real motion various approaches were made. One of them is to stimulate human sensory systems by inducing false sensory input, which, combined with visual information, is interpreted as realistic information by the brain. Galvanic vestibular stimulation (GVS) stimulates the vestibular system by sending electrical signals to the inner ear. Maeda et al. [17] indicate that a visually induced feeling of self-motion can be increased by combining visual stimuli with GVS. Further, Gálvez-García et al. [6] point out that galvanic cutaneous stimulation (GCS) mitigates simulator sickness symptoms. However, technical limitations and medical concerns are currently too immense for GVS and GCS to be used in consumer grade hardware.

Walking setups are another approach to bridge the gap between vestibular and visual information. Room scale tracking allows the user to freely roam around in the real world, free of any sensory conflict as real and virtual motion match. However, in most settings only limited space is available. Therefore, redirected walking [20] aims at redirecting the users steps in the real world to walk curved paths while walking straight in the virtual world. Another way to provide natural and immersive virtual locomotion is the walking-in-place (WIP) approach. VR-STEP [26] offers intuitive real-time pedometry to implement virtual locomotion. Users stand and provide continuous stepping input while walking through the virtual wold. In combination with head-tilt WIP can even be used for multidirectional navigation in the direction of the user's gaze [25]. However, redirected walking and WIP approaches may not be used for longer periods of time due to physical exhaustion.

Another way to create motion in the real world when moving in the virtual one are motion platforms that create real related motions to match virtual ones. While in the past motion platforms with six degrees of freedom were used to create motion [16, 11], it has been shown that smaller setups suffice to create a sense of realistic motion. The advantage of these smaller platforms and feedback devices is that they can be used in domestic settings. *HapSeat* [4] uses three actuators for both arms and head to simulate motion through applying force feedbacks on the user's seated body. Ouarti et al. [18] use a haptic force feedback in the hands of the user to enhance the sensation of self-motion. When coherent with the virtual camera motion, the force feedback stimulation creates a higher sensation of self-motion in contrast to visual feedback alone in moving a virtual environment. However, these systems only create a sensation of motion by simulating motion through an applied force feedback. But humans perceive motion by interpreting information from their visual, auditory, vestibular and kinesthetic sensory systems [2, 9]. Therefore, *VRSpinning* is based on a swivel chair [8] that creates real motion instead of simulating it.

ON THE DESIGN OF MOTION USING ROTATION

Our aim was to represent both, forward and rotational motion in VR based on a swivel chair as motion platform. Since the vestibular system measures acceleration, but does not detect constant motion, we concentrated on representing rotational and forward accelerations in VR. While rotation is rather easy to represent, forward motion is more problematic as it cannot be displayed as a one to one match by the chair. As indicated by related work, the vestibular system is not very accurate and human perception can be tricked into interpreting an acceleration stimulus as orthogonal or opposite to its actual direction. We take advantage of the inaccuracy of human perception and present visual stimuli synchronously with non-matching vestibular stimuli (rotational acceleration) that are interpreted as forward acceleration.

Besides the limits of human perception, usability should be considered. Motion platforms may increase the feeling of self-motion by adding physical motion to the virtual one. However, accelerations are known to cause simulator sickness. More aspects that have to be considered are peoples' preferences on what kind of motions should be enriched with motion feedback (e.g. walking, driving, flying). Therefore, we used an user-centered design approach to get further insights on how to design a motion approach on the basis of an actuated swivel chair as motion platform.

FIRST PROTOTYPE

We implemented a first prototype based on the SwiVRChair platform [8] (see Figure 2). The prototype consists of a motorized swivel chair with a VR ready laptop on its back.

In terms of feedback we used a one to one mapping of virtual to physical rotations (e.g. when the user rotated left inside the virtual world the chair would rotate left). Additionally, we added an oscillation of the chair when a forward motion was performed inside of the virtual environment (*wiggle*). The main idea of that oscillation was to stimulate the users' vestibular system and trick him into perceiving a forward motion. The concept is illustrated in Figure 3.

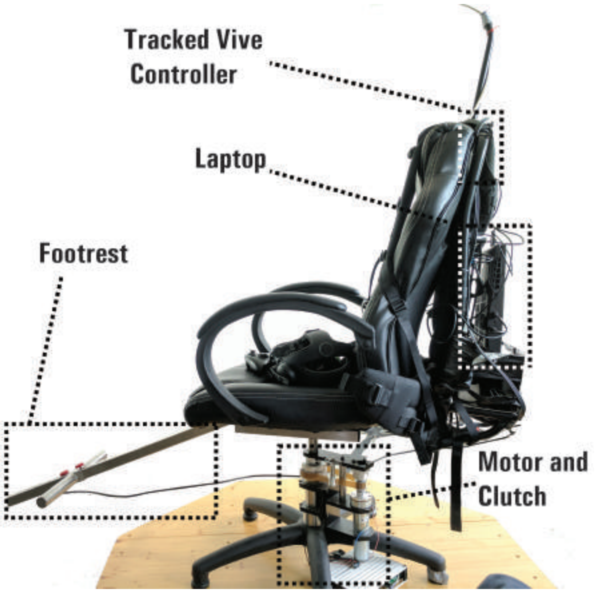

Figure 2. Technical setup of our prototype. A footrest is attached to the chair to have a more comfortable position and to not perceive rotational direction. A VR ready laptop is attached to the back of the chair, as well as an HTC Vive controller, the rotation values of which are used to remove the chair's physical rotation from the virtual view (participant keeps looking in the same direction although the chair is rotating).

While the driving and flying conditions included an avatar in form of a car or a cockpit, the player was represented only by a marker on the ground in the walking condition.

Setup

We equipped a swivel chair with a gearbox, a clutch and an electric motor to enable automatic rotation of the chair. To alleviate some performance issues, several design modification were made. The wireless connection was replaced with an USB connection to reduce latency and increase reliability, which are both crucial for the feedback mechanism we evaluated. Additionally, the motor driver board was replaced with an additional 20 V power supply to enable a gentler motion of the chair, while enhancing the grip of the clutch, which could then be powered with the full 24 V. Furthermore, the Samsung Gear VR headset used in the SwiVRChair project was replaced with the HTC Vive, which drastically increased processing power and overall performance. The chair's physics integration into the virtual world was one of the most challenging parts of the setup, as it's virtual representation had to match the real world object. Therefore, we attached a Vive controller to the back of the chair. We only regarded the Euler angle's Y component to describe the chair's rotation in 3D space, since the other parts are most of all results of tilting the chair. Finally, we added a footrest to the setup (see Figure 2) to avoid participants perceiving the direction of the rotation by having their feet drag over the floor.

Design

We chose a study method which is a mix between a quantitative and qualitative approach aimed towards better understanding user preferences and the overall experience of a 1D motion platform. The study was conducted using a within-subject design with the type of motion (*walking, driving, flying*) as independent variable. Additionally three options of motion feedback were applied (*chair rotation, chair oscillation, chair rotation & oscillation*). Participants were free to turn the options on/off according to their preferences using an Xbox 360 controller. The three scenarios were presented to the participants using a Latin square for counterbalancing. Users were encouraged to talk out loud and the whole session was video recorded, transcribed and analyzed. The motion feedback options worked as follows:

Chair rotation Using this option the chair was rotated synchronously with the virtual rotation at a fixed rotation speed. This feature could either be turned on or off.
Chair oscillation This option was applied during forward motion. Besides turning the feature on and off, participants could adjust frequency and motor strength during the oscillation.
Oscillation during rotation While either moving forward or rotating, either the rotation or the oscillation was presented. Rotating while being in motion is though a combination of both. We therefore decided to include another option that allowed participants to combine the chair rotation with the oscillation. This feature could either be turned on or off.

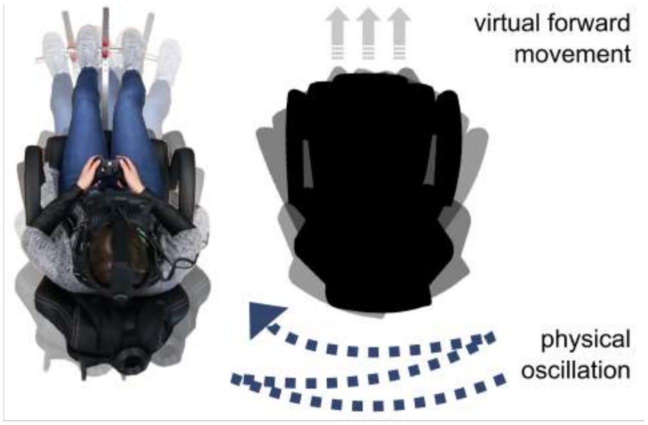

Figure 3. The *wiggle* concept is realized by letting the chair oscillate within a given rate during visual forward or backward motions. The movement is mapped e.g. steps during walking.

We designed three applications including the most common motion types: walking, driving and flying (see Figure 4).

Procedure

The study was conducted in an university lab. Participants were introduced to the topic of the study, stated their consent, and completed a demographics questionnaire. They also self-assessed their susceptibility to motion and cybersickness. After introducing the setup (chair, HMD, Xbox controller), participants were given some time to freely explore and get familiar with the setup. Then each of the three scenarios was presented in a counterbalanced order. Participants were asked to freely move in the virtual environment and test the different options for force feedback. Participants were encouraged to constantly talk about their decisions and explain why they

Figure 4. The different motion types used in the first study: a) walking scenario; b) car driving scenario; c) flying through asteroids.

did what. This was audio recorded and later transcribed and coded to deeper understand the needs for such a rotational locomotion platform.

Participants

The study was conducted with 24 participants (5 female) with an average age of 24.7 ($SD = 3.03$) years. All participants were university students or employees and participated voluntarily. Although participants showed great interest in VR technologies (mdn 6 on a 7-point Likert-scale), their experience levels varied greatly. However, the effect of this potential bias on the results could be neglected, as the target demographic of this study are all potential VR users. Participants reported low susceptibility towards motion sickness (mdn 2 on a 7-point Likert-scale), values for cybersickness were slightly higher (mdn 3 on a 7-point Likert-scale).

Measures

The study aimed to include users early in the design process of evaluating forward motion approaches for a rotational locomotion platform. We mainly wanted to find out what type of feedback can be used and how people react to the *wiggling* we designed for forward motion. We further aimed to elicit user preferences and leverage ideas about designing a locomotion platform solely on a rotational impulse. Additionally, we collected participants' preferences on oscillation and rotation values (frequency and motor strength).

Quantitative Results

The following results are based on the preferences we logged during the study and the user feedback we recorded.

Chair Rotation was a desired feature, which most participants turned on (see Fig. 5). Most of the participants that turned the rotation off reasoned their decision by the circumstance that the behavior of the character becomes too unrealistic when following the physical boundaries of acceleration. Other participants talked about an increase of the perception of actually turning and the reduction of simulator sickness.

Chair Oscillation was seen as controversial. While some participants turned it on in all conditions, others turned it off for each condition. The majority of participants desired to map chair oscillation to a virtual event (e.g. driving off-road or clashing with an asteroid), instead of using it for actual motion. As long as there was no mapping they stated to prefer some kind of vibration instead of oscillation, which they would map to the motor. In the case of walking however, 75% of the participants turned oscillation on as they mapped it on steps. Here, they chose a low frequency (2.2 Hz) for slow walking and a slightly higher frequency (3.4 Hz) for running. Participants who did not use the oscillation feature, argued again with the too intense feeling of motion, which would disturb them during longer experience.

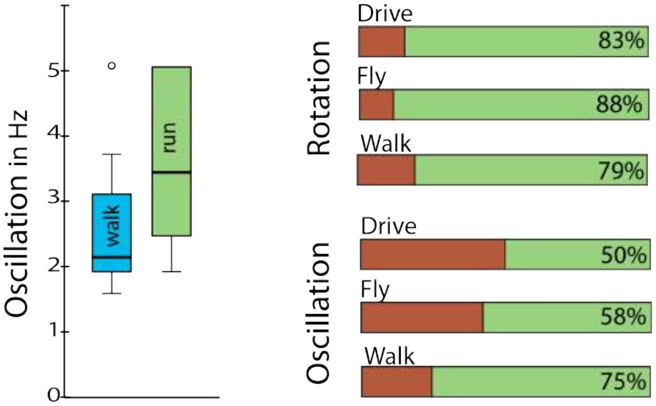

Figure 5. Participants set the oscillation to very low frequencies. As the results of the think aloud suggest, the oscillation was mapped to steps, with having a higher frequency for running (green) then for slow walking (blue). Most participants liked to be rotated with the virtual avatar, while the oscillation was only appreciated in the walking condition.

Discussion and Calibration Results

The following results are based on the thematic analysis of the transcript of each participant and the verbal feedback we collected about the rational behind each decision.

Wiggling as a good metaphor for walking: Participants mainly adapted the frequency of the *wiggle* to match a walking motion (slow for walking fast for running). Since we already are familiar with a slight nudge while walking this metaphor was positively perceived. Participants reported this could potentially increase the sense of presence but did not work perfectly with the rotation. When rotating on the spot the inertia of the chair lead to the perception one is sitting inside a robot. Overall, participants reported that it is a nice feedback mechanism but it could become annoying and cumbersome to use over a longer duration.

Stabilization of the head compensated the wiggle: During the study we observed an interesting effect when using the wiggling mechanism. When being inside the virtual scene and focusing on a certain point participants always managed to keep their head stable and thereby compensated the *wiggle*. Similar to the stabilization of the head of a chicken humans also tend to stabilize certain motion when focused on a target. Therefore, we could not use this *wiggle* motion to induce any form of signal to the vestibular system.

Wiggling as a force feedback of the environment: Participants reported that most types of feedback should rather come from the environment and would fit better to simulate the surrounding virtual world than a motion. When hit by some virtual object the chair could imitate the impact. When driving over a rough road the wiggling could mimic the underground. When flying through an asteroid field the wiggling could simulate the impact the asteroids do on the spaceship. We deducted that the wiggling motion is mainly usable to simulate environmental impact rather than using it as a metaphor for acceleration.

No big differences between the motion metaphors: Besides the incidental metaphor of walking and wiggling, participants reported no big differences between the three motion approaches (walking, flying, driving). Since the main preference was to map the feedback on the environment the actual simulation of the motion should be similar across all the modalities.

Based on the quantitative and qualitative findings we learned that our wiggling approach works best to simulate environmental properties or that it can be used as metaphor for steps during walking. Furthermore, we used the feedback to design an new motion approach. Since people reported that a constant *wiggle* is cumbersome we decided to only use one short impulse burst when a virtual acceleration occurs. To also avoid the stabilization of the head we decided to not have a one to one mapping between virtual and physical rotation of the chair but compensate for every physical rotation so the virtual direction is always fixed. This allowed us to have physical rotation while visually being stable and having a forward acceleration. This should potentially stimulate the vestibular system with an impulse and also trick the user in perceiving a forward motion. Since participants asked for the same form of motion along all three motion approaches we decided not to distinguish between them anymore and design one motion approach suitable for the general concept of forward acceleration.

SECOND PROTOTYPE

For the second prototype we implemented a general motion approach for virtual reality aiming to represent forward motion. To give vestibular cues during forward acceleration we stimulated the vestibular system with a short rotational impulse presented synchronously with visual acceleration. To make sure the rotational acceleration impulse would be mapped to forward movement we subtracted the chair's physical rotation from the visual one (see Video). By iterative testing, we adjusted the physical rotation to be short (50 ms of acceleration), but relatively strong (up to˜$20^{\circ}/m$). The idea was to create a vestibular stimulus that is strong enough to be recognized, but too short to be mapped to the actual direction. The concept is illustrated in Figure 6.

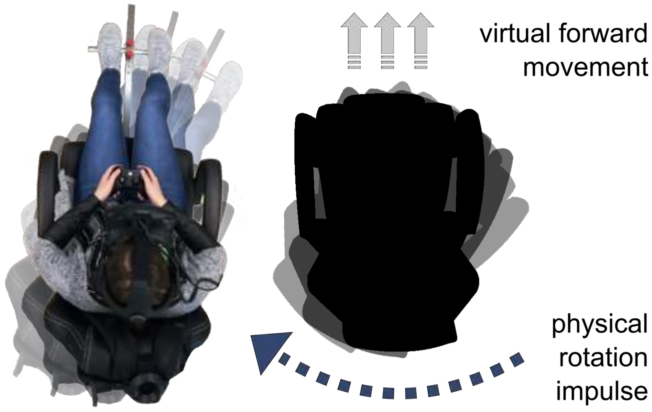

Figure 6. The *spin* concept is realized by a short rotational acceleration impulse synchronous to the visual forward or backward acceleration.

Setup

We used the same motorized swivel chair and HMD as in the first iteration. As physical and virtual rotation should be separated for this second study we used the HTC Vive controller attached to the back of the swivel chair. We added the controller's inverse rotation value to the virtual camera's one in order to remove the chair's rotation from the view. This way, the virtual camera remains in the same orientation even when the chair is rotating.

Design

The study was conducted in a within-subjects design with the form of rotational stimulus as independent variable. The participants experienced a strong but short ($20\ ^{\circ}/s^2$ over 0.3s) rotation to the right at the start of an acceleration and the inverse when braking (or accelerating backwards). The two tested conditions were (1) visual stimulus only (*visual*) and (2) visual and physical stimuli (*physical*). The order was counterbalanced using a Latin square.

Procedure

The study took place in an university lab. Participants were introduced to the topic of the study, stated their consent, and completed a demographic questionnaire. Then they were placed in a virtual environment using an HTC Vive while sitting on the motorized swivel chair. The virtual environment contained a virtual road (see Figure 7) and participants took part in an experience similar to car driving on the road. The experience comprised of several phases of acceleration and braking (as well as accelerating backwards). We designed the application in a way that acceleration, braking and constant motion alternated within small time frames. The longest phase of moving with a constant velocity was three seconds long. Overall the participants were exposed around one minute to virtual motion. For both conditions participants were passive observers of the virtual scene and did not have an active task.

After they finished all conditions, participants were compensated with 10€ . The respective experiment lasted for around 30 minutes.

Figure 7. In the second experiment the participants drove through a virtual canyon.

Participants
We recruited 20 participants (8 female) with an average age of 24.3 (*SD* = 2.7) years. They were mostly university students with a technological background. Their previous experience in virtual reality was comparably low. Seven participants stated that they had never experienced VR before, while two stated they consumed more than 50 hours of VR (mdn: 1-10 hours). 11 participants reported that they get motion sick, e.g. when reading in a moving car.

Measures
In this experiment we were interested in the participants' levels of simulator sickness, presence, and experience of vection. Simulator sickness was measured in two ways. The sickness during the experience was assesed by using the question "On a scale from 1 to 10, 1 being how you felt before the test, 10 is that you wanted to stop, how did you feel during your time in the virtual world?". To measure the symptoms after the experience we used the SSQ [13]. The participants' presence was assessed using Slater, Usoh, and Steed's (SUS) presence questionnaire [24]. To measure vection, we employed a question asking the participants to rate their feeling of self-motion similar to [10]. They propose to present an explanation of the illusion of self-motion and to rate to which degree they experienced such on a 4-point Likert scale from "no feelings of self-motion" to "very strong feelings of self-motion".

Since vection is based on the feeling of self-motion, which can also occur during longer phases of forward movement, we also asked for the more critical aspects of self-motion: acceleration and braking. These situations are also the ones considered to cause simulator sickness, which made them to be of special interest. This is also the reason why we did not include longer phases of forward motion, but included multiple, alternating accelerations and braking time frames. In addition to the prior named questions, the participants should state how much they agree to the following statements: "I felt a physical acceleration" and "I felt a physical braking". In addition, we asked the participants to state how realistic the perception of acceleration and braking was ("The feeling of physical acceleration(/braking) felt realistic". The used scale was from 1: "not at all" to 7: "absolutely".

Results
Vection: We count the vection item, as well as the own items concerning acceleration and breaking to be contributing to vection. We compared each item separately using the Wilcoxon signed rank test. Differences are considered to be significant on the 5% level, while being highly significant when being below the 1% level. Boxplots of the results are shown in Figure 8. We found a highly significant increase of vection in the *physical* condition ($p < .01$, $Z = -2.24$, $r = .50$). The feeling of acceleration ($p < .01$, $Z = -2.06$, $r = .46$) and braking ($p < .01$, $Z = -2.37$, $r = .53$) was also highly significantly increased. The perceived realism of acceleration ($p < .01$, $Z = -2.19$, $r = .49$) and braking ($p < .01$, $Z = -2.01$, $r = .45$) was also increased highly significantly.

Simulator Sickness: We asked the participants to rate the intensity of symptoms of simulator sickness during the experience on a scale from 1 to 10. Additionally, we included the SSQ questionnaire to measure the symptoms after the VR experience. Boxplots of the results are shown in Figure 8. Sickness symptoms during the experience (measured using the single question) were significantly stronger in the *visual* condition ($p < .05$, $Z = -1.57$, $r = -.35$) than in the *physical* one. Sickness symptoms after the experiences (measured with the SSQ) were rather low (visual: 19.2 (mdn), physical: 9.6 (mdn)) and did not vary significantly between both conditions ($p = .11$, $Z = -1.12$, $r = -.25$).

Presence: The SUS presence score was increased highly significant by introducing the short vestibular stimulus ($p < .01$, $Z = -1.83$, $r = .41$) and is illustrated in Figure 8.

DISCUSSION
Vection: We found that the short rotational acceleration we applied strongly increased vection compared to presenting visual stimuli only. Similar to Wright [28] we found an increased feeling of self-motion in the condition with vestibular stimulus compared to using only visual cues, though the vestibular stimulus was applied in another direction. We assume that the short duration of the vestibular stimulus was enough to increase the feeling of self-motion, while being too short to perceive its direction.

Simulator Sickness: Concerning the question how participants felt during their time in the virtual world, a significant decrease of simulator sickness in the physical condition compared to the visual one could be found. For the symptoms that occurred after the VR exposure no significant difference could be found, as for both conditions SSQ values were relatively low (visual: 19.2 (mdn), physical: 9.6 (mdn)). Although we did not find a significant difference, we observed an interesting trend towards decreased SSQ scores in the physical condition compared to the visual one. These findings were quite surprising as we applied various stimuli that are known to increase simulator sickness (multiple accelerations/brakes and short amounts of time driving with constant velocity).

Presence: Applying rotational stimuli did significantly increase the feeling of being present in the virtual world. Therefore, we assume our forward motion approach to be a natural way of simulating forward motion in virtual reality.

Countering the Conflict: Our results indicate that the approach of simulating forward (or backward) accelerations in virtual reality increases the feeling of self-motion while decreasing simulator sickness at the same time during the VR experience.

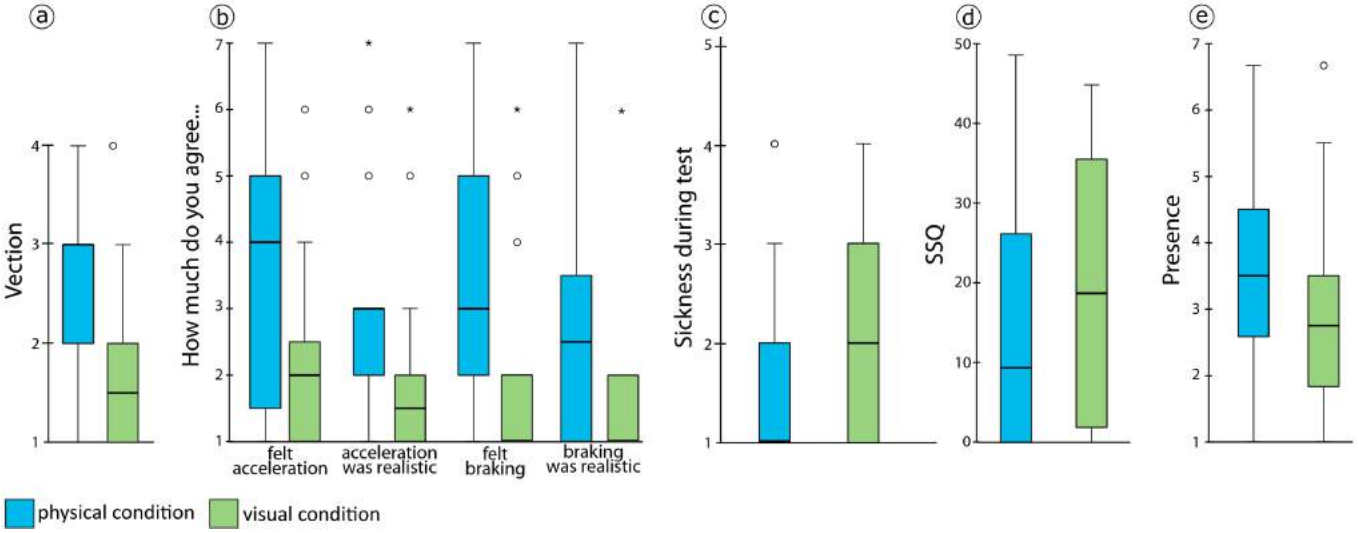

Figure 8. The results of the second study: (a) vection was significantly increased when a physical rotation was applied. (b) participants stated a higher feeling of acceleration and braking in the *physical* condition. In both conditions acceleration and braking were not considered as *realistic*, however, ratings for both were slightly increased by the physical rotation. (c) simulator sickness symptoms during the test were significantly reduced by the physical rotation. (d) there was no significant difference regarding simulator sickness symptoms after the test. (e) the SUS presence score was significantly higher during the *physical* condition.

Interestingly, these findings are in contrast to the results proposed by related work, where it is stated that an increased feeling of vection also leads to an increase of simulator sickness [10, 14]. Although we applied a rather short rotational stimulus it seems to suffice in duration and force to positively influence the experience of simulator sickness. We explain the results by avoiding a sensory conflict, which is assumed to cause simulator sickness [21], as we present visual stimuli synchronously with short vestibular stimuli and trick human perception into interpreting a rotational acceleration cue as forward acceleration.

Inducing Acceleration: Due to the short time of physical accelerating the chair, it also came to rest after a short time. We therefore used the same physical rotation stimulus for both kinds of acceleration, although they differed in terms of direction. Thus, braking was not simulated by actually reducing the velocity of rotation, but by increasing it in the inverse direction. Although participants gave lower values for the feeling of braking than for accelerating, they still had a stronger feeling of slowing down compared to the *visual only* condition. Participants also gave comparable values for realism of accelerating and braking when a physical rotation stimulus was applied. While vection can occur during longer phases of constant velocity, the feeling of acceleration is different. It is harder to induce by visual cues only, since acceleration is – in contrast to constant velocity – also measured by the vestibular system. Our results show that even acceleration can be perceived using our approach.

Less is More: While fine tuning our impulse, we were surprised how little movement actually was physically needed to simulate the acceleration that happens visually (see video). We only had to rotate for approx. $8^\circ/s^2$ with a short burst to mimic this form of visual forward acceleration. When we used a longer impulse we found several side effect that were considered unpleasant (e.g. when spinning for too long and too fast moving the head resulted in the perception of the gyroscopic effect). However, applying our short bursts resulted in a more realistic experience. We argue that this is even an advantage since it implies that to simulate this form of locomotion a 360 degree rotational platform is not necessary. To counter simulator sickness it could be enough to have 180 degree or even less.

CONCLUSION

In this work we presented *VRSpinning*, a seated locomotion approach based around stimulating the user's vestibular system using rotational impulses to amplify the perception of forward or backward self motion. We designed the feedback in a user centered design approach, involving participants early in the process and iterating the feedback mechanism. We found that participants preferred the *wiggle* mechanism as a form of feedback of the environmental impact. We further found that using a short burst of rotation with a corresponding visual forward acceleration leads to a significantly increased perception of self motion and reduces simulator sickness. Our work shows that to tackle the problem of simulator sickness and vection in virtual reality we can leverage the inaccuracy of the human vestibular system. We showed that a rotational acceleration during a visual forward acceleration can induce a perception of self motion. Based on our results we argue that different forms of "non-matching" stimuli should be tested synchronously to visual linear motion to generate the perception of self motion and fight simulator sickness.

We plan to test our approach in a self-controlled racing game to measure long term effects on simulator sickness and the effect on presence and enjoyment.

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