# CarVR: Enabling In-Car Virtual Reality Entertainment

**Philipp Hock*‡, Sebastian Benedikter*, Jan Gugenheimer*, Enrico Rukzio***
Institute of Media Informatics*
Institute of Psychology and Education‡
Ulm University, Germany
[philipp.hock, sebastian.benedikter, jan.gugenheimer, enrico.rukzio]@uni-ulm.de

## ABSTRACT
Mobile virtual reality (VR) head-mounted displays (HMDs) allow users to experience highly immersive entertainment whilst being in a mobile scenario. Long commute times make casual gaming in public transports and cars a common occupation. However, VR HMDs can currently not be used in moving vehicles since the car's rotation affects the HMD's sensors and simulator sickness occurs when the visual and vestibular system are stimulated with incongruent information. We present CarVR, a solution to enable VR in moving vehicles by subtracting the car's rotation and mapping vehicular movements with the visual information. This allows the user to actually feel correct kinesthetic forces during the VR experience. In a user study (n = 21), we compared CarVR inside a moving vehicle with the baseline of using VR without vehicle movements. We show that the perceived kinesthetic forces caused by CarVR increase enjoyment and immersion significantly while simulator sickness is reduced compared to a stationary VR experience. Finally, we explore the design space of in-car VR entertainment applications using real kinesthetic forces and derive design considerations for practitioners.

### ACM Classification Keywords
H.1.2 User/Machine Systems:: Human factors; H.5.2 User Interfaces:: Haptic I/O, Prototyping, User-centered design

### Author Keywords
force-feedback; motion platform; immersion; virtual reality; automotive; entertainment; gaming

## INTRODUCTION
Mobile virtual reality (VR) is currently becoming a consumer product. Major companies such as Google (Cardboard), Samsung (GearVR) and Zeiss (VR One) are releasing high-quality and low-cost mobile VR head-mounted displays (HMDs). Due to their low price and easy accessibility, they are more likely to penetrate the consumer market. One of the major application scenarios for current consumer VR HMDs is entertainment,


CHI 2017, May 06 - 11, 2017, Denver, CO, USA

ACM 978-1-4503-4655-9/17/05...$15.00
DOI:http://dx.doi.org/10.1145/3025453.3025665


**Figure 1. A player is sitting on the front passenger seat playing the game while the car is moving. Kinesthetic forces caused by the car match the movements in VR.**

and gamin in particular. With its ability to generate highly immersive environments and manipulate a user's time perception [29] in a mobile scenario, mobile VR has the potential to revolutionize casual gaming for commuters.

However, current mobile VR HMDs cannot be used inside moving vehicles. Rotations of the vehicle are interpreted as the user's head movements resulting in unintended shifts of the virtual environment. Additionally, the mismatch between virtual movement (visual system) and the perceived physical movement (vestibular system) can lead to simulator sickness [25].

This work introduces CarVR, a solution to enable VR in moving vehicles by subtracting the car's rotation and mapping vehicular movements with the visual information (Figure 1). We present the design and implementation of a working prototype consisting of a Samsung GearVR, a mobile inertial measurement unit (IMU), and a car diagnostic tool (OBD-II). In a user study (n = 21), we show that CarVR significantly increases enjoyment and immersion over a stationary experience while reducing simulator sickness. Finally, we provide an analysis of the design space for developing VR entertainment in moving vehicles and present design considerations for practitioners.

Our main contributions are (1) the concept and implementation of CarVR, a proof-of-concept prototype enabling VR in moving vehicles, (2) findings of our user study (n = 21), showing a significant increase of enjoyment and engagement and reduced simulator sickness using CarVR in comparison to a stationary setup, and (3) an analysis of the design space of VR entertainment applications inside moving vehicles and a set of design considerations for practitioners.

Our work shows that the usage of VR in moving vehicles is not only possible, it is more fun and less vertiginous than while not moving. Thus it can be used to bridge the time when traveling or to improve the traveling experience as an additional offer in general. Taxis and buses could provide VR entertainment as an additional offer. It can also be used to entertain children on the road, reducing the dangers of distractions.

## RELATED WORK

The idea of combining VR with a moving vehicle has several related research topics. First, we give an overview of projects and research regarding VR in moving vehicles. Then, related work regarding the use of kinesthetic forces in VR is presented, followed by research that addresses game design in cars. Subsequently, related work regarding the design space of being a passenger while playing games is reported. Finally, we explain simulator and motion sickness.

In a PR campaign by Jaguar [17], participants were seated in a moving Jaguar F-Type while wearing a VR device. In their campaign, Jaguar pretended that the visual information was a simulation and kinesthetic forces were simulated by a hexapod hydraulic platform. In reality, the visual and kinesthetic forces were real, what people felt and saw was real motion caused by the car, instead of a VR simulation as alleged. In their PR video, Jaguar stated that participants had no idea that they were actually being driven. Though the whole VR impression was not real, the idea of our work is very close to Jaguar's campaign: improving the VR experience by using kinesthetic forces of the moving vehicle. A similar project was realized by Lockheed-Martin [2]. They prepared a school bus in a way that it could create the impression of driving on Mars. This was realized by projecting images of Mars' surface onto the windows of the bus. While the bus was driving through the city, movements of the bus were mapped to visualize a corresponding route on Mars with actual Mars images. The idea of the project is also very close to CarVR, however both the Mars and Jaguar projects lack an evaluation regarding immersion, enjoyment or any kind of sickness. Bock et al. [6] propose a driving experience in VR, but in contrast to CarVR, their work focuses on driving while wearing a VR device, allowing an augmentation of the driving experience, for example by virtually presenting other traffic or infrastructure. A combination of moving in reality and experiencing similar, sometimes even partially exaggerated visual information in VR, is found in the upcoming *VR coaster*, wherein people are sitting in real roller coasters while wearing VR HMDs [22].

Breaking it down to the very basic idea, CarVR enables kinesthetic forces in VR and therefore improves the VR experience. Gugenheimer et al. [14] proposed *SwiVRChair*; a VR storytelling device that enhances the VR experience by rotating the user to face certain directions. Their goal was to build a chair that generates kinesthetic feedback to match virtual movements. Findings were that the physical movement reduced simulator sickness and increased enjoyment.

Danieau et al. developed a chair equipped with force-feedback devices to apply forces while playing games or watching videos [10]. It was shown that in combination with visual information, their seat could trigger the sensation of motion thus improving the quality of the experience. In contrast to CarVR, motion is only applied to parts of the body, rather than the whole body. Their technique could be complementary applied to a car complementary alongside CarVR. *Haptic Turk* [8] aims to enhance the (VR) experience by applying kinesthetic forces. In their work, participants were used to apply forces to a single user that is wearing a VR device. *Birdly* [26] aims to enhance the VR experience of flying by adding wind that is blown into the user's face. The user lies in a belly-down position on a platform that acts as an input and output device for the user's extremities.

CarVR enhances the VR experience by exploiting real world properties, such as kinesthetic forces and movement. A similar concept was shown by Simeone et at. [30]. In their paper, they exploited physical objects like chairs, tables and walls to enhance the immersion. In CarVR, real forces of a moving vehicle are used to enhance the immersion.

Besides enhancing immersion, CarVR aims to enable VR gaming in moving vehicles. Bichard et al. developed *Backseat Playground* [4], a framework designed to enable playing games as passenger in the backseat of a car. Their framework adapts to the current environmental conditions, such as geo-location. Exploiting environmental conditions to build up the virtual scene is also a core idea of CarVR. Here, the player follows the same route that is driven by the car. In an advanced future implementation, the world could be built on the trajectory and route planning of the car. Sundström et al. [36] developed games where the sitting pose in the car is an integral part of the game. However, their intention was to teach children how to sit properly in cars.

Brunnberg et al. investigated the design space of passengers in [7]. In their work, they focus on location-based games, like interactive storytelling. An interesting finding is that movement speed has an influence on the perceived vulnerability. Participants stated that driving slowly or standing creates the feeling of being more vulnerable whereas driving fast feels more like observing the environment.

While sitting in a car, especially when being a passenger, the journey often seems never ending and time is wasted. Entertainment applications are useful tools to overcome boredom and make time pass by faster. VR can increase such an experience. In [29], Schatzschneider et al. show that the perception of time can be influenced in VR, for example by manipulating the movement of the sun.

Motion sickness is a wide-spread problem and affects nearly one-third of all people who travel by land, sea, or air [27]. It is a condition marked by symptoms of nausea, dizziness, and other physical discomfort. It has been shown that visual stimuli have the most impact on provoking motion sickness [16]. Activities like watching a video or reading, abruptly moving the head or looking down in a moving vehicle lead to symptoms of motion sickness [23]. The reduced ability to anticipate the direction of movement can also lead to motion sickness [5]. Passengers with no external forward view cannot see the road ahead and are not able to predict any further motion. Even the absence of a visual field by restricting the outside view [37], or the lack of control over the direction of motion can cause sickness [28].

Symptoms of simulator sickness include dizziness, drowsiness, headache, nausea, fatigue and general malaise [18], for which speed and acceleration are influencing factors [34]. Simulator sickness is a form of visually induced motion sickness and occurs without actual motion of the body [19]. People who are prone to motion sickness in vehicles tend also to experience simulator sickness [35]. Simulator sickness can occur in stationary driving and flight simulators. The user can see a visual motion but remains stationary in the simulator. Movement in the virtual environment can lead to illusory perception of self-motion (*vection*), which is one of the main reasons for simulator sickness [15].

## VR IN CAR: CONCEPT

In our concept, the player has the role of a passenger sitting on the front passenger seat. Consisting of a mobile VR device and external sensors to measure vehicle dynamics, the lightweight and portable setup has affordable hardware requirements: an measured by an inertial measurement unit (IMU) to measure the rotation of the car, an on-board diagnostics (OBD) II reader to measure the speed of the car, and a VR HMD (see Figure 2). Although the driver is not involved in the game mechanics, their part of the game is to drive the vehicle. Driving the car is not intended to be the main purpose of the ride. Instead, playing the game is intended to be part of the ride.

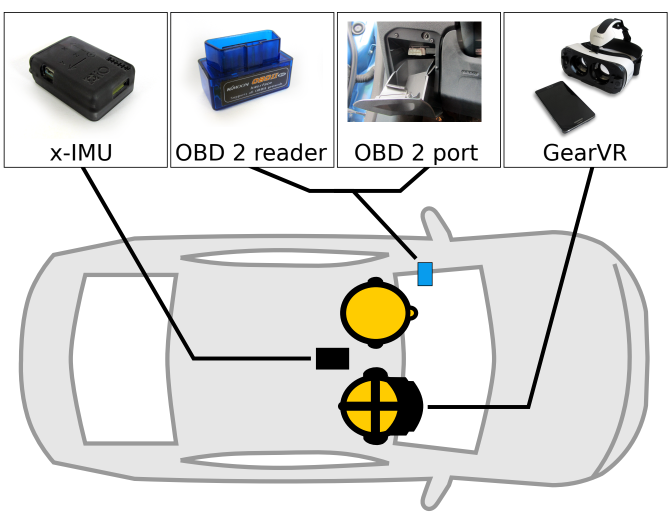


**Figure 2. Schematic view of the position of devices and people involved in the apparatus. The driver acts as normal driver, following a route to a destination, the co-driver is playing the game on the font-passenger seat with a Samsung GearVR attached. An x-IMU measures the vehicle's inertia. An OBD-II reader attached to the car's diagnostic port is used to measure the car's velocity.**

The movements of the vehicle influence the gaze direction in VR because the inertial sensor of the VR device cannot distinguish between head movements and the yaw-rotation of the vehicle. Increased nausea are likely to occur because of a combination of simulator and motion sickness.

To compensate for vehicle movements, two approaches are possible: (1) subtracting the vehicular rotation in the VR scene by an IMU placed inside the car. This allows for example VR scenarios where the player is not moving at all. Interfering forces are subtracted. (2) Mapping the vehicle movements with the movements in VR. The movement of the car is rendered in VR. The former has the benefit that the VR scene has no restriction in mobility. However, this approach does not address motion sickness, the incongruence of visual and vestibular information remains. The latter has the benefit that occurring acceleration forces of the vehicle are in line with the forces in VR. To enable VR in moving vehicles, we use the second approach: actual movements of the vehicle are used as input for the player movements. We show that this increases immersion, enjoyment, engagement and reduces simulator sickness.

This approach's drawback is that the movements in VR are predefined by the route of the vehicle. This restricts the content of the VR scene to some sort of guided tours, where the user has no or little influence on the provided route. A common application of this scenario is found in rail shooters, where movements of the player are predefined. Aiming and firing remaining the main task. Further, unpredictable changes in velocity or direction may not be adequately represented in VR. The virtual scene has to adapt to the driving conditions; for example, when the car suddenly stops, an appropriate reason for this should be presented in VR.

On the other hand, realizing continuous movement in VR while not actually moving in the appropriate direction, like moving forward in VR while sitting in reality, causes increased simulator sickness. Our approach solves this problem.

## DESIGN SPACE

The design space for VR entertainment can be categorized into two applications, as discussed in the previous section: one that compensates the forces caused by movements of the vehicle, and applications that exploit these forces. An application that compensates these forces could be a seated in a VR cinema, where occurring kinesthetic forces must be compensated in a way that the VR device does not interpret these forces as head movements. This can be done by placing an IMU inside the vehicle and calculating a compensative rotation of the camera. The problems of increased simulator sickness, or in this case, motion sickness, remain. Following the approach of exploiting kinesthetic forces, we provide an analysis of the design spaces subsequently.

*Level Design:* The connection between real life movements and VR movements make level design important. The virtual world can be generated along a planned route, for example by using the route to create a depth map (see Figure 3).

If the car deviates from the planned route, the change in the environment must be somehow included in level design and

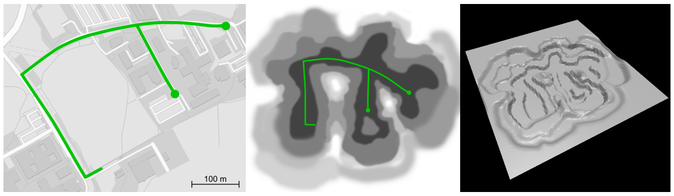


**Figure 3. Route generation based on predefined route. (left) The trajectory is extracted from the topology, (center) A depth map based on the trajectory is generated. (right) The terrain according to the depth map is generated.**

story. To address this, alternative routes or even a whole city could be modeled or generated. The integration of the story could be an important aspect when it comes to storytelling and immersion. The immersion of flying through a canyon can be disturbed when the car brakes due to traffic conditions, while in VR, no reason for a sudden stop is presented. The story of the VR scene should react to such changes. To overcome most of these problems, a route-independent world can be used, like space or air. The user then flies above obstacles. Sudden changes in speed can be interpreted as asteroids in space or debris. However, a lack of cues where the car and therefore the player is heading might be a problem: unpredictable directional changes result in increased simulator sickness.

*Velocity:* Visual cues are important for the perception of self-motion [13]. In an environment with few objects, for example in space, additional elements should be rendered in the scene that also react to player movements. Depending on the story, dust, rain, snow, and other particles can be used to provide visual cues to support the impression of velocity.

*Acceleration:* Acceleration is a change in velocity, therefore the visualization of movement also visualizes acceleration. To emphasize the effect of acceleration, game designers often use motion blur. However, using motion blur in VR will result in increased simulator sickness [24]. Alternatively, a warp effect can be used (see Figure 4).


**Figure 4. The warp effect can be used to visualize acceleration.**

*Rotation:* The occurring forces while driving cause a weight transfer of the car. Braking, accelerating and turning result not only in rotations along the yaw axis, but also along the pitch and roll axis of the car, which can be applied in VR. The Oculus guidelines discourage from a rotation of the horizon line [1]. This limitation can be overcome by rendering the player inside a cockpit, where the rotation is applied instead. The horizon line stays as point of reference (see Figure 5).

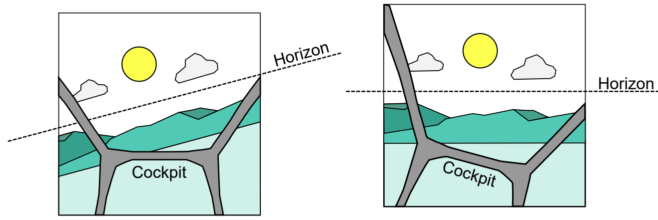


**Figure 5. Two approaches of visualizing roll rotation. Left: the cockpit and the camera rotates along the roll axis. Right: only the cockpit rotates along the roll axis, the camera's roll rotation stays in line with the horizon. This concept also applies for the pitch axis.**

The degree or even the direction of rotation can be altered. We tested altering the direction in an informal self-evaluation. When accelerating, the cockpit is normally rotated upwards, and when decelerating, downwards. When inverted, the cockpit rotates upwards on deceleration and vice versa (see Figure 6). For a rotation along the roll axis, a rotation as well as an inverse rotation were reported as realistic but the interpretation was different: when rotation is inversed, it would feel more like flying. This sounds reasonable because an airplane flying a curve, would roll towards the curvature. On a rotation along the pitch axis, participants stated that the inverted rotation feels unrealistic and uncomfortable. This is surprising because this would match a helicopter's behavior. Further research regarding force shifts is necessary. One possible explanation could be the dominance of our visual sense. Our mind often accepts visual information as the highest priority; this is known as the *Colavita visual dominance effect* [9, 20]. When the conflicting information is subtle enough, the visual impression might be dominant enough to suppress the incongruent information from the vestibular system. However, when the conflicting sensory information from the vestibular system is strong enough, the reported feeling of disturbance can occur. In the aforementioned situation, this could be the case: the lateral forces on the roll axis might be subtle enough that the dominance of the visual system is strong enough. The inverted roll movement is accepted despite incongruent visual and vestibular information. However, longitudinal forces along the pitch axis when accelerating are strong enough to be in conflict with the visual impression.

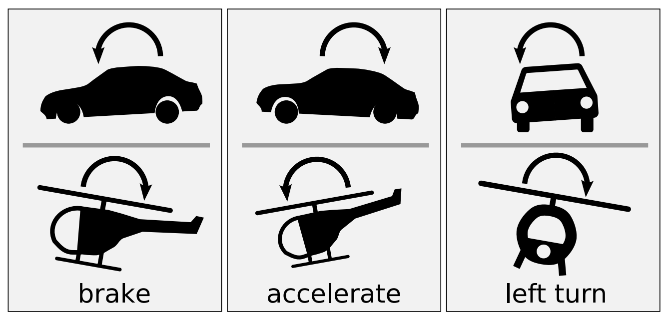


**Figure 6. Effects of vehicular rotation while braking, accelerating and turning. The weight transfer due to inertia in a car forces the car to rotate forward when braking, backward when accelerating on the pitch axis, and towards the outside of a curve when turning on the roll axis. The rotation in a helicopter behaves inversely.**

*Springs:* Occupants perceive vertical forces as shaking, vibrating, or bouncing in the vehicle. When driving and watching the road ahead, it remains stable because of the vestibulo-ocular reflex; the motion is visually filtered out. However, these forces can be recognized by observing dirt on the windshield. While the road remains stable, the dirt shakes and bounces up and down. This means that vertical forces are visually perceived by the moving interior of the vehicle, as is angular motion. To visualize vertical forces in virtual reality, they can be added to a virtual cockpit. To make the appearance of vibrating and bouncing realistic, springs and dampers of the vehicle can be simulated by a physics engine. Measured vertical acceleration from the moving vehicle is mapped to the mass of the cockpit and pulls it downwards. The attached spring tries to pull the cockpit back to the default position. The cockpit begins to oscillate up and down elastically. The damper weakens this motion and prevents the spring from oscillating endlessly. The strength of spring and damper can be configured. These values were heuristically evaluated and tested. Wrong configuration quickly leads to an unrealistic and disturbing behavior of the cockpit.

*Force Shifts:* The movement of the vehicle and the movement of the player in VR are not necessarily mapped 1:1. An altered representation in VR is possible, we call this *force shifts*. Forces can be exaggerated, understated or completely different. A 90 degree turn might result in a virtual 30 or 120 degree turn. Redirection techniques are used in other studies to distort the user's motions. Azmandian et al. showed that such illusions work on grabbing objects [3].

The *Einsteinian equivalence principle* states that the effects of gravity are indistinguishable from certain aspects of acceleration and deceleration [11]. This means that sensing acceleration of a car in VR cannot be distinguished from a gravitational force. This allows us to shift forces in VR, meaning that it is possible to render a completely different physical condition, like being attracted by gravitational forces, when the occupants are exposed to acceleration forces. Acceleration and deceleration could also result in rendering the player flying up and down. The concept of force shifts has to be investigated further; this concept has not been tested in user studies so far.

## IMPLEMENTATION

As a proof of concept and study apparatus, we implemented our concept as a 3D VR rail shooter. The game is intended to be played by a passenger. While the car is moving, the player inside the VR scene moves the exact same way as the car does. The player position is defined by the vehicle. The player has the ability to aim and shoot a laser beam towards the gaze point by pressing a button on a wireless game controller. The view is from inside a cockpit (see Figure 8). In the scene, the player can shoot at 34 balloons, while a counter shows how much balloons are already hit and left. To support aiming, a target lock was implemented that helps the player to aim at the balloons because gaze aiming turned out to be frustrating without target lock due to subtle movements of the car that disturbed proper aiming which could not be filtered out. The vehicle in the game is realized as a helicopter, flying in a valley. The map is static, no dynamic route adaption is implemented. Therefore, the map is tailored to a fixed track. The map is shown in Figure 7.

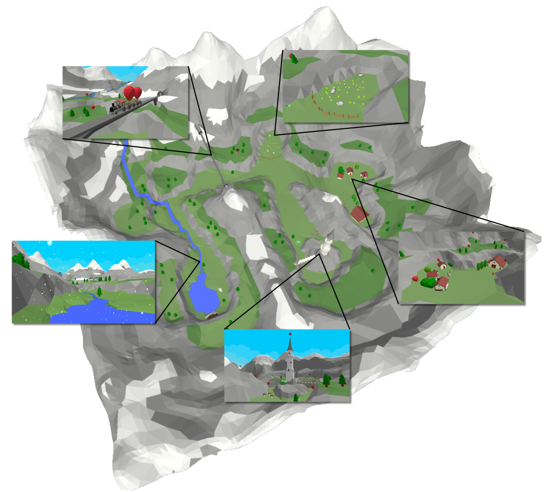

**Figure 7. The scene the player is flying through. The map is a valley with different highlights (a train, sheep, houses and a castle). The five small images show the view from the ego perspective but without the cockpit.**

When moving, not only the vehicle's yaw axis, but also the roll and pitch axis are delegated to the game. The yaw axis is mapped to the helicopter and the player, whereas the pitch and roll axis influence only the helicopter, resulting in motions of the cockpit, but not the player. The horizon-fixed view with a rotating cockpit was chosen because this is already applied as best practice in VR to reduce simulator sickness.

The game starts as soon as the car moves. The environment is designed as a valley,which the player flies through. The map encompasses 810 km$^2$. The path of the corridor corresponds to a predefined track in reality. Visual cues and details were placed to make the scene more interesting: trees, houses, sheep, a castle and a train (see Figure 7). Snow flakes in the air were added to amplify the perception of movement in the scene, especially acceleration and deceleration. Acceleration is additionally supported by a warp effect. The graphical representation is optimized for maximum performance in order to achieve an adequate frame rate that ensures a minimal amount of simulator sickness.

The game was implemented with the Unity 3D game engine. A Samsung GearVR with a Samsung Galaxy S6 Edge mobile phone was used as the VR device.

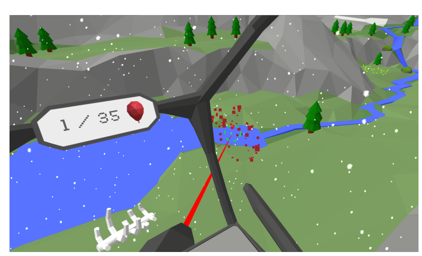


**Figure 8. The view from inside the cockpit. A balloon is shot through aiming via gaze and shooting via button press on a game controller.**

### Sensors

To measure the vehicle position, speed and direction, we combined different sensors. The sum of the car and head rotation are measured by the head-mounted display (HMD). When the vehicle rotates, e.g. when turning, the HMD's sensors measure such turns. Because the HMD is on the player's head, not only the car's rotations but also the player's rotation are measured by the HMD. The HMD cannot distinguish between these two rotations. Therefore, the car's rotation is measured by an IMU placed inside the car. With this, we can calculate the head rotation alone. This enables us to gather all rotations independent of any parent rotation. The car's movement is calculated by dead reckoning (using rotation and speed). Speed is measured by the OBD-II reader. The OBD-II reader was connected to the car's service port and via Bluetooth to the phone to measure the vehicle's speed and send it to the game. We used the OBD-II reader in combination with an x-IMU to measure the vehicle's location and speed instead of GPS, because GPS was not accurate enough and update cycles of the provided data were too slow. Increasing immersion and reducing simulator sickness demanded update cycles in rendering and sensors to be as fast as possible.

The information of the x-IMU represents the car's rotations. Therefore, the x-IMU sensor data is mapped to the cockpit. The OBD-II sensor data represents the car's speed, which is mapped to the player and the cockpit to move the cockpit with the player inside. The GearVR's inertial measurement sensor is mapped to the player, not the cockpit, to represent only the player movements. Because the GearVR's IMU measures also the rotation of the car, cockpit rotation and player are not linked in the game.

The inertial and magnetic as well as the quaternion data output rate of the IMU was set to 64 Hz. The update rate of the OBD-II reader was set to 10 times per second. To get an absolute reference for the heading, the internal algorithm mode was set to Attitude Heading Reference System (AHRS). In order to prevent lags, speed as well as the rotation data was interpolated linearly.

## STUDY

Our research question in the study was whether the presence of real forces of a moving vehicle that match the forces of a player in VR, increase the player experience and reduce simulator sickness in our prototype. In the study, the independent variable was the vehicle's state. In one condition, the vehicle was moving (*moving condition*), in the other condition, the vehicle was not moving (*parking condition*). As dependent variables, simulator sickness, engagement, enjoyment and immersion were measured using the SSQ, $E^2I$ and a questionnaire that directly compares the two conditions directly after both trials. According to our research question, we derived the following hypothesis: H1: *Participants will report more engagement, enjoyment and immersion in the driving condition compared to the parking condition.* H2: *Participants will report less simulator sickness in the driving condition compared to the parking condition.*

### Procedure

The participants were seated on the front passenger seat. They were informed about the purpose of the study and the following procedure. A consent form was filled out subsequently. Before the first trial was started, participants filled out questionnaires about demographical data and motion sickness. In the latter questionnaire, questions were asked about situations in which participants might generally feel motion sick while traveling. Lenses and the head strap were adjusted. After the participants had familiarized themselves with the hardware and the game. The order of the conditions was chosen according a Latin square to ensure a counterbalanced setup. Either the parking condition or the moving condition was started first. During the trials, the participants played the game. In the moving condition, the vehicle moved along the same trajectory as the player in VR, albeit in a scene and context that differed from the real world. The game vehicle was a helicopter and the area was a canyon where the participant had to shoot at balloons. Shooting at balloons was achieved by directing a crosshair by gazing at a target and pressing a button on a gamepad. A target lock supported aiming by locking on the target when the crosshair was near the target. Before each trial, participants could shoot at three balloons to become accustomed to shooting. Shooting was added to the trails as an element of gameplay and to avoid boredom. In the parking condition, the vehicle was standing, but participants flew the same track and had the same task as in the moving condition, but without kinesthetic forces. To isolate them from surrounding noises, participants wore headphones in both conditions. After each trial, the participants were asked to complete the $E^2I$ and SSQ. After the first trial, the GearVR could be adjusted again. As soon as participants felt comfortable to start, the second trial was started. After the second trial, an additional questionnaire was filled out that directly compared the two conditions regarding simulator sickness and enjoyment. Each trial took about five minutes. The study lasted about 40 minutes.

### Participants

In the study, 23 participants (5 female) between 19 and 44 ($M = 26.17$, $SD = 5.04$) years old took part. Recruitment was achieved through flyers, social media advertising and personal approach of random people. Our sample was randomly selected, although the recruitment mainly took place at university. However, we do not consider this a limitation because we assume that potential consumers and early adopters are well represented by this sample. 10 participants were students of computer science or similar. One participant was excluded due to severe symptoms of simulator sickness in the parking condition. Another outlier was excluded because the values of simulator sickness was higher than the three-fold standard deviation. Post-study video analysis showed that the car had to drive backwards to turn during the study, this behavior was not correctly displayed in VR, which my have caused that reaction.

Therefore, from initially 23 participants, 21 participants were taken into the analysis. On average, the participants spent 3.17 ($SD = 1.42$) hours as driver and 1.43 ($SD = 1.43$) hours per week as passenger. 14 participants had never before worn a VR devices and reported this as a reason for participation. 5 Euros were paid for participation.

### Apparatus

A Samsung GearVR with a Samsung Galaxy S6 Edge was used as the VR device. A wireless game controller was used for additional input to fire at balloons. Participants also wore around-ear headphones to isolate the VR experience from distractig outside sounds, for example engine sound or construction site noise. Participants were recorded to capture their behavior during the study. The vehicle used was a Ford Fiesta with 5 seats and about 60 kW engine power. An x-IMU was used to measure the vehicle's kinesthetic forces, while an OBD-II reader was used to measure speed. For the communication between the x-IMU and smartphone, as well as between the OBD-II reader and smartphone, we used Bluetooth. The track was a 2.2 km circuit on a public road; because of the direct mapping, the track in VR was also 2.2 km (see Figure 9).

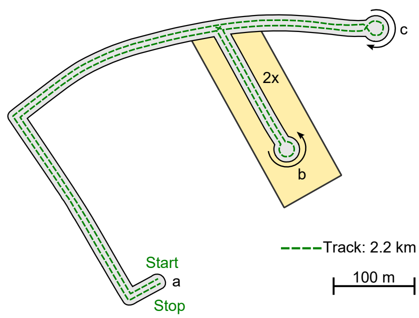


**Figure 9. The track driven during the study consisted of 6 curves (3 left-hand and 3 right-hand 90-degree curves) and three 360-degree turn (2 left-hand and 1 right-hand). It started in the parking lot (a). After three right-hand curves, the first 360-degree turn (b) was reached. Followed by another right-hand curve, the second 360-degree turn (c) was reached. Then after a left curve, the track went back to the first 360-degree turn (b). After three further left-hand curves, the track ended in the parking lot from the beginning s(a).**

### Design

A within-subject design with repeated measures was chosen because we assumed that assessment of simulator sickness and enjoyment are dependent on personal attributes and therefore only meaningful in high sample sizes. After both trials we also asked participants for a comparison of simulator sickness and enjoyment. This was done because we expected the SSQ and $E^2I$ to be less accurate in measuring significant effects. The conditions were counterbalanced by a Latin square. Vehicle movement was used as the independent variable, resulting in two conditions: a trial in which the vehicle was standing (parking condition) and a trial in which the vehicle was driving (driving condition). In both conditions, the same virtual route was driven in the game. As dependent variable, simulator sickness, engagement, enjoyment and immersion were elicited by the SSQ [18], $E^2I$ [21] and a comparing questionnaire after both trials. Participants rated enjoyment, presence and general physical discomfort on the final questionnaire.

### Results

For all items, a 7-point Likert-Scale was used. A Shapiro-Wilk test showed that all $E^2I$ scores were distributed normally:

**Table 1. Results of the Shapiro Wilk Test for the $E^2I$ score and subscores showing that all scores were distributed normally.**

| | Shapiro Wilk | | |
|---|---|---|---|
| | Statistic | df | Sig. |
| $E^2I$ Total Score (Parking) | .929 | 21 | .134 |
| $E^2I$ Total Score (Driving) | .973 | 21 | .792 |
| $E^2I$ Presence Score (Parking) | .974 | 21 | .825 |
| $E^2I$ Presence Score (Driving) | .985 | 21 | .976 |
| $E^2I$ Enjoyment Score (Parking) | .946 | 21 | .290 |
| $E^2I$ Enjoyment Score (Driving) | .911 | 21 | .058 |

A subscale score for presence and enjoyment was calculated using separate items from the questionnaire. This allowed us to compare a total score, a presence score and an enjoyment score from the $E^2I$. Analysis of the three scores was performed by a paired-samples t-test (see Figure 10). In all three scales, a significant difference was found when comparing the two conditions driving and parking:

**Table 2. Test statistic of the paired samples t-test for the $E^2I$ score and subscores.**

| score | t(20) | p |
|---|---|---|
| total | -5.84 | p < .001 |
| presence | -4.11 | p = .001 |
| enjoyment | -6.30 | p < .001 |

The according means and standard deviations are as follows:

**Table 3. Means and standard deviations of the $E^2I$ score and subscores.**

| | total | | presence | | enjoyment | |
|---|---|---|---|---|---|---|
| condition | mean | sd | mean | sd | mean | sd |
| *parking* | 3.64 | 1.01 | 3.67 | 1.00 | 3.60 | 1.32 |
| *driving* | 4.53 | .73 | 4.28 | .73 | 4.90 | .88 |

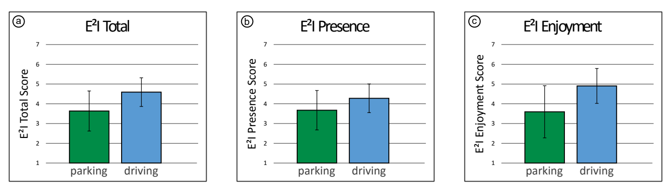


**Figure 10. $E^2I$ total score and subscale score for the two conditions parking and driving. It can be seen that the rating for driving in all three scores (total, presence and enjoyment) is higher than for the parking condition. The effect is significant. Error bars represent one standard deviation of uncertainty**

These results suggest that vehicle movement really affect the $E^2I$ score, and also that engagement, enjoyment, and immersion increases when playing the game in the moving condition. The effect size indicated that the effect was substantial.

To evaluate simulator sickness, the SSQ score for each condition was calculated. A Wilcoxon Signed-Ranks Test was used because no normal distribution was given. The test revealed no significant differences ($T = 58, Z = -.520, p > 0.05, Mdn_{parking} = Mdn_{driving} = 11.22$).

Additionally to the SSQ, participants had the chance to compare simulator sickness directly as an item in the final questionnaire. The question was about physical discomfort concerning both conditions.

A Shapiro-Wilk test showed, that the data significantly deviated from a normal distribution ($p < 0.05$). A Wilcoxon

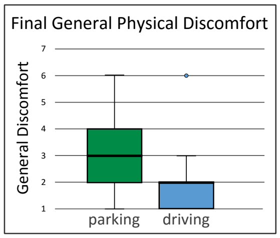


**Figure 11. Directly compared simulator sickness between the parking condition and the driving condition.**

signed-ranks test reveled a significant lower reported simulator sickness ($T = 84, Z = 2.72, p < .01$) in the driving condition ($Mdn = 2$) compared to the parking condition ($Mdn = 3$). Figure 11 shows the results of the final comparison regarding general discomfort between both conditions.

### Discussion

Our study revealed significantly more presence, enjoyment and engagement in the moving condition. Also the calculated subscores for presence and enjoyment were significantly higher in the driving condition.

Results of the SSQ were not significant. This indicates that the driving condition did not cause less simulator sickness. However, we believe that in this case, the SSQ is not accurately enough to measure the differences of simulator sickness in the two conditions. The SSQ was designed for extreme situations in military aviation scenarios for pilot candidates for whom it is more likely that severe symptoms occur than in VR scenarios. The SSQ measures simulator sickness by asking for symptoms like headache, sweating, fatigue or burping. Therefore, we think that such questionnaires are generally good to measure the presence of simulator sickness but tend to deliver insignificant results when it comes to a comparison between two or more systems where only some of the symptoms occur at all. In other research the SSQ had no significant differences while other questionnaires showed significant results, for example [38, 12].

The results of the final direct comparison regarding general discomfort indicates that a difference in simulator sickness occurred between both conditions. During the study, self reports of participants clearly indicated that the sickness was lower in the driving condition.

The results of the $E^2I$ and the final questionnaire indicate that both hypotheses can be confirmed: engagement, enjoyment and immersion is higher while simulator sickness is lower when the game is played in the moving vehicle compared to the condition where the car is standing while playing.

Participants reported the movement and visualization as realistic and that movements enhance the feeling of flying. One participant stated that the matching between the actual ride and the virtual ride feels great. Another mentioned that in the moving condition, an actual feeling of flying occurred. Our findings are in line with other research that states that perceived movements that match the visual information increase the sense of presence [31, 32, 33]. Participants completely lose their sense of where the car was moving in the real world. No participant could tell the pathway of the actual track afterwards. It was stated that feeling real motion to a corresponding visual impression was exciting and entertaining whereas visually perceived locomotion without kinesthetic forces was reported as uncomfortable, especially when flying curves and during acceleration. Overall participants reported playing in the moving condition as more enjoyable in the final questionnaire. Only two participants stated that the experience is equally enjoyable in both conditions.

Another interesting finding was that some participants reported that as a front-passenger, they felt engaged in the traffic situation as well. Being in VR creates a certain dissonance between the wish of participating in the real traffic scenario and being isolated in VR.

In the final questionnaire, situations with most discomfort were asked. In the moving condition, braking was reported as uncomfortable, the reason for this could be the surprising character of the action. Flying curves could be anticipated because the map was a valley where the player flies through, therefore the track was predictable. However, braking was not. This finding could also be interesting when designing levels. The map could also be designed without visual cues of the track, which may lead to an overall increase of simulator sickness.

### Design Considerations

In this section, we present design considerations for developers based on (1) statements made by participants during the study, (2) observations by the developer and experimenter during developing, testing and conducting the study and (3) by qualitative user feedback at the end of each trial during the study.

*Create an awareness of time:* As mentioned in the discussion, participants completely lose their awareness of where they are in the real world. Furthermore, we experienced through the development of CarVR that the sense of how much time has passed since the beginning of the ride can also be distorted. Especially when driving in public transport, this awareness should be included in the game because missing a train station or bus stop while playing is very likely without such measures. This could be done by estimating the time of arrival and limiting the game duration to that amount.

*Develop for visual dominance:* In the design space section, we mentioned that the rotational axis can sometimes be inverted. While accelerating, the inversion of the pitch axis led to an uncomfortable feeling but inversion of the roll axis while turning was perceived as realistic. The situations where the visual representation of forces can be altered are not intuitive and may depend on several factors. Designers of VR entertainment systems should keep in mind that the sensory information is commonly the one that is accepted as truth while information that is diverging from the visual impression is interpreted as erroneous, and if this error increases, the feeling of discomfort might occur. Deviating the visual from the vestibular information is possible but only to a certain point. This point differs between users and use cases.

*Prevent sickness through predictability:* When designing levels, it might be a tempting approach to create levels that are independent of the track driven in real world. For example flying in the air, over a city or in space. However, an important aspect of increased simulator sickness is the absence of predictability. Sudden and unpredictable changes in direction are likely to increase simulator sickness. Therefore, some sort of visualization of upcoming turns should be included in the game. In our prototype, we visualized the route by generating a canyon along the track. This approach is a very intuitive and realistic realization but in real world scenarios hard to achieve. Not only generating a complete level along the track would be necessary, also reacting to unforeseeable changes of the actual route should be included in the story line and level generation algorithm. A rather simple approach could include some sort of open space where auditory information predict upcoming turns. In a space shooter, approaching asteroids could be used as an element of style to predict upcoming turns.

*Deprive responsibility:* Participants stated that on the front passenger seat, they normally feel responsible for being involved in the traffic but by playing a fully immersive game, their role comes into conflict with playing the game. Being not able to see what is going on in the real world could disturb users and might lead to an uncomfortable feeling while playing. A high level of trust in the driver or changing seat positions could be enough to counteract the feeling of being responsible. Some participants did not report such responsibility, therefore we assume that this kind of feeling depends on personality.

*Consider involvement of the driver:* While playing, we observed that the movements of the player's vehicle are accepted as part of the game and not performed by the driver sitting next to the player. Even though players were aware that a driver next to them was controlling the vehicle and the vehicle's movements were directly mapped to the player's vehicle, the awareness was not present during the game. During our study, participants did not ask to change the driving style, for example to hit a target. However, this feeling could have been so strong because the game elements are optimized to the track. Another explanation could be an experimenter bias. In this case, this means that participants did not want to participate in the driving style because the driver was the experimenter and a stranger. In situations where friends drive together, we assume communication between the player and the driver regarding the game.

*Never persuade to risky driving:* The passenger's wish to influence the driving behavior could be an element of the game as well and could be used to increase driving safety. For example, while driving on a road on which speeding is common, the number of targets in the scene could be increased. By this, the player might ask the driver to slow down a bit in order to be able to hit all targets in the scene. However, this would require the driver to be part of the game which might be triggered in any way. On the other hand, a specific game design could lead to a risky driving behavior. For example when chasing an object in front, the player could be incited to convince the driver to speed. A game design that could lead to risky driving should be avoided.

*Design for incompleteness:* When the player's vehicle drives in a way that targets are hard to reach or hit or other goals are impossible to achieve, the player might blame the driver or the game itself for this and frustration could occur. A target that is impossible to hit because the car is never moving in the required position should either be avoided or not punished by the game play. Levels and game goals should be designed that the feeling of incompleteness does not occur. This could be reached by not defining an upper limit for targets, e.g. by not defining a goal such as, hit all objects in the scene. Note that in our study, the goal was in fact to hit all targets, but the route was tailored to the targets in the game, therefore all targets could be reached properly.

### Limitations

The study track was the same for each participant. However, because the study took place on public road, sudden brakes, longer waiting time on crossings or different acceleration rates could not be controlled for and differed between participants. The game in our study was specifically designed for the chosen track of 2.2 km, therefore different tracks with other road geometry, speed limits and overall duration, like driving on a highway, should be tested in further studies. Also our design considerations are based on the small sample size of the study and should be evaluated with a bigger sample size. Our study results could be influenced by the experimenter bias effect because when comparing between a standing and driving condition, we can assume that participants are aware of the experimenter's preferred condition.

## CONCLUSION

In this work, we presented a functional prototype to enable virtual reality in moving vehicles. To enable this, we mapped the vehicle's movements and the visual information of the VR content. By this, the vestibular and visual information is congruent. We provide a technical implementation, an analysis of the design space and an evaluation based on a user study, in which we showed that our prototype reduces simulator sickness and increases enjoyment and immersion in comparison to a VR experience in a standing vehicle. We provided design considerations based on our experiences while developing and conducting our study that serves developers as guidelines when creating VR entertainment applications in moving vehicles.

Effects of the seat position regarding trust in the driver and the player's wish for being involved in the traffic situation could be the focus of future work. Also level design while being in a vehicle playing VR games regarding simulator sickness should be investigated further. Different kinds of force shifts should also be investigated, where kinesthetic forces are not only mapped 1:1 but altered from actual movements. For example, flying loopings or changing height while the car is accelerating.

## ACKNOWLEDGMENT

This work was funded by the Carl-Zeiss-Scholarship for PhD students.

## REFERENCES


1. 2016. Developer Center – Documentation and SDKs | Oculus. (2016). https://developer.oculus.com/documentation/intro-vr/latest/concepts/bp_intro/
2. 2016. Lockheed Martin school bus takes you on virtual journey to Mars. (2016). http://generation-beyond.com/mars-experience
3. Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.
4. John Bichard, Liselott Brunnberg, Marco Combetto, Anton Gustafsson, and Oskar Juhlin. 2006. *Backseat Playgrounds: Pervasive Storytelling in Vast Location Based Games*. Springer Berlin Heidelberg, Berlin, Heidelberg, 117–122. DOI: http://dx.doi.org/10.1007/11872320_14
5. Willem Bles, Jelte E Bos, and Hans Kruit. 2000. Motion sickness. *Current opinion in neurology* 13, 1 (2000), 19–25.
6. Dipl-Ing Thomas Bock, Prof Dr-Ing Markus Maurer, Dipl-Ing Franciscus van Meel, and Dipl-Ing Thomas Müller. 2008. Vehicle in the Loop. 110, 1 (2008), 10–16. DOI:http://dx.doi.org/10.1007/BF03221943
7. Liselott Brunnberg, Oskar Juhlin, and Anton Gustafsson. 2009. Games for Passengers: Accounting for Motion in Location-based Applications. In *Proceedings of the 4th International Conference on Foundations of Digital Games (FDG '09)*. ACM, New York, NY, USA, 26–33. DOI:http://dx.doi.org/10.1145/1536513.1536528
8. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic turk: a motion platform based on people. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 3463–3472.
9. Francis B Colavita. 1974. Human sensory dominance. *Perception & Psychophysics* 16, 2 (1974), 409–412.
10. Fabien Danieau, Julien Fleureau, Philippe Guillotel, Nicolas Mollet, Anatole Lecuyer, and Marc Christie. HapSeat: Producing Motion Sensation with Multiple Force-feedback Devices Embedded in a Seat. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology* (2012) *(VRST '12)*. ACM, 69–76. DOI: http://dx.doi.org/10.1145/2407336.2407350
11. Albert Einstein and others. 1911. On the Influence of Gravitation on the Propagation of Light. *Annalen der Physik* 35, 898-908 (1911), 906.
12. Ajoy S Fernandes and Steven K Feiner. 2016. Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 201–210.
13. James J Gibson. 2014. *The ecological approach to visual perception: classic edition*. Psychology Press.
14. Jan Gugenheimer, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. 2016. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1996–2000. DOI: http://dx.doi.org/10.1145/2858036.2858040
15. Lawrence J Hettinger, Kevin S Berbaum, Robert S Kennedy, William P Dunlap, and Margaret D Nolan. 1990. Vection and simulator sickness. *Military Psychology* 2, 3 (1990), 171.
16. Makoto Igarashi, F Owen Black, and Includes Index. 1985. Vestibular and Visual Control on Posture and Locomotor Equilibrium. (1985).
17. Jaguar New Zealand. 2015. Jaguar creates Actual Reality prank. (2015). https://www.youtube.com/watch?v=_zpx0Eb1Tvo
18. Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.
19. Eugenia M Kolasinski. 1995. *Simulator Sickness in Virtual Environments.* Technical Report. DTIC Document.
20. Camille Koppen and Charles Spence. 2007. Seeing the light: exploring the Colavita visual dominance effect. *Experimental brain research* 180, 4 (2007), 737–754.
21. J. J. W. Lin, H. B. L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness. 2002. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*. 164–171. DOI: http://dx.doi.org/10.1109/VR.2002.996519
22. Daniel Michaels. 2016. Roller Coasters Ride Into Dizzying Realm of Virtual Reality. (2016). http://goo.gl/qnzsCL
23. Akihiro Morimoto, Naoki Isu, Daisuke Ioku, Hitoshi Asano, Atsuo Kawai, and Fumito Masui. 2008. Effects of reading books and watching movies on inducement of car sickness. In *Proc. of FISITA 2008 World Automotive Congress, in print*.
24. Oculus VR, LLC. 2016. Virtual Reality Best Practices. (2016). https://docs.unrealengine.com/latest/INT/Platforms/VR/ContentSetup/
25. James T Reason and Joseph John Brand. 1975. *Motion sickness.* Academic press.
26. Max Rheiner. 2014. Birdly an Attempt to Fly. In *ACM SIGGRAPH 2014 Emerging Technologies (SIGGRAPH '14)*. ACM, New York, NY, USA, Article 3, 1 pages. DOI: http://dx.doi.org/10.1145/2614066.2614101

27. Rose Marie Rine, Michael C Schubert, and Thomas J Balkany. 1999. Visual-vestibular habituation and balance training for motion sickness. *Physical therapy* 79, 10 (1999), 949–957.
28. Arnon Rolnick and RE Lubow. 1991. Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics* 34, 7 (1991), 867–879.
29. C. Schatzschneider, G. Bruder, and F. Steinicke. 2016. Who turned the clock? Effects of Manipulated Zeitgebers, Cognitive Load and Immersion on Time Estimation. 22, 4 (2016), 1387–1395. DOI: http://dx.doi.org/10.1109/TVCG.2016.2518137
30. Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3307–3316. DOI: http://dx.doi.org/10.1145/2702123.2702389
31. Mel Slater, John McCarthy, and Francesco Maringelli. 1998. The influence of body movement on subjective presence in virtual environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 40, 3 (1998), 469–477.
32. Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of presence in virtual environments. *Presence: Teleoperators & Virtual Environments* 3, 2 (1994), 130–144.
33. Mel Slater, Martin Usoh, and Anthony Steed. 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)* 2, 3 (1995), 201–219.
34. Richard HY So, WT Lo, and Andy TK Ho. 2001. Effects of navigation speed on motion sickness caused by an immersive virtual environment. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 43, 3 (2001), 452–461.
35. Kay M Stanney, Kelly S Hale, Isabelina Nahmens, and Robert S Kennedy. 2003. What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 45, 3 (2003), 504–520.
36. Petra Sundström, Axel Baumgartner, Elke Beck, Christine Döttlinger, Martin Murer, Ivana Randelshofer, David Wilfinger, Alexander Meschtscherjakov, and Manfred Tscheligi. 2014. Gaming to Sit Safe: The Restricted Body As an Integral Part of Gameplay. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 715–724. DOI: http://dx.doi.org/10.1145/2598510.2600882
37. Mark Turner and Michael J Griffin. 1999. Motion sickness in public road transport: the relative importance of motion, vision and individual differences. *British Journal of Psychology* 90, 4 (1999), 519–530.
38. Robert Xiao and Hrvoje Benko. 2016. Augmenting the Field-of-View of Head-Mounted Displays with Sparse Peripheral Displays. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1221–1232.