Comparative Evaluation of the Effects of Motion Control on Cybersickness in Immersive Virtual Environments

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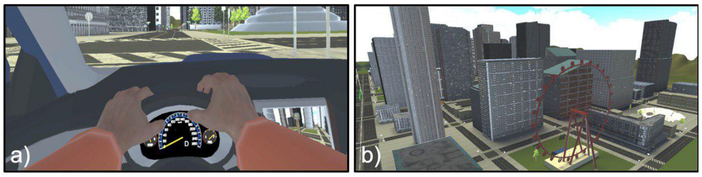

Figure 1: (a) First person point of view of VR driving simulation. (b)Virtual city scape environment

ABSTRACT

The commercialization and lowering costs of consumer grade Virtual Reality (VR) devices has made the technology increasingly accessible to users around the world. The usage of VR technology is often accompanied by an undesirable side effect called cybersickness. Cybersickness is the feeling of discomfort that occurs during VR experiences, producing symptoms similar to those of motion sickness. It continues to remain one of the biggest hurdles to the widespread adoption of VR, making it increasingly important to explore and understand the factors that influence its onset. In this work, we investigated the influence of the presence/absence of motion control on the onset and severity of cybersickness in an HMD based VR driving simulation employing steering as a travel metaphor. Towards this end, we conducted a between subjects study manipulating the presence of control between three experimental conditions, two of which (Driving condition and Yoked Pair condition) formed a yoked control design where every pair of drivers and their yoked pairs were exposed to identical vehicular motion stimuli created by participants in the driving condition. In the other condition (Autonomous Car condition), participants experienced a program driven autonomous vehicle simulation. Results indicated that participants in the Driving condition experienced higher levels of cybersickness than participants in the Yoked Pair condition. While these results don't conform to findings from previous research which suggests that having control over motion reduces cybersickness, it seems to point towards the importance of the fidelity of the control metaphor's feedback response in alleviating cybersickness. Simply allowing one control their motion may not readily alleviate cybersickness but could instead increase it in such HMD based VR driving simulations. It may hence be important to consider how well the control metaphor and its feedback matches users' expectations if we want to successfully mitigate cybersickness.

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

1 INTRODUCTION

The lowering costs and technological advancements in commercial Head-Mounted Displays (HMD) such as the HTC VIVE and the Oculus Rift, have led to a rapid growth in the number of Virtual Reality (VR) users around the world. Consequently, there has been an increased demand for modern VR applications, many of which, are associated with the travel and exploration of expansive virtual environments. Of multiple VR travel metaphors studied in the past, steering is one that is relatively intuitive and straightforward, giving users continuous control over their speed and direction of movement in the scene [54] using physical devices like steering wheels, joysticks, acceleration pedals, etc. Several applications in the areas of gaming, training [13, 15], therapy [53], etc. leverage driving as a means of travel, seeing as how VR can accurately, inexpensively and safely replicate real world driving scenarios. VR driving simulations are also being used to investigate the self driving car paradigm where users are not in control of their motion. These investigations have been focused towards understanding user experiences and evaluating driving behaviors associated with this form of travel [45]. As such, there is a prevalence of VR applications that involve users traveling through virtual environments using virtual vehicles.

Despite the success of VR and its growing popularity with continuously lowering prices, it has yet to become widely adopted. The one major hurdle challenging its widespread adoption is cybersickness. Cybersickness is defined as the discomfort felt by users while experiencing virtual environments and is marked by symptoms such as nausea, sweating, eye strain, dizziness, disorientation, etc. [24]. It usually occurs when users are exposed to visual motion stimuli while remaining stationary in the real world. Cybersickness is also referred to as visually induced motion sickness (VIMS), and is a subset of motion sickness that is experienced from traveling through

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virtual environments [17,29]. There are three prevalent theories that seek to explain the cause of cybersickness; the 'Sensory Conflict Theory' which tries to explain cybersickness in terms of sensory mismatch, the 'Poison Theory' which relates the symptoms experienced to those exhibited when the body is poisoned and the 'Postural Instability Theory' that explains cybersickness as a consequence of the body's failure to maintain postural stability while experiencing new stimuli [42]. While the exact cause of cybersickness is unknown, its onset, measurement, reduction, influencing factors, etc. have been widely studied and discussed in the context of immersive virtual environments (IVE's). Of the many factors influencing cybersickness, control over motion is one that warrants attention due to the upsurge in travel based VR applications.

Providing users with control over their virtual vehicles allows them to control the way they travel in a simulated virtual environment. In IVE's, this control is generally achieved using physical devices like steering wheels, joysticks, pedals, etc. [2]. The subject of vehicular control is highly relevant to the domain of immersive VR because of the growing number of applications that make users drive within the virtual environment. Given its relevance, it is imperative to understand how this presence/absence of motion control in travel affects cybersickness in IVE's if we are to succeed in pushing for the widespread adoption of commercial HMD based VR. While extensive research has been carried out on this front showing that control over motion, be it via a virtual vehicle or via an avatar, leads to lesser cybersickness in virtual environments [6,12,49], to the best of our knowledge, these studies have been limited to desktop VR and have not been conducted in fully immersive environments achieved using modern tracked HMDs. With this in mind, we aim to answer the question of how the presence/absence of control over travel affects the onset and severity of cybersickness in IVEs rendered in tracked HMD's, specifically employing steering as metaphor for travel.

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. [24,32,39,46]. 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 [46]. 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 [42]. 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 [40]. 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 [17]. 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 [21]. 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 [16,23]. 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 [24]. 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.

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 Questionnaires

The simulator sickness questionnaire (SSQ) developed by Kennedy et. al. [20] 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.

The motion sickness susceptibility questionnaire (MSSQ) is a subjective questionnaire often used as a means of determining how likely an individual is to experience motion sickness, and has recently even been used as an exclusion criteria for participants [1,14].

2.2.2 Physiological Measures of Cybersickness

Physiological measures have been shown to be valid indicators of cybersickness [10]. Studies have linked cybersickness to increased heart rates [7]. 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 [22]. Researchers have shown that motion sickness symptoms are associated with increased skin conductance (EDA) [19,30], and have effectively used EDA as a measure of cybersickness in combination with subjective reports [43]. To measure EDA, we used the validated Empatica E4 Wristband which also measures heart rate, blood volume pressure (BVP) and skin temperature [28].

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 immersive virtual environments [50]. As opposed to constant latency, varied levels of latency in head mounted displays have been linked to higher levels of cybersickness [36]. The effects of rest frames on cybersickness in IVEs has been studied, with recent work showing that both static and dynamic rest frames produce lower levels of cybersickness [4]. It has also been shown that the application of dynamic blurring on the retina reduces cybersickness [33]. The evolution of travel techniques in immersive VR 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 [54]. 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 [37]. The reduction of cybersickness has also been achieved by applying alternating user-footstep synchronized haptic cues to users' heads [27]. User eye movements have even been used as additional inputs to 3d convolutional neural networks and have been shown to accurately predict motion sickness [25]. 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 [41]. The effect of having control over motion on cybersickness remains relatively unexplored in the context of IVEs involving tracked HMD's.

2.3 Relationship between Control and Sickness

The etiological influence of motion control on motion sickness has been acknowledged by several theories that explain motion sickness [38]. 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 [44], virtual vehicles that involve user controlled vehicles in desktop virtual environments [8, 12], and virtual avatars that involve user controlled characters in virtual environments [6, 49]. 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 [23]. Furthermore, predictability about motion affects the ability of people to stabilize their posture, which has been shown to precede cybersickness [5, 26, 48, 51]. 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 and work studying sickness in people with multiple sclerosis [47], highlighting the importance of motion control in the induction of sickness. The degree of user initiated control has been shown to have a significant bearing on cybersickness levels in virtual environments, showing that a combination of both active and passive control produced least sickness [49]. By comparing cybersickness scores across participants that were solely given either passive, active or coupled (both active and passive) control over locomotion tasks, it was shown that a combination, i.e. coupled control, minimized the symptoms by providing participants with task oriented control. However, this study was limited to VR achieved without the use of head mounted displays.

The closest work that has examined how the presence/absence 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 [12]. A yoked control design offers a valid comparison between conditions because each driver and their yoked pair experience the same motion stimuli in the simulation. There is however a concern that can be raised regarding control metaphors over motion in IVE's because the feedback obtained need not match users' expectations that are built from experiencing real world travel. This failure to enforce expectations can cause sickness [40]. 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 [31]. With immersive virtual reality 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 immersive 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.

Figure 2: Car seat, steering wheel and pedal setup

3 SYSTEM DESCRIPTION

A large scale virtual environment featuring a cityscape was created for this experiment. The IVE was displayed on a HTC Vive Pro HMD connected to a desktop computer with an Intel Xeon processor, 64 GB of RAM, and a dedicated NVIDIA GTX 1080 Ti graphics card. To provide a realistic experience, participants were seated on a car seat mounted on top of a wooden platform and could use a Logitech Driving Force GT[1] steering wheel and pedals to control the vehicle (see Figure 2). The seating apparatus was constructed such that the height and positioning of the steering wheel, pedals and the car seat matched that of an SUV. The simulation ran at an average of 71 frames per second. The average HMD latency, as described and measured using the method described by Niehorster et. al. [34], was 63.75 milliseconds.

3.1 Virtual World Construction

The virtual environment used for this experiment featured a realistically scaled city with skyscrapers, shorter buildings, apartment complexes, etc. along with distinguishable landmarks that were distributed evenly across 120 city blocks, see Figure 1. The environment was created in Unity using custom 3D objects modeled in Maya and Blender and downloadable assets from the Unity[2] Asset Store. We followed a concentric square pattern alternating between small and tall buildings to provide a smooth and consistent optic flow across the city, see Figure 3. To give users a sense of direction in the city, all streets were marked with street signs and the two streets intersecting at the center were broader. Speed signs and stop signs were placed on street intersections to communicate traffic laws. To increase the visual realism and reduce monotony, trash cans, trees and graffiti textures were placed in different parts of the city. The landmarks were simple structures like monuments, statues, tennis courts, etc. that could easily be distinguished from other buildings in the scene. A total of 16 landmarks were placed strategically in the city with each quadrant having four landmarks.

A custom automated script along with a Unity plugin[3] was used to provide users with a gender matched, custom scaled self avatar whose hand movements matched those of the participants. The HTC Vive controllers were strapped to the user's arms to facilitate this.

In the virtual city, participants were seated in a 3D modelled, scaled replica of a Subaru Forester SUV. The interiors of the virtual SUV were modified to accommodate a center console display unit where the landmarks were displayed. The Logitech steering wheel's movements in the real world were mapped to the virtual steering

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

[2] `https://unity3d.com/`

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

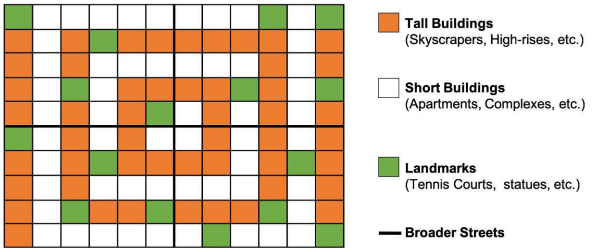

Figure 3: Layout of the city.

wheel of the car. The virtual car's speed and driving mode (Drive or Reverse) were accurately represented in the speedometer using text and a 3D needle respectively. The car's behavior matched that of the Subaru SUV and was achieved using a modified version of the standard Unity car controller. The car controller scripts were modified to accommodate inputs received from the Logitech steering wheel and its pedals. The gear knob allowed users to switch between the drive and reverse modes. The car's rigidbody properties, including weight and the center of mass, were set to match the SUV. Additionally, the dynamic properties of the car like the suspension, traction control, acceleration time, braking time, torque, etc. were programmed to act like a real life Subaru SUV[4]. The car also generated sounds associated with acceleration, deceleration, braking and gear shifts that were played continuously and transitioned at appropriate times. The state of the virtual car in terms of its position, rotation, speed, revs, acceleration, braking, etc. along with the user's input from the Logitech steering wheel was recorded on every frame.

3.2 Driving Trajectory Playback

For the Yoked Pair condition (see section 4.1), we needed to precisely replicate the motion of the car as controlled by a previous participant in the Driving Condition. To achieve this, 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

This study also included an Autonomous Car condition (see section 4.1) the implementation of which, made use of a custom programmed car controller that handled automatic acceleration and deceleration at constant rates while steering the car based on a predetermined trajectory. This controller achieved this consistency in driving profile by initiating deceleration upon detection of a stop sign at a certain distance from the car, and accelerating the car three seconds after every stop. It made sure to consistently use the same rates of acceleration and deceleration while traveling, also abiding by speed limits posted throughout the city. The controller would accelerate the car at a constant rate of approximately 3 miles per hour per second and decelerate the car at a constant rate of approximately 16 miles per hour per second until it came to a complete halt at the stop sign. The maximum velocity that the car would move at was 35 miles per hour. The predetermined path included all landmarks and was conceptualized taking into account rules regarding lane keeping, lane changing, turning, merging, etc. This was based on the drivers handbook issued by the Department of Motor Vehicles (DMV).

4 EXPERIMENT

4.1 Study Design

To empirically evaluate how the presence/absence of motion control over a virtual car affects the severity of cybersickness, 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 of the car and could freely drive around the city. In the Autonomous Car condition, the virtual car drove the subjects around the virtual city with consistent self-driving car like behaviors (acceleration, deceleration, velocity, lane keeping, turning behaviors etc.) and performance. In the Yoked Pair condition, each participant experienced a simulation that was created and experienced by a participant in the driving condition (as conducted in a study employing similar methodology [12]). This was achieved by recording all properties (trajectories and driving profiles: acceleration, deceleration, velocity, turn speeds, etc.) of the simulations created in the driving condition and randomly assigning them to participants in the yoked pair condition where they would be replayed without repetition. This meant that the drivers and their yoked pairs were exposed to the same motion stimuli with the only difference being the ability to control the car for the drivers, thus ensuring that there wasn't any extraneous or confounding influence of driving styles/profiles between these two conditions. Participants in all three conditions had to perform a search task that is described in section 4.2. Subjects across all experimental conditions were seated in the driver's seat to ensure consistency between conditions.

4.2 Task

The task required participants to locate landmarks in the virtual city. The landmarks were presented to participants on the center console display unit of the car in a randomized order. To make participants familiar with the task, the first landmark was within viewing distance of the start point of the simulation. Participants were instructed to inform the experimenter when they located the presented landmark. The experimenter would then verify the claim and present a new randomly chosen landmark on the display unit. If participants inaccurately identified a landmark, they were asked to continue their search for the landmark. This continued for the entirety of the study which lasted at most 30 minutes. Participants hence identified as many landmarks as they could for as long as the simulation lasted. Participants in all three conditions had to perform this task.

We designed this search task to increase engagement with the environment so as to reduce boredom, and to expose participants to higher levels of optical flow by encouraging them to direct their attention outside the car. The search task also served as a reason for participants to stay in the simulation for as long as possible. As such, participants were not scored on their performance of how many landmarks they located or how long it took them to find specific landmarks because the intent of the task was not to measure performance but to keep participants engaged throughout the simulation.

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.

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[4] Weight=3651 lbs, Torque=258 lb-ft, Acceleration Time(0-60mph)=7.3 seconds, Braking Time (70-0 mph)= 4.7 seconds

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 [20]. 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 [20], the MSSQ [14] and the SUS Presence Questionnaire [52]. Upon completing the SSQ, participants 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 SSQ 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 Preparation

Prior to analysis, SSQ scores for the pre-simulation and post-simulation were calculated following the procedure laid out in [20]. In addition to the total SSQ score, subscale scores for nausea, oculomotor, and disorientation were also calculated. In order to assess the change in SSQ 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. Additionally, MSSQ scores were calculated following the procedure laid out in [14].

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.

4.6 Research Questions and Hypotheses

The overarching research questions addressed by this study was as follows: How does the presence/absence of control in an HMD based VR driving simulation (employing steering as the travel metaphor) affect the onset and severity of cybersickness? Based on this research question, we developed three hypotheses that reflect work discussed in Section 2:

H1: Participants in the Driving condition will exhibit lower levels of cybersickness when compared to the other conditions
H2: Participants in the Driving condition will spend more time in the simulation when compared to the other conditions
H3: Participants in the Yoked Pair condition will get sick at an accelerated rate as compared to other conditions

5 RESULTS

Prior to the analysis, assumptions for linear regression were tested. Notably, SSQ and MSSQ scores were heavily skewed. Despite this, residuals of the regression models revealed a normal distribution, suggesting that the assumption of multivariate normality had been met. Hence, there was no need to transform any variables. Outliers were removed by deleting standardized residuals more than 3 standard deviations away from the average. Further, in each analysis, significant effects are presented with measures of effect size. The sr^2 measures the proportion of variance accounted for by a single variable's addition to the regression model. For the following regression models, effects of continuous predictors are indicated by the regression coefficient (B - found in Tables 1-8), and effects of categorical variables are indicated by the omnibus F test.

5.1 Post-simulation cybersickness (SSQ)

The SSQ difference scores (nausea, oculomotor, disorientation and total score) between pre and post were submitted to a stepwise linear regression using Condition (Driver vs Autonomous vs Yoked), duration in the simulation, and Motion Sickness Susceptibility (MSSQ scores) as predictors.

5.1.1 SSQ Total Scores

Condition was a significant predictor of total sickness (F(1, 61) = 6.10, p = 0.02, sr^2 = 0.09). Post-hoc Bonferroni corrected t-tests revealed that the Yoked condition had significantly lower total sickness scores than the Driving ondition (t(40) = 2.66, p = 0.01), and marginally lower scores than the autonomous condition (t(40) = 2.00, p = 0.052). There was no difference between the Driving condition and the Autonomous condition. Further, participants who spent more total time in the simulation produced lower total sickness scores. Lastly, participants who reported higher motion sickness

Table 1: Regression Model predicting SSQ Difference Scores

Predictor	B	SE	t	sr^2
Intercept	77.48	12.77	-	-
Duration	-1.84	0.48	-3.81***	0.17
MSSQ	0.14	.07	2.00*	0.05

note: * denotes $p < .05$, *** denotes $p < .001$

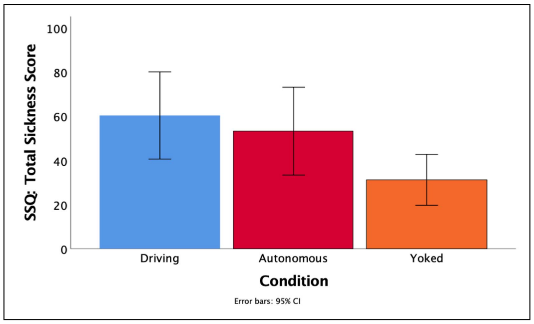

Figure 4: Average SSQ Scores by Condition.

susceptibility produced higher total sickness scores. Motion sickness susceptibility did not moderate the effect of condition. See Table 1 and Figure 4 for results of the regression and average scores of SSQ totals across the conditions respectively.

5.1.2 Nausea

Group differences were also found in Nausea scores across conditions (F(1,61) = 10.45, p = 0.002, $sr^2 = 0.15$). Bonferroni corrected t-tests revealed that the Yoked condition had significantly lower nausea scores than the Driving condition (t(40) = 3.26, p = 0.002) and the Autonomous condition (t(40) = 2.25, p = 0.03), but there was no difference in nausea scores between the Autonomous and Driving conditions. Again, participants who spent longer amounts of time in the simulation had lower nausea scores, and participants more susceptible to motion sickness had higher nausea scores. See Table 2 and Figure 6 for results of the regression and the average nausea scores across the conditions respectively.

Table 2: Regression Model predicting SSQ Nausea Scores

Predictor	B	SE	t	sr^2
Intercept	86.32	12.75	-	-
Duration	-1.94	0.47	-4.01***	0.19
MSSQ	0.14	.07	2.14*	0.04

note: * denotes $p < .05$, *** denotes $p < .001$

5.1.3 Disorientation

Group differences were also found in disorientation across conditions (F(1, 61) = 4.18, p = 0.04, $sr^2 = 0.06$). Participants in the yoked condition had significantly lower disorientation scores than participants in the driving condition (t(40) = 2.12, p = 0.04) and marginally lower scores than those in the autonomous condition (t(40) = 1.93, p = 0.06). Additionally, participants who spent longer in the simulation reported lower disorientation scores. There wasn't any significant difference between the driving and autonomous conditions and there was no effect of motion sickness susceptibility on disorientation. See Table 3 and Figure 5 for results of the regression and average disorientation scores across the conditions respectively.

Table 3: Regression Model predicting SSQ Disorientation Scores

Predictor	B	SE	t	sr^2
Intercept	86.40	17.15	-	-
Duration	-2.34	0.66	-3.58***	0.17
MSSQ	0.15	.09	1.61	-

note: * denotes $p < .05$, *** denotes $p < .001$

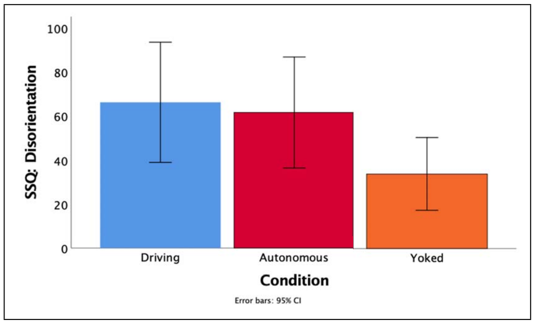

Figure 5: Average SSQ Disorientation Scores by Condition.

5.1.4 Oculomotor

There were no differences in oculomotor scores across conditions (F(1, 61) = 2.08, p = 0.16). The main effect of duration indicated that participants who spent more time in the simulation had lower oculomotor scores ($p < .05$). There was no effect of MSSQ.

5.2 Duration in the simulation

There were no significant effects of Condition on time spent in the simulation (F(1,61) = 0.11, p = 0.75). There was a main effect of motion sickness susceptibility, such that participants with higher susceptibility stayed in the simulation a shorter period of time. This effect was not moderated by condition. See Table 4 for results of the regression predicting duration in the simulation.

5.3 Rate of Cybersickness Change

To assess the rate of change in cybersickness during the simulation, two repeated measures variables were collected. First, in intervals of 3 minutes, participants gave a self-report comfort rating (1 being least comfortable and 10 being most comfortable). Second, the normalized EDA data was averaged across 1 minute intervals to assess the overall SCL at each minute.

Since some participants stayed in the simulation for longer than others, participants had different amounts of comfort ratings and SCL measurements. Additionally, the introduction of a repeated measures variable produced multiple levels of variance in the data: variance occurring within-participants and variance occurring between-participants. That is, since each participant responded at multiple measurement occasions, a portion of the variance in their re-

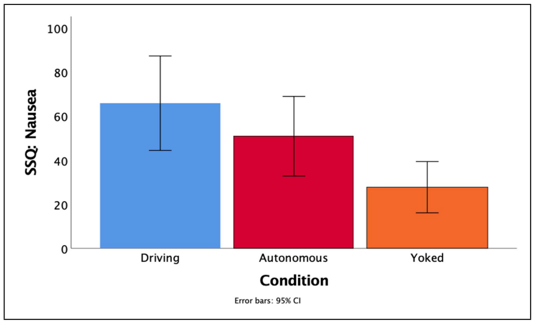

Figure 6: Average SSQ Nausea Scores by Condition.

Table 4: Regression Model predicting Duration in Simulation

Predictor	B	SE	t	sr^2
Intercept	20.50	3.07	-	-
Condition	-0.46	1.42	-0.32	-
MSSQ	-0.04	.02	-2.63*	0.1
MSSQ * Condition	-0.04	0.03	-1.11	-

note: * denotes p <.05, *** denotes p <.001

sponses can be attributed to a common source - the fact that the same participant was responding each time. This represents within-participant variance. Both Condition and MSSQ variables represent sources of between-participant variance. The Intra-Class Coefficient (ICC) indexes the percentage of total variance found at the between-participants level.

In order to properly account for variance at each level, a Hierarchical Linear Modeling (HLM) growth model was used [3, 18]. Instead of using a single regression equation to represent the entire dataset, HLM produces a model in which the within-participant variables predict the dependent variable, followed by a model in which between-participant variables predict the slope and intercept of the first model. In other words, HLM allows the researcher to model how effects of within-participant variables are affected by between-participant variables. Further, HLM is robust enough to account for different numbers of measurement occasions across participant [35].

5.3.1 Rate of Change in Self-report Comfort Ratings

At the within-participants level, there was a significant main effect of Interval. The initial comfort rating averaged across all participants was 8.57, and participants' reported being less comfortable over time, such that for every additional three minute interval, comfort ratings reduced by 0.19. There were no significant main effects of Condition, MSSQ, or VR Experience. A significant interaction between Condition and Interval was found (F(2,31) = 3.56, p = 0.04, sr^2 = .11) showing that individuals in the Driving Condition became less comfortable at a faster rate than individuals in the Yoked Condition (t = -2.67, p = 0.01). See Figure 7. No significant differences existed between any other pairs of conditions. There were no other significant interactions among the variables. See Table 5 for results of the hierarchical linear model predicting Comfort Ratings.

Table 5: Hierarchical Linear Model predicting Comfort Ratings

Predictor	B	SE	t	sr^2
Intercept	8.57	0.76	-	-
Interval	-0.19	0.03	-6.61***	0.84
MSSQ	.02	.01	1.67	-

note: * denotes p <.05, *** denotes p <.001

5.3.2 Rate of Change in Skin Conductance Levels

The initial SCL averaged across all participants was 0.11, and values increased over time such that for every one minute increase, SCL increased by 0.04. There was a significant main effect of condition (F(2,37) = 4.85, p = 0.014, sr^2<.001), such that the initial SCL of individuals in the Drivers Condition was significantly less than the SCL of individuals in the Yoked (t = -2.8, p = .008) and Autonomous Conditions (t = -2.58, p = .014). No significant difference in individuals' initial SCL existed between the Yoked and Autonomous Conditions. There were no significant interactions among the variables. See Table 6. Values ranged from 0 to 1, with higher values representing higher autonomic responses. See Figure 8 which shows the predicted effect of interval on EDA.

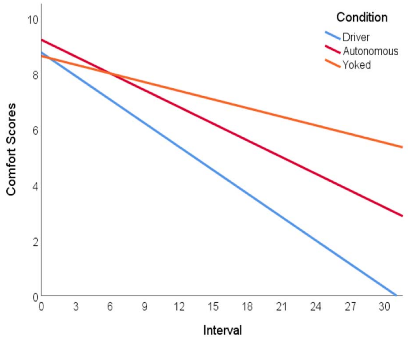

Figure 7: Effect of Interval on Comfort ratings, moderated by Condition

Table 6: Hierarchical Linear Model predicting Skin Conductance Levels

Predictor	B	SE	t	sr^2
Intercept	0.11	0.12	-	-
Minute	0.04	0.005	8.52***	0.63
MSSQ	-0.003	0.002	-1.38	-

note: * denotes p <.05, *** denotes p <.001

5.4 Head Rotation

A multiple linear regression was calculated to predict average yaw experienced per minute based on Condition and Time. A significant Regression equation was found (F(2,1266) = 18.362, p < .000), with an R^2 of .028. Participants' predicted average yaw per minute was equal to $1635.21 - 49.23(Condition) - 13.411(Time)$ where condition is coded as 1 = Driving, 2 = Autonomous, 3 = Yoked Pair and Time is measured in minutes. Participants' average yaw per minute decreased 13.11 degrees with each minute and every change in condition was associated with a reduced average yaw per minute by 49.23 degrees. Both Condition and Time were significant predictors of the average yaw per minute. See Fig 9.

A multiple linear regression was calculated to predict the average roll per minute based on Condition and Time. A significant regression was found (F(2,1281) = 30.83, p<.000) with an R^2 of .046. Participants' predicted average roll per minute was equal to $10478.62 - 33.47(Time) - 1241.917(Condition)$ where condition is coded as 1 = Driving, 2 = Autonomous, 3 = Yoked Pair and Time is measured in minutes. Participants' average roll per minute decreased by 33.478 degrees for each minute and a change in condition was associated with a decrease of roll per minute of 1241.91 degrees. Both Condition and Time were significant predictors of the average roll per minute.

6 DISCUSSION

We discuss our results urging readers to keep in mind that our interpretations apply to contexts involving modern HMD based immersive VR driving simulations that employ steering as the travel metaphor for controlling motion in the virtual world.

The statistical analysis of the SSQ scores revealed that there was a significant effect of condition on sickness and the results obtained did not support our first hypothesis stating that participants in the Driving condition would exhibit lower levels of cybersickness. On the contrary, participants in the Driving condition reported higher levels of sickness than those in the Yoked Pair condition. This seems to suggest that having control over one's motion in HMD based VR driving simulations, could increase the severity of cybersickness, thereby going against results obtained from previous research in real and virtual world experiments which have shown that passengers tend to get more motion sick than drivers [12, 44]. It is possible that our results were obtained because such HMD based driving simu-

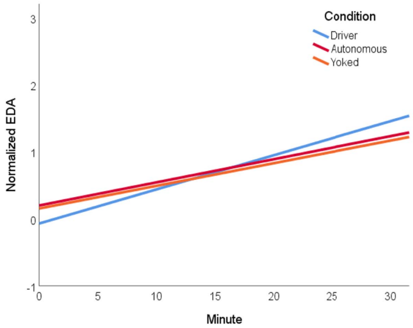

Figure 8: Predicted Effect of Interval on SCL/EDA, moderated by Condition

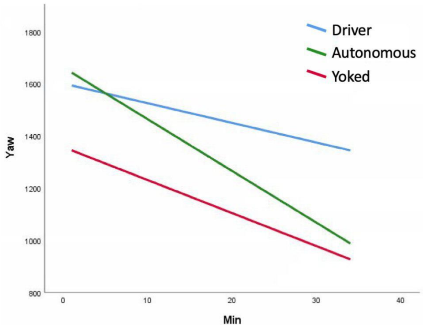

Figure 9: Effect of Interval on Average Yaw per Minute moderated by Condition

lations offer no inertial feedback as a response to exerting control. This inability to match vestibular sensory expectations can cause cybersickness [40]. Essentially, even though the visual characteristics of the VR experience may have compelled users into believing that they were actually driving a real world car, the behavior of the virtual car along with the feedback received in response to the control exerted may not have conformed to their expectations of driving a real vehicle. There may hence be a gap between what the visual system sees and what the vestibular system is prepared to receive by virtue of these expectations. Drivers may have hence had a larger degree of mismatched sensory-motor expectations than their yoked pairs, causing them to get more sick. A similar explanation was offered by Milleville et al. [31], which speculated that an inability of experienced drivers to exert mastery over a driving simulator could potentially cause simulator sickness because expectations are not matched.

Analysis of the head rotation data revealed that drivers experienced both more yaw and roll than their yoked pairs. This could have been a consequence of having to control the car because drivers probably had to look around more to ensure that the car traveled safely. The increased head rotation and a possible difference in optic flow rates as a consequence of having to control the car could be why drivers exhibited more sickness than their yoked pair counterparts. Further investigations involving eye tracking and analyses on head movement are needed to test these theories.

From the analysis conducted on the duration of virtual experience across conditions, we found that there weren't any significant differences between the conditions, countering our second hypothesis H2. Upon further analysis of the SSQ trends exhibited by participants in relation to duration, we found that participants who stayed longer in the simulation experienced lower levels of cybersickness. This finding is analogous to the results obtained by Domeyer et al. [11], who explained that participants can acclimate to the IVE thereby reducing their sickness. It may also be the case that participants that spent longer durations in the simulation, did so only because they were more comfortable and less sick in the first place.

The analysis of the periodic self-reported comfort ratings revealed that there was an interaction effect of condition by time interval, suggesting that drivers became less comfortable at a rate faster than their yoked pairs. These trends counter our expectation in the third hypothesis predicting participants in the yoked pair condition to become sick at a faster rate. The analysis of the SCL data didn't reveal any significant differences between conditions. However drivers tended to start out with lower levels of SCL than their yoked pairs. These results also tend to reflect trends that deviated from our predictions. The analysis of the SCL data hence didn't contradict any of our other measures of sickness but in isolation was inconclusive.

We acknowledge that factors such as cognitive load and engagement could have differed between the conditions, causing the difference in sickness levels observed. Additionally, the search task may have rendered drivers performing two tasks thus increasing mental fatigue, but we believe that this was a necessary addition for ecological validity and to ensure that participants looked outside the car. The differences in these factors could also be natural consequences of having to control motion. For example, compared to passengers, drivers experience higher workloads [9]. Furthermore, it is well established that interaction is an integral component of presence [55]. Since Drivers had to control the car, they may have had an added interaction with the VE that other participants (passengers) may not have had causing potential differences in engagement levels.

Considering the trends observed in the analyses we carried out, we can see that in VR using HMDs, having control over one's motion can potentially lead to increased levels of cybersickness. It is plausible that simply providing control isn't enough to alleviate cybersickness and that this could consequentially worsen the symptoms. It may hence be important to consider the fidelity of the travel metaphor, its faithfulness in replicating feedback obtained in response to control inputs, and its accuracy in matching expectations drawn from experiences in the real world if we want to thoroughly understand the relationship between cybersickness and the provision of control in IVE's.

7 CONCLUSION AND FUTURE WORK

In this work, we conducted a study that empirically evaluates how the presence/absence of motion control affects the onset and severity of cybersickness in an HMD based VR driving simulation employing steering. We conducted a between subjects study manipulating the affordance of motion control across three experimental conditions. Two of these conditions formed a yoked control design which involved participants experiencing the same vehicular motion stimuli and the third condition involved participants experiencing a program driven autonomous vehicle simulation. Results indicated that participants that had control over their motion experienced greater levels of cybersickness than their yoked pairs. Furthermore, subjects in control over their motion stimuli had significantly larger amounts of head rotation than the Yoked Pair condition which didn't provide control. These results may be indicative of the importance of the control metaphor matching users' expectations that are drawn from past real world experiences. Simply providing motion control in IVE's needn't readily reduce cybersickness but could even increase it. It may hence be important to consider the fidelity of the control metaphor and the ability of the feedback produced to faithfully match expectations drawn from real world experiences.

For future work, we plan to investigate how cybersickness is affected by driving scenarios with different fidelities of control metaphors. Specifically, our immediate interests lie in determining if our results will hold if accurate inertial sensory-motor feedback is provided and how cybersickness will be affected if we manipulate the fidelity of this feedback. Furthermore, we plan to assess how workload affects sickness in IVE's providing motion control and also wish to investigate the role of control in other travel metaphors.

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