Review of Travel Techniques in VR with a focus on Simulator Sickness

Hayden Norrie
Cape Town, South Africa
hnorrie18@gmail.com

ABSTRACT

Recent releases of more affordable and widely available VR equipment is allowing more users than ever to experience virtual reality in the commercial, educational, health and gaming sectors. VR experiences are still prone to inducing Simulator Sickness in its users. As VR becomes more widely adopted it is crucial that we learn and develop methods to reduce this SS. In this review, we look at different travel techniques in VR and how their controls can be implemented by using a typology outlined by Boletsis and Cedergen. We also look at how these techniques and controls have an affect on SS and compare what travel techniques will be useful in which situations.

Following this, we take a deeper dive into SS itself and theories behind its existence. We show that SS can be caused not only by the technology itself but it can be influenced greatly by individual differences such as gender and age. Finally, we will look at current methods to prevent Simulator Sickness. While this review shows there has been significant research into SS and how to reduce it there is still more research to be done and SS still plagues many VR experiences.

Author Keywords

Simulator Sickness, Cyber-Sickness, Virtual Reality, Travel Techniques, Head Mounted Display (HMD)

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Interaction paradigms;* Virtual reality;

INTRODUCTION

Virtual Reality(VR) is a method by which users have the ability to immerse themselves in a virtual environment. It is used in autism intervention [30][38], education[21], military training[6] and gaming, most of which require a user to move around the virtual environment, whether it be long or short distances. Locomotion in the VR setting, therefore, is a crucial aspect to a VR experience. Locomotion in VR simulates locomotion in the real world. Users can navigate a virtual environment by walking, running, driving, and even flying. These different locomotive methods could be implemented using a variety of methods as outlined by Boletsis' and Cedergen's locomotion technique typology [10][11]. Each technique presents its own advantages and disadvantages. These techniques can be implemented using hardware or software controls.

In implementing locomotion into VR experiences users often experience symptoms such as nausea, headaches and more[64][22]. These symptoms are caused by what researchers have titled Simulator Sickness(SS), a subset of motion sickness. This is because symptoms of SS closely resemble those of motion sickness. There are many factors that cause SS each contributing to the severity of SS. Thus it is important research be done to remove SS from VR experiences.

Though VR technology has advanced greatly simulator sickness is still an ongoing problem. SS plagues many VR experiences and could be a stumbling block in VRs success. With more advanced VR headsets becoming more widely and cheaply available, it is crucial that the issue of SS be tackled so users have the best possible VR experience so VR can flourish as an emerging technology.

LOCOMOTION

Locomotion refers to movement or the ability to move from one place to another, and is essential to VR. Within a virtual environment, to complete tasks and navigate the virtual environment, there are a variety of techniques to navigate from point A to point B, known as travel techniques. Factors like environment size, path complexity and whether the virtual environment is an indoors environment or not[1] all contribute towards which travel technique is chosen to be used in a given virtual environment. Travel techniques can be sub-categorised into how their controls are implemented.

Locomotion Controls

Before analysing the possible techniques of travel in virtual reality, we must understand that such techniques require users to control them. User controls can implemented using in many different ways, either hardware based or software based. This is shown using Boletsis' and Cedergen's locomotion technique typology (Figure 1.1)[10][11]. Each type of user control implementation can provide advantages or disadvantages based

ISBN 978-1-4503-2138-9.

DOI: 10.1145/1235

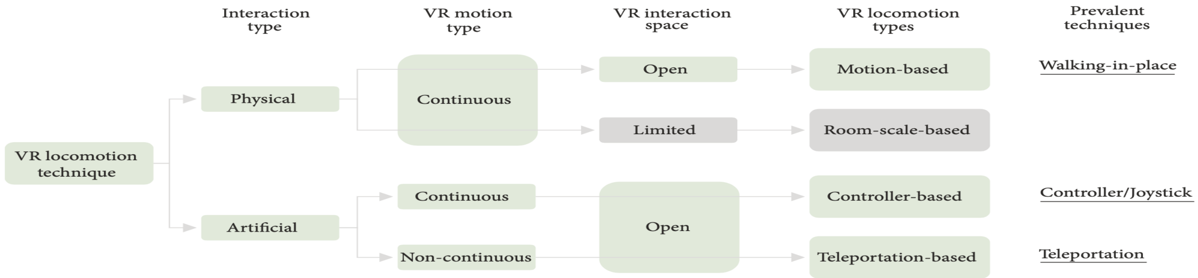

Figure 1. Boletsis' and Cedergen's Locomotion Technique Typology

on the virtual environment you find yourself in. We will be looking at the leaves of the typology tree. The following table describes the leaves of the typology tree, and are the control implementations we will interest ourselves with.

1. Motion-based: This locomotion technique is continuous, meaning you experience the movement from point A to point B. Physical movement in reality translates into movement within the virtual environment.
2. Room-scale-based: This locomotion technique is the same as the above mentioned motion-based with a key difference. The user interaction is constrained by the size of the physical environment they find themselves in.
3. Controller-based: This technique is continuous and requires a user to use a hardware controller (E.g. JoyStick, Steering wheel) to navigate a virtual environment. This control implementation is not limited by any physical constraints as the user remains in place while navigating the virtual environment, only having to use the controller and potentially head movement.
4. Teleportation-based: This technique is a non-continuous method, meaning a user moves from point A and appears at point B, rather than experiencing movement from point A to point B, like one would in a real world setting.

Choosing a control implementation depends will affect which locomotion technique one chooses to use, and vice versa. We will now delve into the different locomotion techniques used in VR.

Locomotion Techniques

Walking

Walking in VR can be implemented using any of the control implementations mentioned above. Choosing a controls implementation for walking would be based on factors like physical constraints in the real world and the size of the virtual environment. Real-Walking(RW), a motion-based technique, allows a user to navigate an environment by walking around in the real world. This allows faster traversal of a simulated environment and results in fewer collisions with virtual objects in comparison to a controller-based technique like a Moving-Where-Looking (MWL) or a Moving-Where-Pointing(MWP) technique[65]. These motion-based techniques allow a user to walk in the real world to enable movement in the virtual environment. These walking techniques can utilize re-positioning systems like a linear treadmill, motorized floor tiles or a human sized hamster ball [45], or a free-walking experience can be used where a user is able to walk around a room to enable movement in the virtual environment, without any form of limit on where they can walk (Disregarding the size of the room).
We should also consider a proxy-gesture control implementation, where one uses gestures to navigate the virtual environment. A common proxy gesture technique is the Walking-In-Place technique[14] which is cheaper and more convenient than RW[45] as one is not in need of any hardware. This technique requires a gesture of one marching on the spot thus emulating the action of walking which results in movement in the real world. Other such gestures are foot tapping, and arm swinging, or fist clenching.

Though walking controls can be implemented in a variety of ways, developers must be aware that each method might be prone SS. A study which tried to analyze methods to enhance the immersion and minimize the SS of users, while focused on walking, showed that the WIP method resulted in lower SS levels that that of a gamepad or a hand-gesture based movement implementation[40]. Another study linked higher SS to complex virtual environments as a complex environment requires lots of physical maneuvering for successful navigation[64]. The results suggest that proxy-gestures would be ideal in navigating complex environments in VR in comparison to RW.

Teleportation

Teleportation is a locomotion technique in which a user is transferred from point A to point B non-continuously. Teleportation comes with restrictions such as how far one can teleport. In the Point-And-Teleport technique(PAT) a user is required to point at a location in a virtual environment(point B) using a gesture or a hardware controller[13] following which they will be teleported to point B. The PAT showed increased traversal times and increased number of collisions in obstructed environments[13]. This makes sense as another study has shown PAT to be useful when a user must traverse long distances[12]. This shows that PAT may be more suited to unobstructed environments and may be a useful technique to use in large spaces with few obstructing objects. Furthermore, studies have shown PAT did not improve on simulator sickness is comparison to the WIP technique, but remained higher than the joystick technique. Teleportation is generally known to transfer you instantaneously, but studies have shown that using animations while being transferred, known as the Jumper Metaphor which makes it look more like a continuous method of travel, can increase user satisfaction and make user feel better at completing tasks[12]. Another teleportation technique, known as Arc-Teleportation (AT) can be used. It is similar to PAT but it shows an avatar at point B to show the user their final destination. The AT technique has been shown to reduce simulator sickness in comparison to a free-motion technique while the sense of presence in the virtual environment decreased for AT[28].

Flight

Flying in VR can be used for many travel methods like airplanes, helicopters and even a super hero like human-flying and often takes on a controller-based locomotion technique. Virtual Reality Flight Simulators (VRFS) are even used by companies like Airbus Group Innovations to help train trainee pilots [24] as well as the military to train helicopter pilots[6]. Oberhauser, in 2017, compiled a list of categories of how one can interact with a VRFS[46]:

1. Fully Virtual Virtual Collision Detection: In this way of interacting there are no physical controls. Rather a fully virtual collision detection system is implemented, meaning that the software itself detects when one interacts with objects in the virtual environment[4]. A downside is that this method does not provide haptic feedback making it harder for a user to use the VFRS.
2. Simple Haptic Feedback: In this way of interacting a user has minimal haptic feedback. This slightly improves usability of a VFRS.
3. Advanced Haptic Feedback: In this way of interacting a user is provided with a hardware version of the simulator environemnt. Thus when touching controls, they do so in the real world too. This makes the VR experience way more real to the user but has a downside in that the VR experience becomes more expensive and less flexible, as when the VR environment is changed the hardware needs to be change too, to the exact degree the VR environment is changed.

Thus from above we can see that as you generate a more advanced and complicated haptic feedback system, the less flexible the VR experience becomes.

Research results show that the airplanes are harder to control with VR, with studies showing button hit rates as low as 77%[5] with the deviations of heading direction, altitude and runway alignment all larger than that of a classic hardware flight simulator(CHFS)[47]. Thus, using a VRFS results in pilots needing more time to handle control elements of the airplane. This same study also showed that flight SS was significantly higher than that of a CHFS as shown by the factors of SS. The same study showed that, importantly, after an acclimatization phase, pilots were able to complete flights safely and reliably.

Another VRFS that was used to train helicopter pilots was the Fused Reality(FR) system [6], a high fidelity helicopter flight simulator. It was used to train Navy pilots. This allows them to practice tasks like hover position control during rescue missions, helicopter in flight refueling procedures and hoist control and cargo hook release.

Driving

One of the most common forms of transportation in the real world is driving, whether it be in the form of a personal car, taxi, bus, or even construction vehicles. Just like the other locomotion methods mentioned above driving controls are often implemented using a controller-based technique. Driving in VR raises an obvious question. Can VR be used as a training mechanism for drivers?
It has been shown that younger users find virtual reality driving simulators(VRDS) more comfortable and usable[58].The same study showed that there is a direct correlation between comfort and the amount of simulator sickness one experiences[58]. This shows us that to potentially reduce simulator sickness in a driving virtual environment one may look to increase comfort for users, older and younger. Other studies have shown users to have an immense sense of presence in a virtual reality driving system where they were placed in a real car, and with a VR headset immersing the user in the VRDS meanwhile there was an experienced ghost driver (someone driving for them) to make the experience sound and feel more realistic[23]. Thus, natural sound and feel could contribute to immersion in a VRDS. This is known as congruence between the physical and virtual world. With this immersion and a professional driving imitating the actions of the user they are able to practice difficult/dangerous scenarios in a safe environment and thus develop ones driving skills in a safe environment, even though the virtual scenarios could be dangerous.

VRDS have been shown to increase driver adaptability to a virtual environment[66]. This was shown by getting drivers to do multiple laps around a circuit and used performance data to show that drivers quickly became more comfortable in a virtual environment and went back to their general driving tendencies, as they would in a real world environment.

There are also fields studying autonomous driving[62] and anxiety management[37] using VRDS.

SIMULATOR SICKNESS

Simulator sickness(SS), also known as cybersickness[9], is often experienced during a virtual reality experience for a variety of different reasons. SS resembles motion sickness in its symptoms. SS occurs when ones visual system perceives motion, meanwhile the vestibular system indicates that the body is not moving. There is much research being done on the causes of SS which will be discussed below. Older research has suggested three main theories explaining the reason why humans experience SS.

Theories of Simulator Sickness

The causes for simulator sickness are not entirely known, nor confirmed. The following theories have been proposed.

1. Sensory Conflict Theory
2. Postural Instability Theory
3. Poison Theory

The Sensory Conflict Theory was created at a time when there was no understanding of motion sickness's mechanisms. It suggests that sensory theory can be modelled mathematically thus stating that if stimuli from the outside environment are being perceived differently by different senses, motion sickness will ensue and symptoms will occur[48]. the Postural Instability Theory, as shown by the paper 'An Ecological Theory of Motion Sickness and Postural Instability'[54], states that an animal experiences motion sickness in situations in which they do not know how to maintain postural stability. This theory also claims that sensory conflict does not exist, and stands in direct contradiction of the first theory. The final theory, Poison Theory, rather than explaining why SS takes place from a physical point of view, it explains why it happens from an evolutionary point of view. It is based on the idea that SS provides similar symptoms to that of ingesting poison, thus if an incorrectly perceived environment could have been due to effect of poison in the past, symptoms could show[67].

Measuring Simulator Sickness

In doing VR research it is essential there be a way to measure SS of a VR experience. If there were no way to measure SS we would develop VR applications which could have potential negative affects on its users which is simply unethical. Measuring SS can come in two forms: Subjective and Objective.
Earlier research has made the use of questionnaires, a subjective measure of participants SS. [**?**]The question arises, is there a more objective and accurate way to measure SS? In this section we will analyze existing methods, both subjective and objective, to measure SS.

Subjective

In 1968 research led to the Pensacola Motion Sickness Questionnaire(MSQ) being developed[31]. The MSQ did not do any form of factor analysis and therefore it did not take into account the different factors of motion sickness[35] and for this reason it is not an accurate measure and therefore not used in measuring motion sickness nowadays.

The Simulator Sickness Questionnaire(SSQ), developed by Kennedy et al. in 1993[55], is the most common tool for measuring simulator sickness[26]. One of the main aims of the paper was "to provide a more valid index of overall simulator sickness severity as distinguished from motion sickness". It does this by asking a user to score there symptoms, of which there are 16 symptoms to score, on a scale from 0-3. The symptoms are broken down into three categories: (a) Oculomotor, (b) Disorientation, and (c)Nausea, though the participant doing the questionnaire is not always aware of this. Finally, after evaluating the questionnaire, the SSQ provides an overall score to describe a level of SS a participant experiences. One must consider that VR technology has changed dramatically over the last 20 years, thus it is important to revisit whether this is still a useful measure of SS[7]. A more recent study done in 2020 indicates that the SSQ does not have such validity in comparison to new SS measuring methods, and cannot detect subtle changes in SS between VR environments like the newer methods can[60]. One should also note that the SSQ was developed using an entirely male sample, where we already know women are susceptible to SS[2][22][8], thus the SSQ may not be accurate. The SSQ was also developed using a flight simulation[55], thus limiting its scope and testing to only one VR experience.

The SSQ was developed to measure sickness in simulations rather than VR[55] but has been used for most studies. More recently, a measure of SS was developed with the intention of measuring sickness in VR, rather than any general simulation, known as the Virtual Reality Symptom Questionnaire(VRSQ)[3]. There is a problem in that when the questionnaire was developed the participants were watching a video rather than directly interacting with a virtual environment. This brings us to question the validity of the VSRQ in interactive VR experiences. Though some studies have used the VSRQ to measure SS, it has not be widely used. The VSRQ differs from the SSQ as it tends to focus on eye-strain[3] and is rather composed of two components rather than three: Oculomotor and disorientation. In the development of VSRQ, it was shown that nausua contributed less than the other two factors[34], and thus nausua was left out as a factor. The VSRQ sees VR Sickness as a subset of SS, thus this questionnaire was developed.

Objective

Though the SSQ is more widely used, it is based on the opinion on the participants and participant report back and can therefore be inaccurate. This begs the question, is there a more accurate/precise way we could measure SS? The idea of using physiology to determine a measure for SS has been suggested in older research[16]. Some studies have even used physiological measures like blink rate and heart rate to determine SS[35]. This could be extended further to see if other physiological measures indicate severity of SS.

Causes

Individual Differences

We now know from research that there individual differences play a role in whether a person will experience SS, more specifically the severity of SS. Results from multiple studies have shown females to be more susceptible to SS than men[2][22][8]. Another contributing factor to simulator sickness is age which Park et al. suggest may be due to an older persons slower visual processing[27][49]. A more recent study has challenged this idea and has shown that younger people experience SS more than the older[57]. These direct contradictions indicate more research is necessary to come to a scientifically valid conclusion.

Latency

Translating movement from the real world into movement in a virtual environment is a difficult task. Latency, the time difference between a users actions in real life reflecting in the virtual world, if high enough can contribute towards SS. Latency is caused by either the hardware not being able to cope with the developed software, like an head mounted display, or poorly designed and badly optimised software. An older study showed increased latency is directly correlated with increased

SS[19] and other studies have show that increased latency specifically affects disorientation rather than inducing nausea, the nausea factor of SS[63]. Interestingly though, we can look into latency and find that it is the frequency of latency that affects SS, not its amplitude[36]. The study that showed this even had participants pull of out the experiment early from the SS effects on them.

Flicker
Flicker, shown by older research, has been clearly cited as a main cause of simulator sickness[53][43]. Though hardware has improved and flicker is not as big an issue as it once was, it can affect individuals differently[53], thus caution must be taken in which hardware is used for VR applications.

Field of View(FOV)
The field of view is the range of the virtual environment that one can see when immersed in a VR experience. Thus, it is the maximum visual angle of a VR device. We can change the FOV through either the hardware or the virtual environment itself. To reduce the FOV has been shown to reduce SS. We can do this by distancing a user from the display or by changing the size of the VR display[61].

Exposure Time
Research from as early as 1994[39] has shown that with increased exposure time to a VE, symptoms tend to get more severe. This research was further backed up by research done in 1995[52] and 2000[33]. Though this research is old it is very important and suggests that when designing a VR experience, one should keep task completion limited to certain lengths of time, especially if there are other factors contributing towards VR sickness, all confounding on one another. More recently we have been guided as to how long these tasks should take. Exposure time in VR from times between 1 - 7 minutes tend not to induce SS, and are thus optimal times for task completion [42]

Realism
There has been little research done on the affects of realism on SS. A recent study from 2018[50], contrary to what one would think, shows that high realism actually causes greater levels of simulator sickness.

Prevention Methods
It is important that in developing VR applications that developers ensure they try and reduce SS as much as they can. In this section we will discuss current methods, and emerging methods, on how one can prevent SS in a VR application.

Rest-Frames
The rest frame hypothesis, as proposed by Prothero [51], states that a person uses a reference frame, a coordinate system, to orientations, spaces and positions. The idea is that a person chooses a rest-frame, a frame that will remain stationairy and essential ground the user in the virtual environment, and uses the reference frame to instantly reduce SS. In one study a virtual nose was used as a rest frame and showed a significant reduction is SS[69] and other studies have shown rest frames to reduce SS [15] by exposing undergraduate students to a rest frame condition and a non rest frame condition. There is some research contradicting this with participants stating that the rest frame caused more chaos and confusion[25] indicating that potentially more research is necessary to accurately show that rest-frames reduce SS.

Motion Platforms
According to Sensory Conflict Theory, the main driver of SS is the direct contradiction between the visual and vestibular systems[48]. Thus, one could infer that by tricking the vestibular system into experience what the visual system experiences, one could reduce SS. A study by A.K.T.Ng et al looked into this idea [44]. They used stationary, visual-vestibular synchronous, and self referenced set ups to test all three conditions. The synchronous condition resulted in a lower overall SSQ total in comparison to the other stationary and self-referenced set ups, with an increased amount of joyfulness and lowered amount of misery reported by the participants.

Adaption
It has been found that with repeated exposure to a motion sickness inducing environment that motion sickness can decrease [32][68][29]. It therefore stands to reason that we could test this for SS in VR as SS is simply a subset of motion sickness. This was proven to be true in a study from 2013 [20] where participants, the lag group, were given a 10 minute acclimatization period in a driving simulator. This group showed lower scores in their SS questionnaires. This indicates that there might be a necessity for VR applications to come with compulsory 10 minute acclimatization application within the major VR application.

Natural Preventions
Not all SS prevention methods are hardware and software based. Humans have to the power to reduce SS by controlling room airflow [17] and controlling breathing [56].

Visual Techniques
As discussed earlier, reducing FOV can reduce SS. This has been shown in many studies [41][18][59]. Therefore in developing VR applications one needs to find a balance between between a wide FOV for immersion without making users experience SS.

CONCLUSION
In this literature review we looked extensively into VR travel methods catergorized as per Boletsis' and Cedergen's locomotion technique typology [10][11]. We then sought how certain travel methods in certain VR experiences, such as complex versus simple environments, may induce SS. Following this we looked into the definition of SS and the theories as to how it is induced. Finally, we looked at the causes and preventions of SS.

It is clear that after extensive review of the literature there is still much research to be done in all the above fields. Individual factors have been shown to contribute hugely towards how a person experiences SS and well as the technology a person uses. Not only individual differences, but the VR technology itself contributes greatly towards SS and thus there is more to studied as to how we can decrease SS through these channels.

Many of the studies analyzed above had contradicting studies proving opposite results [27][49][57].

In conclusion, with these study contradictions there is place for more research to be done into the prevention techniques of SS in VR.

REFERENCES

[1] ACM 2008. Proceedings of the IEEE International Conference on Web Services. In *UIST '18 Adjunct*. Association for Computing Machinery, New York, NY, United States, 232—-235. DOI: http://dx.doi.org//10.1145/3266037.3266126

[2] Mustafa Almallah, Qinaat Hussain, Nora Reinolsmann, and Wael Alhajyaseen. 2021. Driving simulation sickness and the sense of presence: Correlation and contributing factors. *Transportation Research Part F Traffic Psychology and Behaviour* 78 (03 2021), 180–193. DOI: http://dx.doi.org/10.1016/j.trf.2021.02.005

[3] Shelly Ames, James Wolffsohn, and Neville McBrien. 2005. The Development of a Symptom Questionnaire for Assessing Virtual Reality Viewing Using a Head-Mounted Display. *Optometry and vision science : official publication of the American Academy of Optometry* 82 (04 2005), 168–76. DOI: http://dx.doi.org/10.1097/01.OPX.0000156307.95086.6

[4] Turgay Aslandere, Daniel Dreyer, and Frieder Pankratz. 2015. Virtual hand-button interaction in a generic virtual reality flight simulator. In *2015 IEEE aerospace conference*. IEEE, 1–8.

[5] Turgay Aslandere, Daniel Dreyer, Frieder Pankratz, and René Schubotz. 2014. A Generic Virtual Reality Flight Simulator.

[6] Ed Bachelder. 2006. *Helicopter aircrew training using fused reality*. Technical Report. SYSTEMS TECHNOLOGY INC HAWTHORNE CA.

[7] S. Balk, Mary Bertola, and Vaughan Inman. 2017. Simulator Sickness Questionnaire: Twenty Years Later. 257–263. DOI: http://dx.doi.org/10.17077/drivingassessment.1498

[8] F. Biocca. 1992. Will Simulation Sickness Slow Down the Diffusion of Virtual Environment Technology? *Presence: Teleoperators Virtual Environments* 1 (1992), 334–343.

[9] Willem Bles, Jelte. E Bos, Bernd De Graaf, Eric Groen, and Alexander H. Werthein. 1998. Motion sickness: Only one provocative conflict? *Brain Research Bulletin* 47 (481–487 1998), 6. DOI: http://dx.doi.org/10.1016/S0361-9230(98)00115-4

[10] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1 (Sept. 2017), 24. DOI: http://dx.doi.org/10.3390/mti1040024

[11] Costas Boletsis and Jarl Cedergren. 2019. VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques. *Advances in Human-Computer Interaction* 2019 (apr 2019), 1–15. DOI: http://dx.doi.org/10.1155/2019/7420781

[12] Benjamin Bolte, Gerd Bruder, and Frank Steinicke. 2011. The Jumper Metaphor: An Effective Navigation Technique for Immersive Display Setups. In *Proceedings of the Virtual Reality International Conference (VRIC)*. 1–7. http://basilic.informatik.uni-hamburg.de/Publications/2011/BBS11a

[13] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point amp; Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. Association for Computing Machinery, New York, NY, USA, 205–216. DOI:http://dx.doi.org/10.1145/2967934.2968105

[14] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2018. Locomotion in Virtual Reality for Room Scale Tracked Areas. *International Journal of Human-Computer Studies* 122 (08 2018). DOI: http://dx.doi.org/10.1016/j.ijhcs.2018.08.002

[15] EunHee Chang, InJae Hwang, Hyeonjin Jeon, Yeseul Chun, Hyun Taek Kim, and Changhoon Park. 2013. Effects of rest frames on cybersickness and oscillatory brain activity. In *2013 International Winter Workshop on Brain-Computer Interface (BCI)*. IEEE, 62–64.

[16] Patricia S Cowings, Steve Suter, William B Toscano, Joe Kamiya, and Karen Naifeh. 1986. General autonomic components of motion sickness. *Psychophysiology* 23, 5 (1986), 542–551.

[17] Sarah D'Amour, Jelte Bos, and Behrang Keshavarz. 2017. The efficacy of airflow and seat vibration on reducing visually induced motion sickness. *Experimental brain research* 235 (09 2017). DOI: http://dx.doi.org/10.1007/s00221-017-5009-1

[18] P. DiZio and J. Lackner. 1997. Circumventing Side Effects of Immersive Virtual Environments. In *HCI*.

[19] Paul Dizio and James Lackner. 2000. Motion Sickness Side Effects and Aftereffects of Immersive Virtual Environments Created with Helmet-Mounted Visual Displays. (11 2000), 4.

[20] Joshua Domeyer, Nicholas Cassavaugh, and Richard Backs. 2013. The use of adaptation to reduce simulator sickness in driving assessment and research. *Accident; analysis and prevention* 53 (04 2013), 127–32. DOI: http://dx.doi.org/10.1016/j.aap.2012.12.039

[21] Laura Freina and Michela Ott. 2015. A literature review on immersive virtual reality in education: state of the art and perspectives. In *The international scientific conference elearning and software for education*, Vol. 1. 10–1007.

[22] Andre Garcia, Carryl Baldwin, and Matt Dworsky. 2010. Gender Differences in Simulator Sickness in Fixed- versus Rotating-Base Driving Simulator. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 54 (09 2010), 1551–1555. DOI: http://dx.doi.org/10.1177/154193121005401941

[23] David Goedicke, Jamy Li, Vanessa Evers, and Wendy Ju. 2018. VR-OOM: Virtual Reality On-ROad Driving SiMulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. DOI: http://dx.doi.org/10.1145/3173574.3173739

[24] Airbus Innovations Group. 2019. Airbus brings cockpit to you with new Virtual Reality Flight Trainer. (dec 2019). Retrieved May 27th, 2021 from services.airbus.com/en/newsroom/stories/2019/12/airbus-brings-cockpit-to-you-with-new-virtual-reality-flight-trainer.html

[25] Joost Heutink, Minou Broekman, Karel A Brookhuis, Bart JM Melis-Dankers, and Christina Cordes. 2019. The effects of habituation and adding a rest-frame on experienced simulator sickness in an advanced mobility scooter driving simulator. *Ergonomics* 62, 1 (2019), 65–75.

[26] Teresa Hirzle, Maurice Cordts, Enrico Rukzio, Jan Gugenheimer, and Andreas Bulling. 2021. A Critical Assessment of the Use of SSQ as a Measure of General Discomfort in VR Head-Mounted Displays. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 530, 14 pages. DOI: http://dx.doi.org/10.1145/3411764.3445361

[27] Jukka Häkkinen, T. Vuori, and M. Paakka. 2002. Postural stability and sickness symptoms after HMD use. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics* 1 (11 2002), 147– 152. DOI:http://dx.doi.org/10.1109/ICSMC.2002.1167964

[28] M. P. Jacob Habgood, David Moore, David Wilson, and Sergio Alapont. 2018. Rapid, Continuous Movement Between Nodes as an Accessible Virtual Reality Locomotion Technique. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 371–378. DOI:http://dx.doi.org/10.1109/VR.2018.8446130

[29] David Johnson. 2005. Introduction to and Review of Simulator Sickness Research. (01 2005).

[30] Naomi Josman, Hadass Milika Ben-Chaim, Shula Friedrich, and Patrice L Weiss. 2008. Effectiveness of virtual reality for teaching street-crossing skills to children and adolescents with autism. *International Journal on Disability and Human Development* 7, 1 (2008), 49–56.

[31] RS KELLOGG, RS KENNEDY, and A GRAYBIEL. 1965. MOTION SICKNESS SYMPTOMATOLOGY OF LABYRINTHINE DEFECTIVE AND NORMAL SUBJECTS DURING ZERO GRAVITY MANEUVERS. *Aerospace medicine* 36 (April 1965), 315—318. http://europepmc.org/abstract/MED/14288892

[32] Robert Samuel Kennedy and Lawernce H Frank. 1985. A review of motion sickness with special reference to simulator sickness. (1985).

[33] Robert S. Kennedy, Kay M. Stanney, and William P. Dunlap. 2000. Duration and Exposure to Virtual Environments: Sickness Curves During and Across Sessions. *Presence* 9, 5 (2000), 463–472. DOI: http://dx.doi.org/10.1162/105474600566952

[34] H. Kim, J. Park, Yeongcheol Choi, and Mungyeong Choe. 2018. Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. *Applied ergonomics* 69 (2018), 66–73.

[35] Young Kim, Hyun Kim, Eun Kim, Heedong Ko, and Hyun-Taek Kim. 2005. Characteristic changes in the physiological components of cybersickness. *Psychophysiology* 42 (10 2005), 616–25. DOI: http://dx.doi.org/10.1111/j.1469-8986.2005.00349.x

[36] Amelia Kinsella, Ryan Mattfeld, Eric Muth, and Adam Hoover. 2016. Frequency, Not Amplitude, of Latency Affects Subjective Sickness in a Head-Mounted Display. *Aerospace Medicine and Human Performance* 87 (07 2016), 604–609. DOI: http://dx.doi.org/10.3357/AMHP.4351.2016

[37] Alexandros Koilias, Christos Mousas, Banafsheh Rekabdar, and Christos-Nikolaos Anagnostopoulos. 2019. Passenger Anxiety when Seated in a Virtual Reality Self-Driving Car. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 1024–1025. DOI:http://dx.doi.org/10.1109/VR.2019.8798084

[38] Uttama Lahiri, Esubalew Bekele, Elizabeth Dohrmann, Zachary Warren, and Nilanjan Sarkar. 2012. Design of a virtual reality based adaptive response technology for children with autism. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 21, 1 (2012), 55–64.

[39] Donald R. Lampton, Eugenia M. Kolasinski, Bruce W. Knerr, James P. Bliss, John H. Bailey, and Bob G. Witmer. 1994. Side Effects and Aftereffects of Immersion in Virtual Environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 38, 18 (1994), 1154–1157. DOI: http://dx.doi.org/10.1177/154193129403801802

[40] Jiwon Lee, Mingyu Kim, and Kim Jinmo. 2017. A Study on Immersion and VR Sickness in Walking Interaction for Immersive Virtual Reality Applications. *Symmetry* 9 (05 2017), 78. DOI: http://dx.doi.org/10.3390/sym9050078

[41] James Lin, Henry Duh, Habib Abi-RAched, and Don Parker. 2002. Effects of Field of View on Presence, Enjoyment, Memory, and Simulator Sickness in a Virtual Environment. *Virtual Reality Conference, IEEE* 0 (01 2002), 164.

[42] Miguel Melo, José Vasconcelos-Raposo, and Maximino Bessa. 2017. Presence and cybersickness in immersive content: Effects of content type, exposure time and gender. *Computers Graphics* (12 2017), –. DOI: http://dx.doi.org/10.1016/j.cag.2017.11.007

[43] Ronald Mourant and Thara Thattacheny. 2000. Simulator Sickness in a Virtual Environments Driving Simulator. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 44 (07 2000). DOI: http://dx.doi.org/10.1177/154193120004400513

[44] Adrian KT Ng, Leith KY Chan, and Henry YK Lau. 2020. A study of cybersickness and sensory conflict theory using a motion-coupled virtual reality system. *Displays* 61 (2020), 101922.

[45] Niels Christian Nilsson, Stefania Serafin, Frank Steinicke, and Rolf Nordahl. 2018. Natural Walking in Virtual Reality: A Review. *Comput. Entertain.* 16, 2, Article 8 (April 2018), 22 pages. DOI: http://dx.doi.org/10.1145/3180658

[46] Matthias Oberhauser and Daniel Dreyer. 2017. A virtual reality flight simulator for human factors engineering. *Cogn Tech Work* 19 (07 2017), 263–277. DOI: http://dx.doi.org//10.1007/s10111-017-0421-7

[47] Matthias Oberhauser, Daniel Dreyer, Reinhard Braunstingl, and Ioana Koglbauer. 2018. What's Real About Virtual Reality Flight Simulation?: Comparing the Fidelity of a Virtual Reality With a Conventional Flight Simulation Environment. *Aviation Psychology and Applied Human Factors* 8 (03 2018), 22–34. DOI: http://dx.doi.org/10.1027/2192-0923/a000134

[48] Charles M. Oman. 1990. Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Canadian Journal of Physiology and Pharmacology* 68, 2 (1990), 294–303. DOI:http://dx.doi.org/10.1139/y90-044 PMID: 2178753.

[49] George Park, Richard Allen, Dary Fiorentino, Theodore Rosenthal, and Marcia Cook. 2006. Simulator Sickness Scores According to Symptom Susceptibility, Age, and Gender for an Older Driver Assessment Study. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 50 (10 2006), 2702–2706. DOI: http://dx.doi.org/10.1177/154193120605002607

[50] Matti Pouke, Arttu Tiiro, Steven M. LaValle, and Timo Ojala. 2018. Effects of Visual Realism and Moving Detail on Cybersickness. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 665–666. DOI:http://dx.doi.org/10.1109/VR.2018.8446078

[51] Jerrold D Prothero. 1998. The role of rest frames in vection, presence and motion sickness. (1998).

[52] Clare Regan. 1995. An Investigation into Nausea and Other Side-Effects of Head-Coupled Immersive Virtual Reality. *Virtual Real.* 1, 1 (June 1995), 17–31. DOI: http://dx.doi.org/10.1007/BF02009710

[53] Helge Renkewitz and Thomas Alexander. 2007. *Perceptual issues of augmented and virtual environments*. Technical Report. FGAN-FKIE WACHTBERG (GERMANY).

[54] Gary Riccio and Thomas Stoffregen. 1991. An Ecological Theory of Motion Sickness and Postural Instability. *Ecological Psychology - ECOL PSYCHOL* 3 (09 1991), 195–240. DOI: http://dx.doi.org/10.1207/s15326969eco0303_2

[55] Kevin S. Berbaum Michael G. Lilienthal Robert S. Kennedy, Norman E. Lane. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* (3 1993), 203–220. DOI: http://dx.doi.org/10.1207/s15327108ijap0303_3

[56] Matthew Russell, Brittney Hoffman, Sarah Stromberg, and Charles Carlson. 2014. Use of Controlled Diaphragmatic Breathing for the Management of Motion Sickness in a Virtual Reality Environment. *Applied psychophysiology and biofeedback* 39 (10 2014). DOI:http://dx.doi.org/10.1007/s10484-014-9265-6

[57] Dimitrios Saredakis, Ancret Szpak, Brandon Birckhead, Hannah Keage, Albert Rizzo, and Tobias Loetscher. 2020. Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and Meta-Analysis. *Frontiers in Human Neuroscience* 14 (03 2020). DOI: http://dx.doi.org/10.3389/fnhum.2020.00096

[58] Maria Schultheis, Jose Rebimbas, Ronald Mourant, and Scott Millis. 2007. Examining the Usability of a Virtual Reality Driving Simulator. *Assistive technology : the official journal of RESNA* 19 (02 2007), 1–8; quiz 9. DOI:http://dx.doi.org/10.1080/10400435.2007.10131860

[59] A.F. Seay, David Krum, Larry Hodges, and W. Ribarsky. 2001. Simulator sickness and presence in a high FOV virtual environment. *Proceedings of IEEE Virtual Reality* (04 2001), 299 – 300. DOI: http://dx.doi.org/10.1109/VR.2001.913806

[60] Volkan Sevinc and Mehmet Berkman. 2019. Psychometric evaluation of Simulator Sickness Questionnaire and its variants as a measure of cybersickness in consumer virtual environments. *Applied ergonomics* 82 (09 2019), 102958. DOI: http://dx.doi.org/10.1016/j.apergo.2019.102958

[61] Hiroaki Shigemasu, Toshiya Morita, Naoyuki Matsuzaki, Takao Sato, Masamitsu Harasawa, and Kiyoharu Aizawa. 2006. Effects of physical display size and amplitude of oscillation on visually induced motion sickness. 372–375. DOI: http://dx.doi.org/10.1145/1180495.1180571

[62] Daniele Sportillo, Alexis Paljic, and Luciano Ojeda. 2018. Get ready for automated driving using Virtual Reality. *Accident Analysis Prevention* 118 (06 2018), 102–113. DOI: http://dx.doi.org/10.1016/j.aap.2018.06.003

[63] Jan-Philipp Stauffert, Florian Niebling, and Marc Erich Latoschik. 2018. Effects of Latency Jitter on Simulator Sickness in a Search Task. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 121–127. DOI:http://dx.doi.org/10.1109/VR.2018.8446195

[64] Evan A. Suma, Samantha L. Finkelstein, Myra Reid, Amy Ulinski, and Larry F. Hodges. 2009. Real Walking Increases Simulator Sickness in Navigationally Complex Virtual Environments. In *2009 IEEE Virtual Reality Conference*. 245–246. DOI: http://dx.doi.org/10.1109/VR.2009.4811037

[65] Evan Suma Rosenberg, Sabarish Babu, and Larry Hodges. 2007. Comparison of Travel Techniques in a Complex, Multi-Level 3D Environment. *3D User Interfaces* 0 (03 2007), null. DOI: http://dx.doi.org/10.1109/3DUI.2007.340788

[66] Meisam Taheri, Kojiro Matsushita, and Minoru Sasaki. 2017. Virtual Reality Driving Simulation for Measuring Driver Behavior and Characteristics. *Journal of Transportation Technologies* 7 (04 2017), 123–132. DOI: http://dx.doi.org/10.4236/jtts.2017.72009

[67] Michel Treisman. 1977. Motion sickness: An evolutionary hypothesis. *Science (New York, N.Y.)* 197 (08 1977), 493–5. DOI: http://dx.doi.org/10.1126/science.301659

[68] Pamela S Tsang and Michael A Vidulich. 2002. *Principles and practice of aviation psychology*. CRC Press.

[69] Carolin Wienrich, Christine Katharina Weidner, Celina Schatto, David Obremski, and Johann Habakuk Israel. 2018. A virtual nose as a rest-frame-the impact on simulator sickness and game experience. In *2018 10th international conference on virtual worlds and games for serious applications (VS-Games)*. IEEE, 1–8.