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A Structural Equation Modeling Approach to Understand the Relationship between Control, Cybersickness and Presence in Virtual Reality

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Figure 1: First person point of view of immersive driving simulation

ABSTRACT

The commercialization of Virtual Reality (VR) devices is making the technology increasingly accessible to users around the world. Despite the success that VR is starting to see with its growing popularity, it has yet to become widely adopted and achieve its ultimate goal- convincingly simulate real life like experiences. The inability to generate adequate levels of presence and to prevent the manifestation of cybersickness are the two prominent barriers that have hindered VR from achieving its ultimate goal. While traditional research has examined factors that influence (correlate with) the onset and severity cybersickness, there is still a gap in our knowledge about the consequences of having motion control on cybersickness in immersive virtual environments (IVE's) achieved using tracked Head Mounted Displays (HMD's). Furthermore, outside of a correlational capacity, it is still unclear as to what causes cybersickness to affect presence in immersive virtual environments. The success of immersive virtual reality as a technology will hence largely come down to our ability to understand the interrelationship between these variables and then address the challenges they pose. Towards this end, we investigated how the affordance of motion control affects cybersickness and presence in an HMD based VR driving simulation by conducting a between subjects study where we manipulated the affordance of control between three experimental conditions. We leverage structural equation modeling in an attempt to build a framework that explains the relationship between virtual motion control, workload, cybersickness, time spent in the simulation, perceived time and presence. Our structural model helps explain why motion control could be an important factor to consider in addressing VR's challenges and realizing its ultimate aim to simulate reality.

Index Terms: Human-centered computing—Empirical studies in HCI——Human-centered computing—Virtual reality

1 INTRODUCTION

The rapid growth and commercialization of Virtual Reality (VR) devices is making the technology increasingly accessible to users around the world. The demand for commercial Head-Mounted Displays (HMD) like the Oculus Rift and the HTC VIVE has hence started to explode. Consequently, there is a growing demand for modern VR applications which often involve users traveling and exploring large virtual environments. Many such modern VR applications in the fields of gaming, therapy [81], training [17, 23], etc. often involve driving as the method of travel because of the ability of VR to safely, inexpensively and convincingly replicate real world driving scenarios. Driving (Steering) is also a relatively intuitive and straightforward travel metaphor because it resembles real world travel where users can continuously control both how fast they are moving as well as where exactly they are moving in a scene [83]. To give users this control over their speed and direction of movement in virtual reality, physical devices like steering wheels, joysticks, acceleration pedals, etc. are used [5]. As such there are a large number of VR applications where users travel through virtual environments using virtual vehicles.

Despite the success that VR has started to see with its growing popularity, it has yet to become a widely adopted technology. The ultimate goal of VR as a technology to accurately and convincingly simulate a real life experience still remains unachieved. The main barrier that has hindered Virtual Reality technology from realizing its ultimate goal has remained the constant manifestation of cybersickness. This is the the feeling of discomfort that confronts users experiencing virtual environments [39]. This malady is marked by symptoms such as nausea, eye strain, sweating, dizziness, disorientation, etc. [39], and usually occurs when users experience visual motion stimuli while remaining stationary in the real world. It is hence often referred to as visually induced motion sickness (VIMS), which can hence be seen as a subset of motion sickness that is experienced as a consequence of traveling through virtual environments [25, 46]. Another prominent challenge that has confronted VR has been its inability to generate adequate levels of presence, whereby users lose conscious awareness that they are in a simulated medium. The success of immersive virtual reality as a technology

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will largely come down to our ability to understand and solve these challenges.

Affording users with control over their virtual vehicles allows for control over how travel occurs in a virtual environment, but it is unknown as to whether this affordance of motion control in IVE's comes at the cost of other aspects in the experience. Having to control motion in a virtual environment could come at the cost of an increased cognitive workload. While there has been extensive research examining the relationship between driving and mental workload with different tasks in the real world, there is limited work that has studied this in immersive virtual environments. Furthermore, the literature has been relatively silent on the relationship between workload and cybersickness in virtual environments. Given the large and ever growing number of applications requiring users to control motion in virtual environments, it is important that we understand the consequences and effects of having vehicular control in immersive virtual reality. With cybersickness remaining an obstacle for VR's success, it is important that we build upon existing theories and frameworks to understand how cybersickness is caused and what consequences it has on other effects of a virtual reality experience. Towards this end, this work leverages structural equation modeling in an attempt to build a framework that explains what consequences virtual vehicular control has on workload, cybersickness, and presence in IVEs and how strong the interrelationships between these variables are. Our structural models help explain why virtual vehicular control could be important in addressing VR's ultimate goal of accurately and convincingly simulating real life.

2 RELATED WORK

2.1 Motion Based Sicknesses

Motion sickness is often defined as a malady that occurs when people experience certain kinds of motion that produce symptoms such as disorientation, nausea, malaise, pallor, cold sweating, headaches etc. [39, 49, 59, 70]. While the exact cause of motion sickness continues to remain a mystery, several theories and explanations have offered to address this question. The well known 'Sensory Conflict' theory claims that motion sickness is caused when the brain obtains mismatched sensory information about motion from multiple senses that include the vestibular system, the eyes, muscles and other tissues [70]. Another prominent theory that seeks to explain motion sickness is the 'Postural Instability' theory which argues that a reduced ability to control postural motion is the cause for motion sickness [64]. While other theories such as the 'Poison Theory', 'Rest Frame Theory', etc. have offered explanations to explain motion sickness, the 'Sensory Conflict' and 'Postural Instability' theories remain the most prominent in the research community [60]. As such, it is generally agreed that motion sickness is caused when people are in motion.

Visually Induced Motion Sickness (VIMS) is a subset of motion sickness that usually occurs when people perceive motion due to visual stimuli when in fact they remain stationary, leading to symptoms similar to those of motion sickness [25]. This perception of self motion, also called vection, is a consequence of the optic flow experienced, and is often correlated with, if not a prerequisite to, VIMS [34]. VIMS usually manifests as cybersickness in contexts associated with Immersive Virtual Environments, and as simulator sickness in contexts involving simulators. Simulator sickness is usually experienced when simulators fail to accurately produce the motion that an individual perceives visually [24, 37]. Cybersickness, however, is most often experienced when users have a compelling sense of self motion in a virtual environment while they remain stationary in the real world [39]. We hence distinguish motion sickness, simulator sickness and cybersickness on the grounds of their induction and motion with respect to the real world, where we consider cybersickness as one that is visually induced when people remain relatively stationary in the real world.

2.2 Cybersickness

The problem of cybersickness associated with VR usage has been widely investigated by the research community. However, it continues to remain a problem that is yet to be completely understood and solved. While the theories that have sought to explain motion sickness also apply to the domain of cybersickness, the precise etiology of cybersickness remains open for further investigation.

2.2.1 Simulator Sickness Questionnaire (SSQ)

The simulator sickness questionnaire (SSQ) developed by Kennedy et. al. [31] is widely used to evaluate the levels of cybersickness induced. The survey is administered twice in a pre and post fashion, thereby allowing to estimate the change in sickness produced as a result of a simulation. We used a shortened version of this questionnaire consisting of sixteen items that contribute to three dimensions of sickness, namely nausea, oculomotor and disorientation. These dimensions combine to produce a total score.

2.2.2 Physiological Measures

Physiological measures have been shown to be valid indicators of cybersickness [15]. Studies have linked cybersickness to increased heart rates [13]. Skin Conductance Levels (SCL)/ Electrodermal activity (EDA) is another physiological characteristic involving changes in the skin's electrical conductance caused as a response to cybersickness amongst a variety of other factors [35]. Researchers have shown that motion sickness symptoms are associated with increased skin conductance (EDA) [27, 47], and have effectively used EDA as a measure of cybersickness in combination with subjective reports [65]. To measure EDA, we used the validated Empatica E4 Wristband which also measures heart rate, blood volume pressure (BVP) and skin temperature [45].

2.2.3 Factors Influencing Cybersickness

Several factors affecting cybersickness have been examined in the past. The addition of latency jitter has been shown to increase levels of cybersickness experienced by users in IVE's [77]. As opposed to constant latency, varied levels of latency in head mounted displays have been linked to higher levels of cybersickness [55]. The effects of rest frames on cybersickness in IVE's has been studied, with recent work showing that both static and dynamic rest frames produce lower levels of cybersickness [9]. It has also been shown that the application of dynamic blurring on the retina reduces cybersickness [53]. The evolution of travel techniques in IVE's has been characterized by the intention to both improve user experience and reduce the levels of cybersickness produced. Work on this front has shown that jumping induces lesser sickness, thereby justifying its use as an alternative to steering wherever applicable [83]. More recently, it has been shown that using animated interpolations as a travel metaphor results in higher levels of sickness than those produced by travel techniques involving pulsed interpolations or teleportation [57]. The reduction of cybersickness has also been achieved by applying alternating user-footstep synchronized haptic cues to users' heads [44]. User eye movements have even been used as additional inputs to 3d convolutional neural networks and have been shown to accurately predict motion sickness [40]. Other factors such as users' VR experience, duration of the simulation, field of view, speed of travel, etc. have been revealed to strongly influence cybersickness levels associated with immersive virtual reality experiences [61]. The effect of control over motion on cybersickness remains relatively unexplored in the context of IVE's involving tracked HMD's.

2.3 Affordance of Control on Sickness

The etiological influence of motion control on motion sickness has been acknowledged by several theories that explain motion sickness

[58]. It has been shown that people who have control over self-motion stimuli are less susceptible to motion sickness than those that do not. Simply put, in a driving scenario, drivers are less likely to become motion sick than passengers. This finding has been verified in the contexts of real world physical vehicles [66], virtual vehicles that involve user controlled vehicles in desktop virtual environments [14,16], and virtual avatars that involve user controlled characters in virtual environments [11,74]. The explanation for this observation in virtual environments is that people in control over their motion can better predict future motion than those without control. This lack of predictability about movement/motion in a virtual environment renders passengers more prone to the symptoms of cybersickness [37]. Furthermore, predictability about motion affects the ability of people to stabilize their posture, which has been shown to precede cybersickness [10,42,72,79]. Owing to its relevance, the likeliness of passengers experiencing higher levels of sickness than drivers has been discussed in work that addresses the self driving car paradigm [71], highlighting the importance of motion control in the induction of sickness. Recent work has acknowledged the influence of control on decreasing cybersickness by intentionally making participants play the role of passengers in a simulation, studying the induction of cybersickness in people with multiple sclerosis [1].

The degree of user initiated control has been shown to have a significant bearing on cybersickness levels in virtual environments [74], with a combination of both active and passive control in locomotion tasks producing the lowest levels of sickness. However, this study was limited to VR achieved without the use of head mounted displays. The closest work that has examined how the affordance of control affects cybersickness in virtual environments involving vehicular travel used a between subjects experiment with a yoked control design. In this study, participants either played the role of drivers or passengers in a racing game (Forza 2) on the XBOX 360 gaming console. The yoked control design meant that every participant in the passenger condition experienced the same trajectory as a paired participant from the driving condition. The results of this study indicated that drivers were less likely to become motion sick than passengers [16]. A yoked control design offers a valid comparison between conditions because each driver and their yoked pair experience the virtual motion stimuli. There is however a concern that can be raised regarding control metaphors over motion in IVE's because the feedback obtained needn't match users' expectations that are built from experiencing real world travel. This failure to enforce expectations can cause sickness [60]. This has been studied by work that has shown that participants may get more sick due to the inability to exert mastery of control over a driving simulator that doesn't respond in ways matching their sensory-motor expectations of feedback received upon the exertion of control [48]. With immersive VR becoming more prominent as a test bed for autonomous driving, it is also fitting to consider the usage of a car journey that closely resembles an experience provided by an autonomous car. Despite there being a number of such studies that have examined how control affects cybersickness in VR, to the best of our knowledge, there is an absence of work that has looked at this in the context of fully immersive virtual environments achieved using tracked HMD's. Given the uptake in consumer based VR, it is crucial that we understand how the ability to control motion affects cybersickness in IVE's. This work seeks to contribute towards that cause.

2.4 Workload and Sickness

The relationship between workload and sickness in immersive virtual environments has been explored by a few researchers in the past. However, the scientific community still doesn't have a concrete position on this relationship because of the disparate results that have been obtained from the studies that have sought to explore this relationship. Early work by Regan suggested that workload and sickness were negatively correlated, explaining that higher levels of concentration and workload could contribute towards the reduction of simulator sickness [63]. This finding was supported by a recent study that showed that adding mental distractions reduced the levels of sickness experienced [4]. However, other recent studies (as well as some earlier work) have reported the existence of a positive correlation between workload and sickness, speculating that higher workload conditions render people with less mental or physical resources to deal with sickness related discomforts, ultimately leading to higher levels of sickness [19, 78]. There is also work that has reported no relationship between these factors, explaining that mental workload and task complexity had little to no impact on simulator sickness [48,50,51]. As such, there is limited work that has explored how cybersickness and workload are related and the literature indicates that there is significant disagreement among the scientific community about the nature, direction and strength of the relationship between these factors.

2.5 Sickness and Presence

Early work has shown evidence of an existence of large negative correlations between presence and cybersickness explaining that sickness symptoms cause people to be more internally focused, rendering them less able to process aspects of the virtual environment, thereby reducing their sense of presence [84, 85]. In a virtual house exploration task, it was found that presence and cybersickness were negatively correlated, suggesting that the symptoms of sickness made users concentrate less on the task and more on the deficiencies of the virtual environment [52]. More recently, an inverse relationship between cybersickness and presence was found in a study employing a driving simulation [48]. Several other studies such as [8, 12, 35] have found negative correlations between cybersickness and presence.

There have also been some studies that have reported positive correlations between presence and cybersickness. Strong positive correlations were found between these two constructs among older adults in a study involving a virtual shopping task, with authors suggesting that higher levels of presence as causers of increased cybersickness levels [43]. More recently, a positive correlation between auditory vection and sickness was found [33], prompting researchers to speculate that sickness and presence are positively correlated given the evidence of the positive correlation between vection and presence established by works such as [21,56]. Other works such as [41] have also found positive correlations between sickness and presence but the number of such works reporting this directionality in relationship are relatively limited [82].

While there have also been some studies that have reported null correlations between cybersickness and presence, the investigations that have found negative correlations strongly outnumber those reporting positive or null correlations between these constructs, suggesting that presence and cybersickness are negatively correlated [82].

2.6 Sickness and Duration

The relationship between sickness and duration of VR exposure has been discussed by several works in the past. A number of works have reported findings that suggest the existence of a positive correlation between exposure duration and total sickness experienced by users [76]. Early work has shown this positive correlation between duration and sickness, explaining that adverse effects even on interaction lead to a largely additive effect of sickness in the virtual environment [32]. Other works have made similar claims on finding such positive correlations between these two aspects of a VR experience [18, 29, 38, 62]. However, there is some work that has shown evidence to the contrary where lower levels of sickness have been associated with longer durations of exposure to the virtual environment. This negative correlation was reported by [75], with the authors suggesting psychological adaption as a reason for the observation of lessening sickness symptomatology with longer exposures, as explained by [73]. The majority of work hence seems to suggest a positive correlation between sickness and duration but it isn't uncommon to hear of studies that do report negative correlations between these two aspects of the VR experience. Some researchers reason that participants stay in the simulation for longer durations only because they feel less sick, thus explaining why negative correlations are observed between duration of VR exposure and cybersickness.

2.7 Duration, Perceived Duration and Presence

Exposure duration in a virtual environment has been shown to correlate with peoples' sense of the presence but there is some uncertainty as to what the nature of the correlation is and should be [75]. It was shown that presence and duration of VR exposure were positively correlated in an investigation exploring virtual navigation tasks and training tasks [29]. Researchers have explained this positive correlation by speculating that longer durations in the virtual environment lead people to adapt, understand and become more familiar with the virtual environment, ultimately causing them to perceive higher levels of presence [76]. However, if the manifestation of cybersickness intensifies with time and does indeed lower presence as discussed in [82], presence may be negatively related to the duration of VE exposure. Given these two schools of thought and the nonexistence of a clear consensus in the community, it is important that we further explore the relationship between presence and duration of exposure in immersive virtual environments.

It is commonly established that people perceive time differently based on context. Idioms such as "Time flies when you're having fun" and "A watched pot never boils" accurately capture the import of this claim. Time perception has been an ever important area in psychological research from the early days. Research on this front has shown that time perception can be measured in two paradigms namely the prospective and retrospective sense of time [28]. In the prospective paradigm, people are aware that they need to estimate time after a certain duration. In the retrospective paradigm however, people are unaware that they will be asked to estimate time after a certain duration, making this measure of time perception a more memory based estimate. It has been shown that task complexity affects prospective estimates of time but not the retrospective estimates [3]. The latter however, is affected by factors such as the duration of the simulation and complexity of the visual stimulus, both of which don't affect prospective time estimates [2]. Retrospective time estimation is more common in everyday life and may hence offer a higher level of ecological validity that prospective time estimation may not [6]. This makes it worthwhile to examine the relationship between retrospective time estimation and immersion. While there is some work such as [20, 68], that have investigated the relationship between immersion and retrospective time estimates, these works have most commonly tried to study how time estimates are affected by varying levels of immersion. Given that duration affects retrospective time perception [2], we sought to examine if perceived time affects presence rather than the reverse.

3 SYSTEM DESCRIPTION

The immersive virtual simulation was displayed on an HTC Vive Pro Head Mounted Display and the computer used to render the simulation featured an Intel Xeon processor with 64 Gigabytes of RAM and an NVIDIA GTX 1080 Ti graphics card. To provide higher levels of immersion, participants were seated atop a real world car seat that was mounted on a wooden platform. They could use a Logitech Driving Force GT[1] steering wheel and acceleration and brake pedals to control the vehicle (see Figure 2). The physical apparatus was built matching a real world SUV in terms of the positioning and distances between the steering wheel, pedals and car seat. The average frame rate of the simulation was 71 frames per second and the average HMD Latency calculated based on [54], was 63.75 milliseconds.

Figure 2: Car seat, steering wheel and pedal setup

3.1 Virtual World Construction

The virtual environment used for this study featured an expansive 120 block city that had realistically scaled skyscrapers, apartment complexes, restaurants, etc see Figure 4. The buildings were arranged in concentric fashion where we alternated between short and tall buildings, enabling smooth and consistent optic flow, see Figure 3. The outskirts of the city featured mountainous terrain with vegetation cover. We created salient landmarks and evenly spread them (4 per quadrant of the city) across different parts of the city, see Figure 3. The landmarks were structures like monuments, Ferris wheels, statues, etc. such that they clearly stood out from the rest of the city. The virtual city also had street signs and stop signs at intersections, trash cans and trees all over the city, making the scene highly realistic. The virtual scene was built using Unity and had objects that were modeled using 3D software like Maya and Blender.

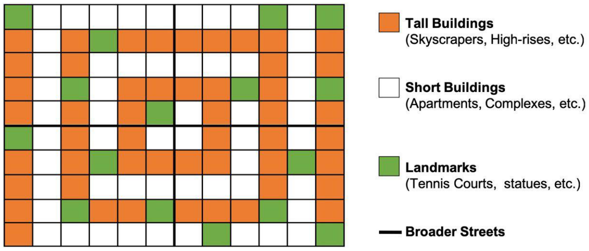

Figure 3: Layout of the virtual city.

A custom automated script along with a Unity plugin[2] was used

Figure 4: Screen shots of the city environment where the participants performed the search task.

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[1] `https://support.logitech.com/en_us/product/driving-force-gt`

[2] `https://assetstore.unity.com/packages/tools/physics/ik-driver-vehicle-controller-54173`

to provide users with a gender matched, custom scaled self avatar whose hand movements matched those of the participants (see Fig 1). The HTC Vive controllers were strapped to the user's arms to facilitate this.

In the virtual world, participants sat in a 3D modelled Subaru Forester SUV. The virtual car was modelled based on real world Subaru SUV, matching its dimensions and looks. The interiors were slightly modified to accommodate a display screen (center console display unit) where landmarks could be presented to the participants for their search task, see Section 4.2. The virtual steering wheel was co-located with the physical steering wheel and its movements were hence mapped to resemble the real wheel. The virtual car featured a speedometer that accurately reflected the speed and driving mode of the car (Drive or Reverse). The behavior of the virtual car resembled a Subaru SUV and was implemented using a custom modified Unity car controller. The scripts were modified to allow the steering wheel, accelerator, brake pedals and gear to drive the car. The properties of the virtual car like its suspension, acceleration and deceleration times, torque, etc. were adjusted to resemble a real world SUV. The position and orientation of the car, the virtual car's dynamic values of speed, acceleration, rev, torque, etc., the inputs from the control devices were recorded on every frame.

3.2 Driving Trajectory Replay

To implement the Yoked Pair condition (see section 4.1), we implemented a mechanism to playback the driving trajectories created by participants that had control over the vehicle (Drivers). The car state data recorded on every frame as mentioned in section 3.1 was used to play back the car's driving trajectory through the city for the participant. To ensure that the playback accurately replicated the original driving simulation, the delta times between frames was also recorded and used to determine when to advance to the next state. This technique was extensively tested with pilot participants and the average playback duration error for the experiment was calculated to be 1.04%.

3.3 Autonomous car

To implement the Autonomous Car condition (see section 4.1) a custom programmed car controller script was used. This handled automatic acceleration and deceleration at constant rates while steering the car based on a predetermined trajectory. This script made the car initiate deceleration on the detection of a stop sign at a specific distance from the car and initiate acceleration three seconds after every time it stopped. The constant rates of acceleration were 3 miles per hour per second and 16 miles per hour per second. The maximum velocity the car could attain was 35 miles per hour. The predetermined trajectory included all landmarks and was conceptualized based on rules established by the Department of Motor Vehicles (DMV). One single trajectory was used for all participants assigned to the Autonomous Car condition after pilot testing established that the virtual car's trajectory resembled a real world autonomous car.

4 EXPERIMENT

4.1 Study Design

To understand how the affordance of motion control affects the different aspects of the VR experience, we conducted a between subjects study manipulating control between three conditions; 1) Driving condition, 2) Autonomous Car condition and 3) Yoked Pair condition.

In the Driving condition, participants had full control over the car and were free to drive around the city as they pleased. They could steer the car using a steering wheel and used accelerator and brake pedals to control the speed of the car. In the Autonomous Car condition, participants experienced a program driven autonomous car simulation which drove around the city with constant acceleration and deceleration profiles, making sure to behave and act (lane keeping, turning profile, velocity, etc.) in a consistent manner. In the Yoked Pair condition, each participant was randomly paired with one participant from the Driving condition, and had to experience a replay of the simulation experienced by their matched pair. This ensured that every participant in the Yoked Pair condition experienced the exact same motion stimuli as their matched pair from the Driving condition with the only difference being that they didn't have control over the car. This eliminated any possible confounding or extraneous influence of driving styles between the two conditions. Participants in all three conditions had to perform a search task that is described in section 4.2. To ensure consistency between experimental conditions, subjects across all conditions were seated in the driver's seat.

4.2 Task

In order to keep participants engaged in the simulation and to expose them to higher levels of optic flow, we designed a search task where participants had to locate landmarks in the virtual city and these landmarks were presented in a random order on the center console display unit (GPS Screen) of the virtual car. To familiarize participants with the task, the first landmark was within viewing distance of the start point of the simulation. Participants were asked to verbally inform the experimenter once they found the landmark presented in the screen and the experimenter would present a new landmark on verifying that the landmark was indeed correctly located. If participants incorrectly identified a landmark, they were asked to continue their search for it. This task spanned the entirety of the study which lasted not more than 30 minutes. The search task hence had no end with participants continually locating as many landmarks as they could. This search task encouraged participants to stay in the simulation for longer and to look outside the car as much as possible, keeping them engaged and exposing them to higher levels of optic flow. Subjects were not scored on any performance metrics of how many landmarks they located or how long they took to locate them seeing as how the search task was intended to keep participants involved and attentive to the virtual scene.

4.3 Participants

A total of 63 participants were recruited for this Institutional Review Board (IRB) approved study, with 21 allotted per condition, from Clemson University. The average age of participants was 24.1 years (std dev = 4.2) and 68% of the them were males. All participants had normal or corrected-to-normal vision. A total of 45 participants reported having less than five hours of VR experience and eight participants reported that they had over 25 hours of VR Experience. Overall, VR Experience did not significantly differ across conditions.

4.4 Procedure

In all three conditions, participants were greeted and asked to read and sign a consent form (informed consent) upon arrival. After consenting to participate in the study, participants filled out a demographics questionnaire that included questions about their age, gender and experience with video games and virtual reality. This was followed by the SSQ [31]. The first 42 participants were randomly assigned to either the Driving condition or the Autonomous Car condition. The final 21 participants were assigned to the Yoked Pair condition, where each participant was randomly assigned to different stimuli recorded in the Driving condition. Participants in the Yoked condition were not interleaved with the Driving and Autonomous condition as it was necessary to complete the Driving condition first to gather the data used to create the experiences for the Yoked Pair condition.

We describe below the procedural sequence for participants in each of the three conditions.

4.4.1 Driving Condition

1. After filling out the surveys, participants were asked to sit on the car seat and were briefed about the task. The instructions did not mention anything about the simulation making them sick because we did not want to prime them. However, they were told that they could quit at any time.
2. The participants were instructed to verbally report their levels of physiological comfort on a ten point scale (10 representing most comfortable and 1 representing least comfortable) whenever they heard an audio clip question that was played by the simulation. This audio clip question was automated to play every three minutes, and was phrased as follows: "On a scale from one to ten, how comfortable do you feel?".
3. The Empatica E4 sensor was then strapped to the participants' wrists. This device was used to record changes in their skin conductance during the experiment. Their arm lengths were then measured to provide them with a calibrated, gender-matched, scaled self-avatar.
4. Following the provision of a virtual avatar, participants were put into the simulation where they began driving and performing the search task. This simulation ended when participants either got sick and could no longer continue or when 30 minutes elapsed.
5. After the simulation, participants filled out the SSQ again [31], the NASA-TLX questionnaire [22], and the SUS Presence Questionnaire [80]. Upon completing the SSQ, participants were asked to indicate how much time they felt they spent in the simulation (Retrospective Time estimate in minutes) and after this they were allowed to take a break and were given refreshments, if they desired. If participants took a break, they completed the remaining surveys after the break but it was ensured that the SSQ and the question on time perception was completed immediately after the simulation ended.
6. Upon conclusion, the experimenter made sure that subjects were okay to leave and instructed them to not drive or operate heavy machinery immediately after.

4.4.2 Autonomous and Yoked Pair Conditions

A protocol similar to the Driving condition was used for the Autonomous and Yoked Pair conditions. Participants in these conditions were informed that they would be driven around the city by a self-driving car and were instructed on how to perform the task. However, they were not informed of the kind of behavior the self-driving car would follow. The trajectory used for the Autonomous Car condition followed all traffic regulations, accelerated and decelerated gradually with consistency in profile, and followed the posted speed limits. The trajectory used in the Yoked Pair condition matched that of one of the participants in the Driving condition and thereby replicated the driving profile created by that participant.

4.5 Data Collection

Apart from the survey responses, the self-reported comfort data and the SCL data, we also recorded simulation based data like the simulation time, position and orientation of the car, the inputs received from the steering wheel and pedals, and the position and rotation of all tracked objects (HMD, HTC Vive controllers) on every frame. Participants' comfort level responses were manually recorded by the experimenter using the keyboard every three minutes.

4.6 Data Preparation

Prior to analysis, SSQ scores for the pre-simulation and post-simulation were calculated following the procedure laid out in [31], and the SSQ subscale scores for nausea, oculomotor, and disorientation were calculated. In order to assess the change in sickness symptoms caused during the simulation, SSQ difference scores were computed as the difference between the pre and post-simulation SSQ scores. The resulting difference scores measured the overall change in cybersickness from before participants entered the simulation until their self-determined termination or end of the simulation.

The Skin Conductance Level (SCL) recorded for each participant using the Empatica sensor were normalized based on a baseline recording that was taken before the participant entered the virtual environment. After the scores were normalized, an average skin conductance level was calculated for every minute to look at trends in the data as the participant progressed through the simulation.

4.7 Data Analysis

To understand how the experimental manipulation of motion control affects different aspects of the VR experience, we leveraged Structural Equation Modeling in an attempt to build a framework that explains the interrelationship between these variables in an HMD based VR driving simulation.

Structural Equation Modeling (SEM) is a form of causal modeling that uses a variety of statistical techniques to fit a network of constructs in a causal path based on theory [30, 36]. It can be decomposed into a measurement model and a path model. The measurement model specifies how well the measures of a construct measure the concept definition of that construct, and the path model specifies a set of directed dependencies among some variables. SEM allows for the easy presentation of results and can be considered as a series of linear regressions between variables specified in a particular path model where variables are individually specified with measurement models. We hence discuss Path Modeling (Path Model) and Confirmatory Factor Analysis (Measurement Model) in an effort to break down SEM.

4.7.1 Path Modeling

A path modeling analysis can be seen as an extension of regression analyses used towards the study of causal effects between a set of variables [36]. A presumed causal path between the variables of interest is mapped out based on existing theory and this path is also referred to as the structural model or path model [30]. A path model is hence a causal chain starting from the predictors and ending at the outcome variables with intermediate variables or constructs set up as mediators to the outcome variable. This type of analysis can hence be treated as a causal mediation analysis which seeks to decompose the effect of a treatment or manipulation among multiple possible paths, providing path-specific effect estimates that can be causally interpreted. We created a path model based on the hypothesized relationships discussed in section 4.8 (See Fig 5). Apart from the hypothesized relationships, the path model features effects added for saturation of the model.

4.7.2 Confirmatory Factor Analysis

A Confirmatory Factor Analysis (CFA) is performed to test how well items or questions measure a construct of interest [36]. A latent factor that is measured by several questions/items can hence be subjected to CFA to see how well each question loads on to the factor [7]. Items that have lower loadings are dropped from the analysis and the factor's measurement is then based on the items that remain. Furthermore, CFA can also be used to bundle higher order factors together by specifying the higher order factors as items in a standard CFA [7, 36]. The only constraint that applies to the CFA is that constructs must be measured by more than one item. The CFA can hence be used as a statistical technique to specify the measurement model of an SEM. We subjected the latent factors of presence and cybersickness to CFA. The CFA of Presence was specified using the six items in the SUS questionnaire and Cybersickness was specified as a higher order CFA with the EDA scores, comfort scores and computed difference scores in nausea, disorientation and oculomotor used as items in the analysis (see Table 1).

Construct	Items	Loading
Sickness AVE = 0.806 alpha = 0.884	Nausea	0.729
	Oculomotor	0.724
	Disorientation	0.901
	EDA	
	COMFORT_LEVEL	
Presence AVE = 0.515 alpha = 0.732	item1	
	item2	0.471
	item3	
	item4	0.524
	item5	
	item6	0.449

Table 1: The CFA results. Items in gray are removed from the analysis due to low loadings. alpha: Chronback's α, AVE: Avg Variance Extracted.

4.8 Research Questions and Hypotheses

The overarching research question addressed by this study was as follows: How are the variables of virtual motion control, workload, cybersickness, time spent in VR simulation, perceived time and presence interrelated in an HMD based VR driving simulation? Based on work discussed in section 2, we hypothesized the following directional relationships (Cause → Effect):

Control → Workload
Workload → Sickness
Sickness → Time Spent
Time Spent → Perceived Time
Perceived Time → Presence

Based on these hypothesized relationships we developed a structural model sequentially linking the variables (see Fig 5).

5 RESULTS

We graphically present our structural equation model (see Fig 5) as a diagram containing the constructs (boxes) and the relationships between them (arrows). Elliptical boxes represent constructs gathered as measures from conducting the study. The rectangular box represents our independent variable and for the sake of clarity, we do not include the questionnaire items themselves in the diagrams. Each regression contains a regression coefficient, the standard error enclosed within parenthesis and the significance level denoted by asterisks. The chi square tests for control, checks whether there is any difference between the control conditions (without specifying where exactly those differences exist). Subsequently, the coefficients for "Drivers" and "Autonomous" demonstrate the difference between those conditions and the "Yoked" condition.

As the first step, we subjected two latent variables of our study (cybersickness and presence) to Confirmatory Factory Analysis. The results of our CFA are reported in Table 5. Items with lower loadings are highlighted in gray and were removed from the analysis. The value of Cronbach's α and average variance extracted (AVE) were high[3], indicating convergent validity amongst the measures measuring each construct. Moreover, the square root of the AVE was higher than the factor correlation for all factors, indicating discriminant validity.

The maximum likelihood estimator of SEM requires normally distributed data for which the Shaphiro-Wilk test should not be significant [69]. The tests conducted suggested that all of our data rows were normally distributed ($p > 0.05$) except for the actual and perceived time. We transformed these two variables using the "bestNormalize" package in r which combines a rank-mapping approach with a shifted logit approximation[4] so that the data meets the normality assumption. We started with a saturated SEM model and trimmed out non-significant paths. Figure 5 depicts our final model.

We subjected the 5 factors and the experimental conditions to structural equation modeling, which simultaneously fits the factor measurement model and the structural relations between factors and the other variables. For a good model fit, the chi square test must not be significant because this ensures that the model misfit isn't significantly different from the saturated model [26]. Our model fit indices indicate a good model fit. $\chi^2(36) = 32.203$ $p = .650$. Furthermore, other model fit indices such as RMSEA = 0.00, CFI = 1, and TLI = 1.021 all lie within accepted thresholds, suggesting that the model has a great fit [26]. The SEM results show that control significantly affects workload: compared to their yoked pairs, drivers had a higher workload ($p < .01$). Drivers also experienced more sickness ($p < .05$). However, this effect was fully mediated by workload. The control conditions also influence perceived time; compared to yoked pairs, those in the autonomous condition perceive the simulation longer ($p < .05$) while drivers perceived the simulation to be shorter; however, this effect didn't reach the significance level ($p = .350$). Finally, users in both the driving and autonomous conditions felt more presence ($p < .05$ and $p < .01$) than users in the Yoked condition (see Fig 5).

Furthermore, our results suggest that for a one standard deviation increase in workload, there was a 0.276 standard deviation increase in sickness as well ($p < .01$). Sickness negatively affects actual time, perceived time and presence ($p < .05$). Users who report a higher perceived time also feel less presence ($p < .05$). Not surprisingly, time spent in VR simulation can predict perceived time ($p < .001$).

6 DISCUSSION

Based on the results of our controlled lab experiment, we can describe in detail how the affordance of virtual motion control in an HMD based VR driving simulation affects different aspects of the VR experience. We can also explain how the variables of control, workload, cybersickness, duration of VR exposure, time perception and presence are interrelated. Finally, we can provide some preliminary suggestions for VR developers focusing on mid fidelity HMD based VR driving experiences that use steering as a travel metaphor.

The structural model highlights the influence of control on several aspects of the VR experience. Affording motion control can increase the amount of workload on the users. The statistical analysis revealed that drivers had a significantly higher workload than their yoked pairs. This is understandable because drivers had to actively control the car while their yoked pairs could have been more passive. The added responsibility of having to control the motion of the virtual vehicle hence seems to come at the cost of an increased workload. Furthermore, the model reveled that an increased workload was associated with an increase in cybersickness. This finding is analogous to [19,78] who found positive relationships between these two constructs. It is possible that higher workload conditions, render people with lesser mental/physical resources to devote towards handling cybersickness symptoms, ultimately leading to higher levels of cybersickness. Overall, this seems to suggest that having control over a virtual vehicle could lead to higher levels of cybersickness because of an increased workload. While this finding goes against previous research (both in the real world and IVE's) showing that passengers get more sick than drivers, it seems to point towards the importance of workload associated with the travel metaphor used. We believe that this finding is applicable to mid fidelity HMD based VR driving simulations that use steering as a travel metaphor for movement in the virtual world. Additionally, affording control seems to directly increase the levels of presence experienced and this indicates the importance of VR interaction as a component in achieving presence [85]. Since drivers had to actively control their own motion using a steering wheel, they may have experienced more levels of presence than their yoked pairs who performed no specific

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[3] For alpha, >.70 is acceptable, >.80 is good, >.90 is excellent. AVE should be >.50 for convergent validity

[4] https://cran.r-project.org/web/packages/bestNormalize/index.html

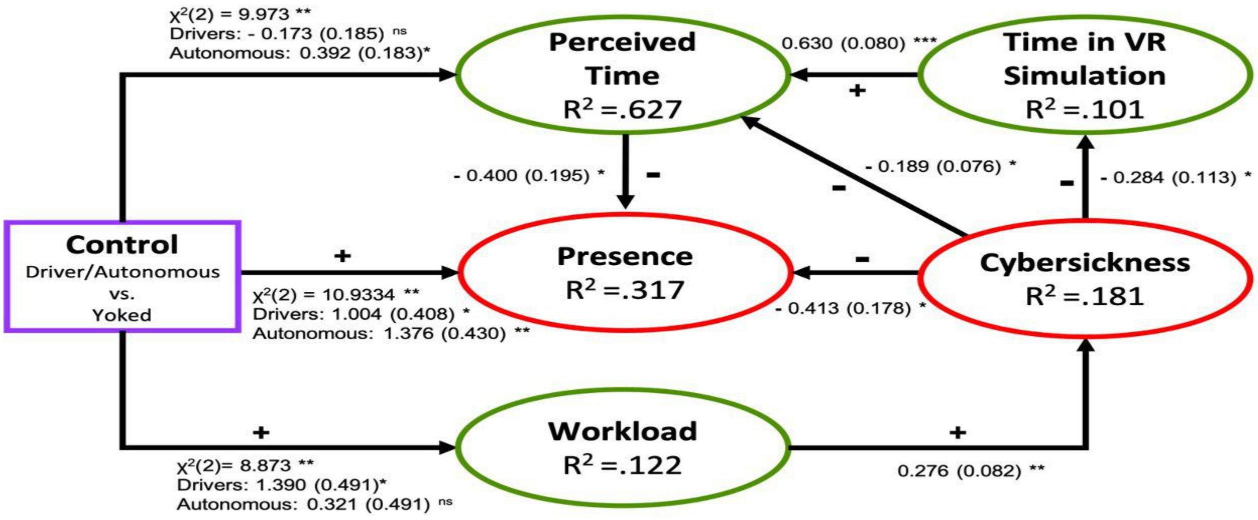

Figure 5: Trimmed Structural Model. The model shows how different levels of control affect different aspects of the VR Experience. Red ellipses represent constructs subjected to CFA. Each arrow has regression coefficients and std errors within parentheses. R^2: Proportion of Variance Explained. '+' and '-' denote positive and negative relationships respectively. Significance levels: *** $p < .001$, ** $p < .01$, *$p < .05$, 'ns' $p > .05$

interactions with the virtual environment.

Our structural model also captures the importance of cybersickness in the VR experience. Firstly, it can be seen that increased levels of cybersickness render users unable to endure the VR simulation for long periods of time (Time in VR Simulation). This negative relationship between sickness and time spent in the VR simulation was reported by [73, 75]. It is possible that participants stay in the simulation for longer durations only when they feel less sick in the first place, thus explaining the negative relationship. Secondly, cybersickness seems to directly lead to lower levels of presence and this aligns with the majority of the work that has reported concurrently on sickness and presence [82]. This is possibly because the sickness symptoms cause people to be more internally focused, rendering them less able to process aspects of the virtual environment, thereby reducing their sense of presence [84, 85]. Overall, we see that cybersickness causes undesirable effects in the VR experience by lowering presence and reducing the amount of time that users spend in VR.

Interestingly, the model sheds some light on time perception. The amount of time that users perceived that they spent in the simulation seems to directly affect the levels of presence experienced by the users. It can be seen that when the users perceive that they spent less time in the simulation, they feel more present (negative relationship between perceived time and presence). This is possibly because less time is perceived when users are more engaged [67], and this can effectively be summarized by idioms such as "Time flies when you are having fun", "A watched pot never boils", etc. It hence seems to be the case that users feel more present when they perceive that they spent less time in the simulation. In addition, we find that retrospective time estimates are affected by the duration of simulation and this conforms to claims made by [2].

Overall, our structural model explains how the variables of motion control, workload, cybersickness, time spent in simulation, perceived time and presence are interrelated in a mid fidelity HMD based VR driving simulation. Based on these findings, it seems apparent that the affordance of control is an important aspect in addressing VR's challenges of generating adequate levels of presence and reducing cybersickness. It seems to be the case that affording control could increase presence, but come at the cost of an increased workload which could in turn cause an increase in sickness. We recognize that these findings apply to such HMD based VR driving simulations that employ steering as a control metaphor. We hence offer the following guidelines: 1) Researchers studying user experience in autonomous vehicles can safely use HMD based VR simulations as platforms for their investigations. 2) VR developers focusing on driving simulations based on steering inputs for travel could try to reduce the workload associated with the control metaphor because this reduction in workload can potentially reduce sickness.

7 CONCLUSION AND FUTURE WORK

In this work, we investigated the how the affordance of motion control affects cybersickness and presence in an immersive virtual Head Mounted Display (HMD) based driving simulation in an attempt to address two important challenges modern Virtual Reality (VR) experiences face - generating adequate levels of presence and reducing cybersickness. Towards this cause, we sought to examine the interrelationship between the variables of virtual motion control, workload, cybersickness, time spent in simulation, perceived time and presence to build a framework that could potentially explain how we can address these challenges. We leveraged structural equation modeling to build a relationship model with these constructs and our model helps explain the importance of control in the Virtual Reality experience and how it affects other constructs. Our findings indicate that affording motion control using steering in such HMD based VR driving simulations could increase sickness because of an increase in workload while also increasing presence because of the added interaction with the VR environment. It may hence be important for developers and researchers to consider reducing the workload associated with the travel metaphor if we are to successfully mitigate cybersickness and maintain adequate levels of presence.

For future work, we plan to investigate if this model applies and holds to other travel metaphors used in controlling motion in the virtual world. Specifically, we are interested in testing the validity of this model in a travel metaphor that involves a lesser workload such as teleportation or animated interpolations. If this model does indeed apply to other travel metaphors, it would be worth our while to compare our results to see if cybersickness can be reduced by altering the mode of travel to one that has lesser workload. We also plan to incorporate other postural constructs into our analyses to broaden our understanding of these interrelationships.

REFERENCES

[1] I. M. Arafat, S. M. S. Ferdous, and J. Quarles. Cybersickness-provoking virtual reality alters brain signals of persons with multiple sclerosis. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1–120. IEEE, 2018.

[2] R. A. Block. Remembered duration: Effects of event and sequence complexity. *Memory & Cognition*, 6(3):320–326, 1978.

[3] R. A. Block and D. Zakay. Prospective and retrospective duration judgments: A meta-analytic review. *Psychonomic bulletin & review*, 4(2):184–197, 1997.

[4] J. E. Bos. Less sickness with more motion and/or mental distraction. *Journal of Vestibular Research*, 25(1):23–33, 2015.

[5] D. A. Bowman, D. Koller, and L. F. Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Virtual Reality Annual International Symposium, 1997., IEEE 1997*, pp. 45–52. IEEE, 1997.

[6] S. W. Brown and D. A. Stubbs. The psychophysics of retrospective and prospective timing. *Perception*, 17(3):297–310, 1988.

[7] T. A. Brown. *Confirmatory factor analysis for applied research*. Guilford Publications, 2014.

[8] B. Busscher, D. de Vliegher, Y. Ling, and W.-P. Brinkman. Physiological measures and self-report to evaluate neutral virtual reality worlds. *Journal of CyberTherapy and Rehabilitation*, 4(1):15–25, 2011.

[9] Z. Cao, J. Jerald, and R. Kopper. Visually-induced motion sickness reduction via static and dynamic rest frames. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 105–112. IEEE, 2018.

[10] C.-H. Chang, W.-W. Pan, F.-C. Chen, and T. A. Stoffregen. Console video games, postural activity, and motion sickness during passive restraint. *Experimental brain research*, 229(2):235–242, 2013.

[11] Y.-C. Chen, X. Dong, F.-C. Chen, and T. A. Stoffregen. Control of a virtual avatar influences postural activity and motion sickness. *Ecological Psychology*, 24(4):279–299, 2012.

[12] N. Cooper, F. Milella, C. Pinto, I. Cant, M. White, and G. Meyer. The effects of substitute multisensory feedback on task performance and the sense of presence in a virtual reality environment. *PloS one*, 13(2):e0191846, 2018.

[13] P. S. Cowings, K. H. Naifeh, and W. B. Toscano. The stability of individual patterns of autonomic responses to motion sickness stimulation. *Aviation, space, and environmental medicine*, 1990.

[14] S. Davis, K. Nesbitt, and E. Nalivaiko. Comparing the onset of cybersickness using the oculus rift and two virtual roller coasters. In *Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015)*, vol. 27, p. 30, 2015.

[15] M. S. Dennison, A. Z. Wisti, and M. D'Zmura. Use of physiological signals to predict cybersickness. *Displays*, 44:42–52, 2016.

[16] X. Dong, K. Yoshida, and T. A. Stoffregen. Control of a virtual vehicle influences postural activity and motion sickness. *Journal of Experimental Psychology: Applied*, 17(2):128, 2011.

[17] D. L. Fisher, A. Pollatsek, and A. Pradhan. Can novice drivers be trained to scan for information that will reduce their likelihood of a crash? *Injury Prevention*, 12(suppl 1):i25–i29, 2006.

[18] A. Graybiel et al. A provocative test for grading susceptibility to motion sickness yielding a single numerical score. *Acta oto-laryngologica. Supplementum*, 274:1–20, 1970.

[19] F. E. Guedry. Visual control of habituation to complex vestibular stimulation in man. *Acta oto-laryngologica*, 58(1-6):377–389, 1964.

[20] K. Hägni, K. Eng, M.-C. Hepp-Reymond, L. Holper, B. Keisker, E. Siekierka, and D. C. Kiper. The effect of task and ownership on time estimation in virtual environments. *Barcelona, Spain*, 2007.

[21] K. S. Hale and K. M. Stanney. *Handbook of virtual environments: Design, implementation, and applications*. CRC Press, 2014.

[22] S. G. Hart and L. E. Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, vol. 52, pp. 139–183. Elsevier, 1988.

[23] W. L. Heinrichs, P. Youngblood, P. M. Harter, and P. Dev. Simulation for team training and assessment: case studies of online training with virtual worlds. *World journal of surgery*, 32(2):161–170, 2008.

[24] L. J. Hettinger, K. S. Berbaum, R. S. Kennedy, W. P. Dunlap, and M. D. Nolan. Vection and simulator sickness. *Military Psychology*, 2(3):171–181, 1990.

[25] L. J. Hettinger and G. E. Riccio. Visually induced motion sickness in virtual environments. *Presence: Teleoperators & Virtual Environments*, 1(3):306–310, 1992.

[26] L.-t. Hu and P. M. Bentler. Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural equation modeling: a multidisciplinary journal*, 6(1):1–55, 1999.

[27] S. Hu, W. F. Grant, R. M. Stern, and K. L. Koch. Motion sickness severity and physiological correlates during repeated exposures to a rotating optokinetic drum. *Aviation, space, and environmental medicine*, 1991.

[28] W. James. The principles of psychology. In *Dover Publications, Mineola, New York*, 1957.

[29] C. Jerome, R. Darnell, B. Oakley, and A. Pepe. The effects of presence and time of exposure on simulator sickness. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 49, pp. 2258–2262. SAGE Publications Sage CA: Los Angeles, CA, 2005.

[30] D. Kaplan. *Structural equation modeling: Foundations and extensions*, vol. 10. Sage Publications, 2008.

[31] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[32] R. S. Kennedy, K. M. Stanney, and W. P. Dunlap. Duration and exposure to virtual environments: sickness curves during and across sessions. *Presence: Teleoperators & Virtual Environments*, 9(5):463–472, 2000.

[33] B. Keshavarz, L. J. Hettinger, R. S. Kennedy, and J. L. Campos. Demonstrating the potential for dynamic auditory stimulation to contribute to motion sickness. *PloS one*, 9(7):e101016, 2014.

[34] B. Keshavarz, B. E. Riecke, L. J. Hettinger, and J. L. Campos. Vection and visually induced motion sickness: how are they related? *Frontiers in psychology*, 6:472, 2015.

[35] Y. Y. Kim, H. J. Kim, E. N. Kim, H. D. Ko, and H. T. Kim. Characteristic changes in the physiological components of cybersickness. *Psychophysiology*, 42(5):616–625, 2005.

[36] R. B. Kline. *Principles and practice of structural equation modeling*. Guilford publications, 2015.

[37] E. M. Kolasinski. Simulator sickness in virtual environments. Technical report, Army research inst for the behavioral and social sciences Alexandria VA, 1995.

[38] D. R. Lampton, E. M. Kolasinski, B. W. Knerr, J. P. Bliss, J. H. Bailey, and B. G. Witmer. Side effects and aftereffects of immersion in virtual environments. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 38, pp. 1154–1157. SAGE Publications Sage CA: Los Angeles, CA, 1994.

[39] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56, 2000.

[40] T. M. Lee, J. Yoon, and I. Lee. Motion sickness prediction in stereoscopic videos using 3d convolutional neural networks. *IEEE Transactions on Visualization and Computer Graphics*, 25(5):1919–1927, May 2019. doi: 10.1109/TVCG.2019.2899186

[41] J.-W. Lin, H. B.-L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Proceedings ieee virtual reality 2002*, pp. 164–171. IEEE, 2002.

[42] E. M. Littman, E. W. Otten, and L. J. Smart Jr. Consequence of self versus externally generated visual motion on postural regulation. *Ecological Psychology*, 22(2):150–167, 2010.

[43] C.-L. Liu and S.-T. Uang. Effects of presence on causing cybersickness in the elderly within a 3d virtual store. In *International Conference on Human-Computer Interaction*, pp. 490–499. Springer, 2011.

[44] S.-H. Liu, N.-H. Yu, L. Chan, Y.-H. Peng, W.-Z. Sun, and M. Y. Chen. Phantomlegs: Reducing virtual reality sickness using head-worn haptic devices. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 817–826. IEEE, 2019.

[45] C. McCarthy, N. Pradhan, C. Redpath, and A. Adler. Validation of the empatica e4 wristband. In *Student Conference (ISC), 2016 IEEE*

EMBS International, pp. 1–4. IEEE, 2016.

[46] M. E. McCauley and T. J. Sharkey. Cybersickness: Perception of self-motion in virtual environments. *Presence: Teleoperators & Virtual Environments*, 1(3):311–318, 1992.

[47] J. C. Miller, T. J. Sharkey, G. A. Graham, and M. E. McCauley. Autonomic physiological data associated with simulator discomfort. 1993.

[48] I. Milleville-Pennel and C. Charron. Do mental workload and presence experienced when driving a real car predispose drivers to simulator sickness? an exploratory study. *Accident Analysis & Prevention*, 74:192–202, 2015.

[49] K. Money. Motion sickness. *Physiological Reviews*, 50(1):1–39, 1970.

[50] W. T. Nelson, R. S. Bolia, C. A. Russell, R. M. Morley, and M. M. Roe. Head-slaved tracking in a see-through hmd: The effects of a secondary visual monitoring task on performance and workload. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 44, pp. 3–390. SAGE Publications Sage CA: Los Angeles, CA, 2000.

[51] W. T. Nelson, M. M. Roe, R. S. Bolia, and R. M. Morley. Assessing simulator sickness in a see-through hmd: Effects of time delay, time on task, and task complexity. Technical report, AIR FORCE RESEARCH LAB WRIGHT-PATTERSON AFB OH, 2000.

[52] S. Nichols, C. Haldane, and J. R. Wilson. Measurement of presence and its consequences in virtual environments. *International Journal of Human-Computer Studies*, 52(3):471–491, 2000.

[53] G.-Y. Nie, H. B.-L. Duh, Y. Liu, and Y. Wang. Analysis on mitigation of visually induced motion sickness by applying dynamical blurring on a user's retina. *IEEE transactions on visualization and computer graphics*, 2019.

[54] D. C. Niehorster, L. Li, and M. Lappe. The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205, 2017.

[55] M. E. S. Pierre, S. Banerjee, A. W. Hoover, and E. R. Muth. The effects of 0.2 hz varying latency with 20–100ms varying amplitude on simulator sickness in a helmet mounted display. *Displays*, 36:1–8, 2015.

[56] J. Prothero. Widening the field of view increases the sense of presence within immersive virtual environments. *Tech. Rep.*, 1995.

[57] K. Rahimi Moghadam, C. Banigan, and E. D. Ragan. Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–1, 2018. doi: 10.1109/TVCG.2018.2884468

[58] J. T. Reason. Motion sickness adaptation: a neural mismatch model. *Journal of the Royal Society of Medicine*, 71(11):819–829, 1978.

[59] J. T. Reason and J. J. Brand. *Motion sickness.* Academic press, 1975.

[60] L. Rebenitsch. Managing cybersickness in virtual reality. *XRDS: Crossroads, The ACM Magazine for Students*, 22(1):46–51, 2015.

[61] L. Rebenitsch and C. Owen. Review on cybersickness in applications and visual displays. *Virtual Reality*, 20(2):101–125, 2016.

[62] C. Regan. An investigation into nausea and other side-effects of head-coupled immersive virtual reality. *Virtual Reality*, 1(1):17–31, 1995.

[63] E. Regan. Side-effects of immersion virtual reality. In *Paper presented at the international Applied Military Psychology Symposium, 1993*, 1993.

[64] G. E. Riccio and T. A. Stoffregen. An ecological theory of motion sickness and postural instability. *Ecological psychology*, 3(3):195–240, 1991.

[65] A. izzo and G. J. Kim. A swot analysis of the field of virtual reality rehabilitation and therapy. *Presence: Teleoperators & Virtual Environments*, 14(2):119–146, 2005.

[66] A. Rolnick and R. Lubow. Why is the driver rarely motion sick? the role of controllability in motion sickness. *Ergonomics*, 34(7):867–879, 1991.

[67] A. M. Sackett, T. Meyvis, L. D. Nelson, B. A. Converse, and A. L. Sackett. You're having fun when time flies: The hedonic consequences of subjective time progression. *Psychological Science*, 21(1):111–117, 2010.

[68] T. Sanders and P. Cairns. Time perception, immersion and music in videogames. In *Proceedings of the 24th BCS interaction specialist group conference*, pp. 160–167. British Computer Society, 2010.

[69] S. S. Shapiro and M. B. Wilk. An analysis of variance test for normality (complete samples). *Biometrika*, 52(3/4):591–611, 1965.

[70] C. R. Sherman. Motion sickness: review of causes and preventive strategies. *Journal of travel medicine*, 9(5):251–256, 2002.

[71] M. Sivak and B. Schoettle. Motion sickness in self-driving vehicles. 2015.

[72] L. J. Smart Jr, T. A. Stoffregen, and B. G. Bardy. Visually induced motion sickness predicted by postural instability. *Human factors*, 44(3):451–465, 2002.

[73] M. J. Smith, G. Salvendy, and R. J. Koubek. *The presence of aftereffects. Design of Computing Systems: Cognitive considerations*, vol. 1. Elsevier, 1997.

[74] K. M. Stanney and P. Hash. Locus of user-initiated control in virtual environments: Influences on cybersickness. *Presence*, 7(5):447–459, 1998.

[75] K. M. Stanney and R. S. Kennedy. Aftereffects from virtual environment exposure: How long do they last? In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 42, pp. 1476–1480. SAGE Publications Sage CA: Los Angeles, CA, 1998.

[76] K. M. Stanney, K. S. Kingdon, D. Graeber, and R. S. Kennedy. Human performance in immersive virtual environments: Effects of exposure duration, user control, and scene complexity. *Human performance*, 15(4):339–366, 2002.

[77] J.-P. Stauffert, F. Niebling, and M. E. Latoschik. Effects of latency jitter on simulator sickness in a search task. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 121–127. IEEE, 2018.

[78] M. Stein and M. Robinski. Simulator sickness in flight simulators of the german armed forces. *Aviation Psychology and Applied Human Factors*, 2012.

[79] T. A. Stoffregen, Y.-C. Chen, and F. C. Koslucher. Motion control, motion sickness, and the postural dynamics of mobile devices. *Experimental brain research*, 232(4):1389–1397, 2014.

[80] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence: Teleoperators & Virtual Environments*, 9(5):497–503, 2000.

[81] J. Wald and S. Taylor. Efficacy of virtual reality exposure therapy to treat driving phobia: a case report. *Journal of behavior therapy and experimental psychiatry*, 31(3-4):249–257, 2000.

[82] S. Weech, S. Kenny, and M. Barnett-Cowan. Presence and cybersickness in virtual reality are negatively related: a review. *Frontiers in psychology*, 10:158, 2019.

[83] T. Weiβker, A. Kunert, B. Frohlich, and A. Kulik. Spatial updating and simulator sickness during steering and jumping in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 97–104. IEEE, 2018.

[84] B. G. Witmer, J. H. Bailey, B. W. Knerr, and K. C. Parsons. Virtual spaces and real world places: transfer of route knowledge. *International Journal of Human-Computer Studies*, 45(4):413–428, 1996.

[85] B. G. Witmer and M. J. Singer. Measuring presence in virtual environments: A presence questionnaire. *Presence*, 7(3):225–240, 1998.