Department for
Business, Energy
& Industrial Strategy

The safety of domestic virtual reality systems

A literature review

BEIS Research Paper Number 2020/038
RPN 4527

September 2020

Any enquiries regarding this publication should be sent to us at:
enquiries@beis.gov.uk

Contents

Executive Summary

Virtual Reality (VR) is the use of computer technology to create a simulated environment. It has been used in commercial applications for many years and is becoming more popular for domestic use. Domestic VR systems involve wearing a headset, sometimes in conjunction with handsets or controllers. This literature review was commissioned to help understand the safety issues that might impact users of domestic VR systems. It considers both the physiological effects that may affect the wellness of users during use, and how the short-term effects might impair their safety in activities immediately after VR use.

Most research focuses on cybersickness, which is a form of motion sickness induced through immersion in VR. The physiological effects that it induces can include:

- loss of spatial awareness
- nausea
- dizziness
- disorientation.

Other short-term effects following VR use include:

- eye soreness and trouble focusing
- impaired hand-eye coordination
- reduced depth perception
- decreased reaction time
- loss of balance
- prolonged nausea.

The time and intensity of cybersickness felt by individuals varies widely with the stimuli and the individual. Many individuals are happy to continue to use a VR system even while experiencing low levels of discomfort, while others still experience after effects over an hour after use.

The most widely accepted theory for cybersickness is sensory conflict theory, which suggests that there is a mismatch between visual and vestibular (this is the system for balance and spatial awareness) sensory inputs which stimulates feelings of nausea and disorientation. Postural instability theory suggests that a loss of postural stability is brought on when an individual responds physically to virtual stimuli, and this leads to cybersickness. However, neither of these theories fully explains why some people develop cybersickness.

Factors affecting cybersickness

There are several characteristics of VR systems that will increase the likelihood of cybersickness occurring:

- **Apparent movement.** The amount of movement is dependent on the rapidity of change in the view, the size of the field of view (FoV), and the visual complexity. A narrow FoV can lead to more head movements and increased cybersickness. However, the perception of vection (this is the feeling that you are moving when you are not) is reduced with a smaller FoV, which can reduce this other cause of cybersickness.

- **Realism of the environment.** Although work to date is limited, it is thought that a more realistic experience will increase the likelihood of cybersickness.
- **Movement within the environment (e.g. walking).** If movement within the simulated environment does not correspond to movement that the user is experiencing in reality, then this can provoke cybersickness. This phenomenon is explained by the sensory conflict theory. Forms of simulated movement which lack motion signals (such as teleporting from various positions within a virtual environment) are less likely to provoke cybersickness but can increase feelings of disorientation.

Reducing cybersickness

There are several methods that have been found to reduce cybersickness:

- Decrease the mismatch between visual senses and the body's positional sensors by stimulating muscles to produce artificial sensations of movement.
- Introduce a depth of field (DoF), which is the range of distance in which an image appears acceptably sharp. This overcomes the issue with most systems where the entire field of vision is in focus.
- Undertake oculo-motor and hand-eye coordination exercises prior to use of VR.
- Taking breaks of 10 to 15 minutes when using VR. It has been suggested that breaks should be taken after between 15 and 30 minutes of use, but further research is needed on this.
- Regular use of VR (habituation), although these effects plateau after prolonged exposure.

Other effects resulting from VR use

Along with cybersickness, VR use can lead to effects on vision, balance and coordination, reaction times and physiological responses.

- Eye strain can result from VR use, and there is some evidence for other short-term effects.
- VR headsets generally block out visibility of the real-world, which exacerbates the danger of the user tripping and falling. There is some evidence that prolonged VR use can negatively impact the users balance.
- Reaction time can be slightly delayed immediately after VR use. This is usually relative to the severity of cybersickness for the user.
- VR use can change the user's physiological state slightly, with heart rate, skin temperature, perspiration and electrodermal activity affected.

Summary

This literature review has identified a range of causes and symptoms of cybersickness. Some of the findings could be useful for designers of domestic VR systems, and for users to take measures to minimize the likelihood and severity of cybersickness during and immediately after use. Users should also be aware of the possibility of short-term or longer-term physiological impairments that can arise following VR use so that they can avoid situations immediately afterwards which could put them in enhanced danger. Users should in any case continue to follow the instructions regarding safety given by the manufacturers of VR systems.

This report gives an overview and assessment of the considerable body of research and experience concerning the physiological impacts of VR use on the user. Fortunately the fast pace of technological development means that many of the issues highlighted will be of lesser concern than at the time that the research was undertaken. This report provides a solid foundation for assessing any consumer safety issues that might arise regarding the use of future designs of VR systems.

1 Introduction

This literature review concerns the safety of using domestic Virtual Reality (VR) systems, which are growing in capability and popularity, (Figure 1). VR is the use of computer technology to create a simulated environment, most commonly with the user wearing a headset, and sometimes also a handset or other controller. Early examples of this technology can be traced back to Morton Heilig's Sensorama machine of 1962[1], and the early flight simulators used to train pilots. Over the last 10 years, the technology has become widespread in training surgeons, engineers and medical rehabilitation, and also for commercial entertainment experiences. More recently, domestic VR systems have been launched and are proving popular. Industry forecasts suggest that domestic VR will grow rapidly and will move from the present early adopters to an established market by 2020.

Figure 1: VR Oculus Rift VR headset (left) and Sony PlayStation VR headset (right).[2]

Scope and purpose of this review
This review covers safety predominantly in the physiological aspects of VR use. It focuses on the occurrences of cybersickness and other negative impacts of using VR, including the immediate after effects. It does not cover in detail the overt physical aspects of using domestic VR equipment such as impaired posture, repetitive strain injuries, headset weight and fit, hygiene issues or immersion injuries, as these were not present within the reviewed literature. However, it does include consideration of balance and coordination difficulties due to the user being unable to view the real world.

. Reported adverse physiological effects can include the loss of spatial awareness, dizziness and disorientation, and nausea, both during and following VR use. Short-term effects following VR use can include eye soreness and trouble focusing, impaired hand-eye coordination, reduced depth perception and prolonged nausea.

The main aim of this literature review is to establish the current state of knowledge on the physiological risks to users of domestic VR systems, and to identify ways to mitigate these

[1] Webster, Rustin and Alex Clark. "Turn-key solutions: virtual reality." In *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection, 2016
[2] Images sourced from Wikimedia Commons and are in the public domain.

risks. The method used for this review is detailed in Appendix A Methodology. There is also insight from interviews with testers of domestic VR systems. Interviewees included:

- A senior lecturer within the psychology department at a UK university who uses VR for research.
- An electronics technician at a UK university who uses VR within their work as well as personally.
- A senior researcher at TRL (Transport Research Laboratory) who uses VR for research.
- A managing director at a financial management company which is interested in exploring the positive effects and applications of VR technology within such areas as behaviour prevention.
- Three individuals who use VR for domestic recreation.

The literature review concludes with a summary of the gaps in the current research.

2 Effects of using VR systems

This section presents the main findings of the literature review.

The majority of the literature reviewed had a focus on cybersickness resulting from the use of VR systems. Cybersickness has been defined as a form of motion sickness which is induced through immersion in VR. The main symptoms of cybersickness include nausea, eye strain, dizziness and disorientation.[3] These symptoms can emerge within the first 10 to 15 minutes of immersion,[4] with longer immersions capable of stimulating greater levels of cybersickness.[5] The research into cybersickness typically investigates either the causes of cybersickness symptoms or the potential to reduce the severity of them. A small amount of literature studied other specific effects resulting from the use of VR systems, such as effects on vision or reaction time. No evidence was found through the review process regarding more physical risks to domestic users of VR, such as trip hazards or repetitive strain injury.

The main findings from the literature review cover:

- Theories behind the cause of cybersickness
- Factors of VR systems that can lead to cybersickness symptoms
- Ways of mitigating cybersickness
- Adaptation after-effects
- Other effects resulting from VR use.

Results from interviews indicate whether first-hand experiences align with the findings of the literature review. Finally, a short summary of findings and research gaps is presented for each topic before the overall summary is provided in section 4.

2.1 Theories behind the cause of cybersickness

Summary of findings

Theories include: sensory conflict theory, postural instability theory and poison theory.

• Sensory conflict theory suggests that there is a mismatch between visual and vestibular (the system for balance and spatial awareness) sensory inputs which stimulates feelings

[3] Nalivaiko, Eugene, Simon L. Davis, Karen L. Blackmore, Andrew Vakulin, and Keith V. Nesbitt. "Cyber sickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time." *Physiology & Behavior* 151 (2015): 583-590; Regan, E. C., and K. R. Price. "The frequency of occurrence and severity of side-effects of immersion virtual reality." *Aviation, Space, and Environmental Medicine* (1994): 527-530.
[4] Wilson, John R. "Virtual environments and ergonomics: needs and opportunities." *Ergonomics* 40, no. 10 (1997): 1057-1077; Lampton, Donald R., Eugenia M. Kolasinski, Bruce W. Knerr, James P. Bliss, John H. Bailey, and Bob G. Witmer. "Side effects and aftereffects of immersion in virtual environments." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 38, no. 18, Los Angeles: SAGE Publications (1994): 1154-1157.
[5] Murata, Atsuo. "Effects of duration of immersion in a virtual reality environment on postural stability" *International Journal of Human-Computer Interaction* 17, no. 4 (2004): 463-477; Kennedy, Robert S., Kay M. Stanney, and William P. Dunlap. "Duration and exposure to virtual environments: sickness curves during and across sessions." *Presence: Teleoperators & Virtual Environments* 9, no. 5 (2000): 463-472.

of nausea and disorientation. This is currently the most widely accepted cause of cybersickness

• Postural instability theory suggests that a loss of postural stability is brought on when an individual responds physically to virtual stimuli and this leads to cybersickness.

• Poison theory suggests that the sickness response is a result of the brain interpreting the sensory input of VR as a hallucination brought on through the ingestion of a toxic substance; hence, the sickness occurs because the body attempts to expel the toxins.

However, no single theory explains the cause of every case of cybersickness. There is also a lack of definitive evidence on the interactions that may exist between the different theories of cybersickness (particularly between sensory conflict and postural instability) and associated factors such as vection (the illusory feeling of self-motion).

Within the literature on cybersickness, there are three leading theories about its cause. These are the sensory conflict theory, the postural instability theory and the poison theory.

The most longstanding and accepted of these theories is sensory conflict theory (sometimes referred to as sensory mismatch theory).[6] This is based on the premise that in certain circumstances (such as when an individual is exposed to a simulated environment as during immersion in a VR system), discrepancies between the visual, vestibular (balance and spatial awareness) and proprioceptive (position and movement) sensory systems occur (see Figure 2**Error! Reference source not found.**). This causes a perceptual conflict which the body does not know how to resolve.[7] For example, an individual may be viewing a virtual environment that shows they are moving while the vestibular system, which contributes to balance, is telling them that their body is stationary.

A mismatch between sensory inputs stimulates the feelings of nausea, disorientation and visual disturbances associated with cybersickness. This idea is compatible with the evolutionary explanation presented in the poison theory, outlined below. The latter offers an explanation for why sensory conflict might result in a sickness response. Related to this is the illusory feeling of self-motion created from the sensory conflict, referred to as 'vection' within the literature. This is the feeling experienced when a person perceives their body to be moving when no movement is actually taking place.[7] An example of this is the feeling of moving backwards in a stationary train while the train alongside moves forward.[8] Vection has been argued to be the root cause of cybersickness;[9] however, some research has found the link to be a lot less clear.[10]

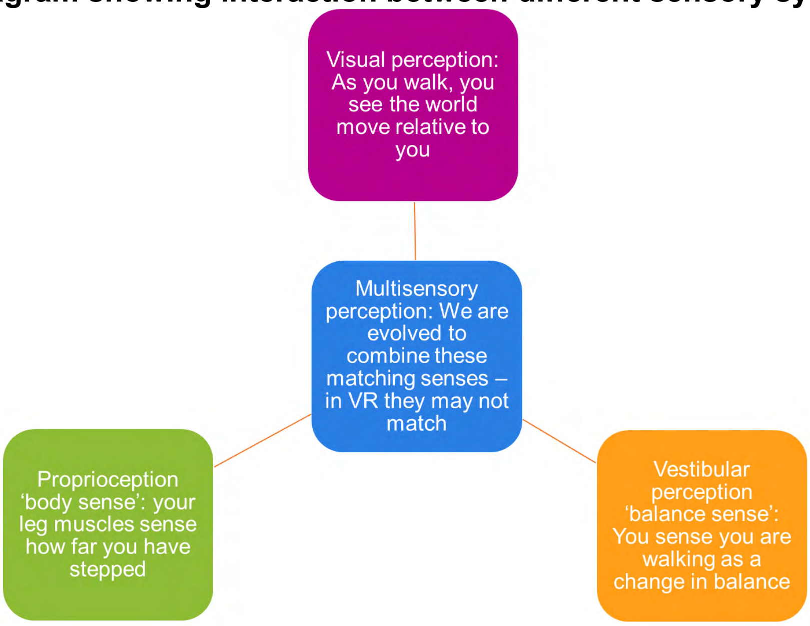
[6] Barrett, Judy. *Side effects of virtual environments: A review of the literature*. No. DSTO-TR-1419. Defence Science and Technology Organisation Canberra (Australia), 2004.
[7] Basting, Oliver, Arnulph Fuhrmann, and Stefan M. Grünvogel. "The effectiveness of changing the field of view in a HMD on the perceived self-motion." In *2017 IEEE Symposium on 3D User Interfaces* (2017): 225-226.
[8] Dennison, Mark Stephen, and Michael D'Zmura. "Cyber sickness without the wobble: experimental results speak against postural instability theory." *Applied ergonomics* 58 (2017): 215-223.
[9] Tiiro, Arttu. "Effect of Visual Realism on Cyber sickness in Virtual Reality." (Master's Thesis, University of Oulu, 2018).
[10] Webb, Nicholas A., and Michael J. Griffin. "Eye movement, vection, and motion sickness with foveal and peripheral vision." *Aviation, space, and environmental medicine* 74, no. 6 (2003): 622-625; Palmisano, Stephen, Rebecca Mursic, and Juno Kim. "Vection and cyber sickness generated by head-and-display motion in the Oculus Rift." *Displays* 46 (2017): 1-8; Kuiper, Ouren X., Jelte E. Bos, and Cyriel Diels. "Vection does not necessitate visually induced motion sickness." *Displays* (in press).

Sensory conflict theory has been criticised for its lack of predictive power in determining how severe the symptoms of cybersickness will be relative to any virtual experience.[11] It also fails to account for why some individuals suffer cybersickness while others do not.[12]

The second theory, proposed by Riccio and Stoffregen,[13] suggests that postural instability is a prerequisite for producing the symptoms of cybersickness. They state that one of the primary goals of humans is to maintain postural stability, and that prolonged instability will produce cybersickness symptoms. The severity of these symptoms is believed to be directly linked with the duration of the instability, with longer periods producing more severe symptoms.[12] It is thought that strategies for gaining postural stability will not work when exposed to the optical movements presented in many virtual environments.[13] For instance, an individual may physically respond to a visually perceived movement creating an unintended divergence from a stable position. The theory therefore suggests that it is postural instability that creates cybersickness.[14]

As with sensory conflict theory, postural instability is also believed to be affected by, or have an effect on, vection.[15] There are arguments that refute this theory, such as how individuals can still experience cybersickness symptoms when their body is at rest.[16] Findings from Dennison and D'Zmura[17] and Häkkinen, Vuori and Puhakka[18] also suggest that postural instability is neither a prerequisite for, nor a symptom of cybersickness, contradicting the original theory entirely. In short, as with other theories discussed here, there is insufficient evidence for this theory to fully explain the root cause of cybersickness.

Figure 2: Diagram showing interaction between different sensory systems



[11] Davis, Nesbitt, and Nalivaiko, "Comparing the onset," 30.
[12] LaViola Jr., "A discussion of cyber sickness," 47-56.
[13] Riccio, Gary E., and Thomas A. Stoffregen. "An ecological theory of motion sickness and postural instability." *Ecological psychology*, no. 3 (1991): 195-240.
[14] Arcioni, Benjamin, Stephen Palmisano, Deborah Apthorp, and Juno Kim. "Postural stability predicts the likelihood of cyber sickness in active HMD-based virtual reality." *Displays* (in press).
[15] Kennedy, Robert S., and Kay M. Stanney. "Postural instability induced by virtual reality exposure: Development of a certification protocol." *International Journal of Human-Computer Interaction* 8, no. 1 (1996): 25-47.
[16] Shafer, Daniel M., Corey P. Carbonara, and Michael F. Korpi. "Modern virtual reality technology: Cyber sickness, sense of presence, and gender." *Media Psychology Review* 11 (2017): 1-13.
[17] Dennison and D'Zmura. "Cyber sickness without the wobble," 215-223.
[18] Hakkinen, Jukka, Tero Vuori, and M. Paakka. "Postural stability and sickness symptoms after HMD use." In *IEEE International Conference on Systems, Man and Cybernetics* 1 (2002) 147-152.

Poison theory proposes an evolutionary explanation for cybersickness. Treisman[19] suggests that the physiological effects of cybersickness are similar to sensory hallucinations from the ingestion of some toxic substances. In response to this, the body attempts to boost its chances of survival through nausea and vomiting to remove toxins from the stomach.[20] This theory on the cause of cybersickness has been criticised. LaViola Jr. argues that the theory lacks predictive power, giving no explanation for the varied individual responses and broader spread of symptoms.[21] In short, there is little evidence supporting this theory.

All three of the theories discussed within this section present arguments for the cause of cybersickness. An understanding of these background theories can be useful because they are frequently referred to within the research literature and in the following sections. For instance, sensory conflict theory and postural instability theory have both been used to explain why VR systems cause cybersickness and how the effects of cybersickness might be reduced. However, as noted by LaViola Jr.,[21] there are examples for each theory in which the explanation cannot be substantiated.

As it stands, none of these theories currently provide a full explanation of cybersickness. Further research could help identify the exact causes.

[19] Treisman, Michel. "Motion sickness: an evolutionary hypothesis." *Science* 197, no. 4302 (1977): 493-495.
[20] Davis, Simon, Keith Nesbitt, and Eugene Nalivaiko. "Comparing the onset of cyber sickness using the Oculus Rift and two virtual roller coasters." In *Proceedings of the 11th Australasian Conference on Interactive Entertainment* 27 (2015): 30.
[21] LaViola Jr, Joseph J. "A discussion of cyber sickness in virtual environments." *ACM SIGCHI Bulletin* 32, no. 1 (2000): 47-56.

2.2 Factors of VR systems that can lead to cybersickness symptoms

Summary of findings

• The visual field of view of a VR display appears to affect cybersickness, with a wide field of view showing an increased likelihood of stimulating cybersickness.

• There is evidence that virtual environments with high-visual realism are more likely to stimulate cybersickness. VR systems with visually abstract virtual environments seem less likely to cause cybersickness.

• Different movement options, used to navigate virtual environments (e.g. walking, 'warping' or 'flying'), can elicit negative responses from the user. For example, the motions associated with warping can lead to feelings of disorientation while walking leads to feelings of nausea. The terms 'warping' and 'flying' are explained in Section 2.2.3.

• Findings from the interviews suggested that system lag (where 'real time' was running too slowly, or where the frame rate drops noticeably) can also stimulate cybersickness.

• Taking these findings together suggests a possible trade-off between immersion and cybersickness.

Research gaps

• There is poor understanding of the relationship between field of view and cybersickness, and between visual realism and cybersickness.

• How movement options and system lag affect cybersickness needs to be better understood.

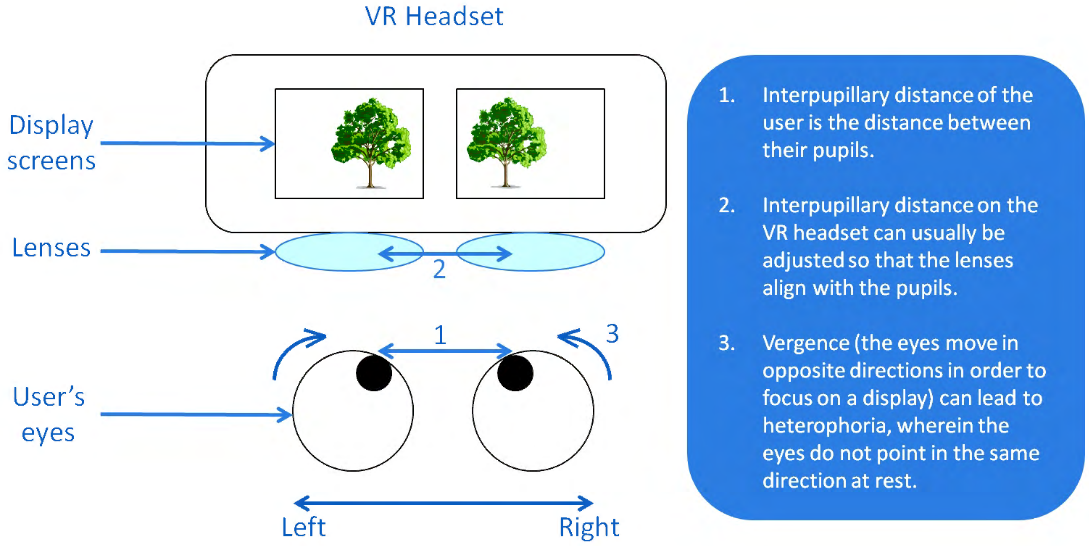
• Future research should also look to identify other factors that may share a relationship with cybersickness; for example, the physical weight of the system.

• Studies which have significant limitations, such as those featuring a small sample or outdated technology, would benefit from replication with a more up-to-date and robust method.

Domestic VR systems such as the Oculus Rift (as illustrated in the introduction to this review), use a head-mounted display (HMD) to allow users to immerse themselves in a virtual environment. Such VR systems typically present two separate images to each eye through a stereoscopic display to mimic how each eye works together. Due to the closeness of the display to the eyes, most HMDs allow for better focus by positioning adjustable optics between the display screen and the eyes (this is illustrated in Figure 3).

VR HMDs are also able to track head movements, allowing for the user's movements to be reflected in the virtual space. Sensory conflict theory predicts that a mismatch between the user's visual and vestibular sensory systems during VR immersion, could lead to feelings of cybersickness. Research to test this theory has investigated whether technical aspects of VR systems, such as the visual display, have the potential to provoke cybersickness. An understanding of which features of a VR system cause cybersickness in an average user, will allow developers and manufacturers to mitigate these effects through improved system design.

Figure 3: Diagram showing typical setup of a VR HMD and interpupillary distance



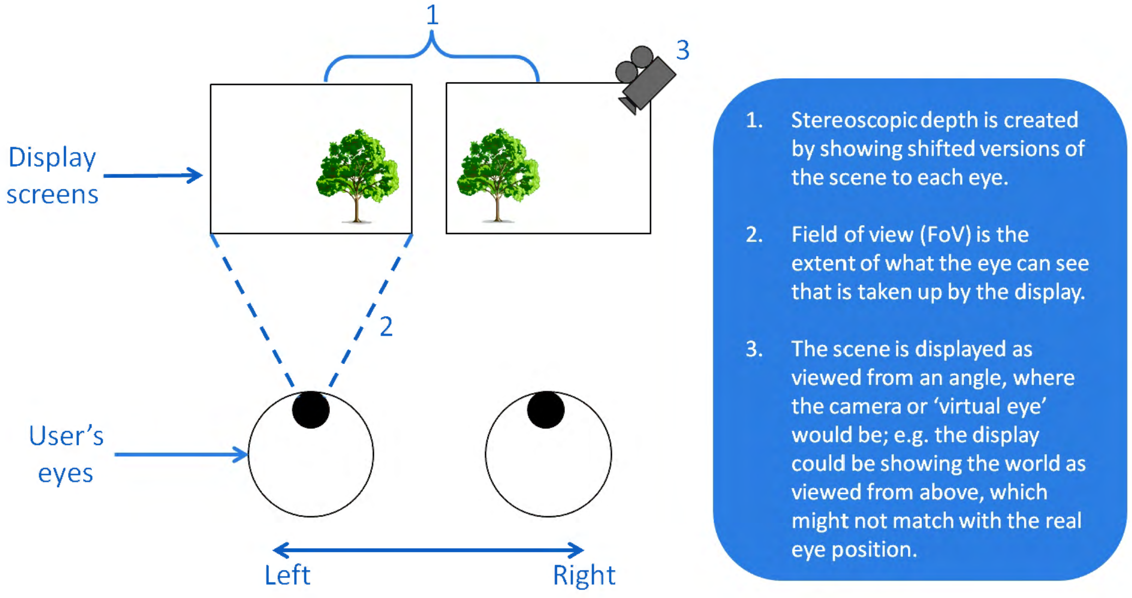
2.2.1 Field of view (FoV)

Research indicates that the more movement that exists in a scene, the more likely it is to cause cybersickness.[22] Therefore, perhaps having a wider field of view (that is the extent of what the eye can see, as shown in Figure 4) would allow more motion to be visible to the user and increase cybersickness symptoms. Moss and Muth[23] conducted a study looking into the display characteristics of HMDs. They investigated whether changes to the FoV influenced cybersickness. Their study required participants to locate a variety of objects within a virtual environment from a stationary position.

The HMD used for this study was the ProView XL 50. It differs from modern VR HMDs in that the display does not cover the eyes entirely, allowing for peripheral vision to see the external environment. Some participants in this study had a narrower FoV, where eyecups were attached to the HMD to occlude peripheral vision. Findings showed that a narrower FoV resulted in users making a greater number of head movements. These increased head movements were also faster than those made with a wide FoV. Both the number of head movements and the speed of them were associated with greater levels of cybersickness. The authors concluded, therefore, that HMDs should be designed to avoid blocking out all peripheral vision of the external (real-world) environment. This conclusion is worth noting because current domestic devices are designed to completely block any view of the external environment in order to increase immersion in VR. Unfortunately, Moss and Muth's study is limited, not least because of a significant drop out rate of participants (only two of the 80 participants completed all trials within the experimental session). Their study also failed to account for any other factors that may have contributed to feelings of cybersickness (such as postural sway or the amount and speed of head movement). The latter, in particular, could create sensory mismatch, which may have explained individual differences in the results. This study could benefit from replication with a consistent number of participants and to address some of the concerns outlined above.

[22] So, Richard HY, and W. T. Lo. "Cyber sickness with virtual reality training applications: a claustrophobia phenomenon with head-mounted displays." In *Proceeding of the 1st world congress on ergonomics for global quality and productivity* (1998): 209-212.
[23] Moss, Jason D., and Eric R. Muth. "Characteristics of head-mounted displays and their effects on simulator sickness." *Human factors* 53, no. 3 (2011): 308-319.

Figure 4: Diagram showing typical display features of a VR HMD



A more recent study by Basting et al.[24] also investigated the effect of changing the FoV of an HMD. This study looked at how FoV affected vection where an individual's perception makes them think they are moving when they aren't. The research looked at the intensity of the perceived vection for participants viewing a virtual environment using an HTC Vive and under a variety of different FoVs. Each participant was required to move straight ahead through a rotating cylindrical tunnel for some 30 seconds. The different FoVs did not allow users to view the external environment. Instead, different-sized black borders were placed around the visual display, limiting how much of the virtual environment could be seen at any given time. It was found that the majority of participants felt a greater amount of vection when the FoV was larger. Likewise, the intensity of vection was found to reduce as FoV decreased. Unfortunately, this study did not include any measure of cybersickness.

Webb and Griffin[25] conducted a similar study to Basting et al. This looked at the impact of both foveal vision (which refers to vision in the centre of the field of vision, where visual acuity is at its highest) and peripheral vision on vection. This study also recorded feelings of cybersickness and the findings were similar to those of Basting et al. in that a reduced peripheral vision showed a reduction in vection. However, they did not manage to show that a reduction in vection resulted in a decrease in feelings of cybersickness.

Palmisano et al.[26] used simulated apertures to investigate how changes in FoV affect vection and cybersickness. They managed to demonstrate that a smaller FoV reduced the effects of cybersickness. Against expectations, they found that those who experienced stronger vection also felt less cybersickness. These findings demonstrate that the relationship between vection and cybersickness is unclear. This has also been found in other research.[27]

Unfortunately, all the studies that investigate FoV and which are discussed here have limitations. For instance, the virtual stimuli used in each of these studies are arguably too abstract and often designed to cause nausea. These stimuli are not likely to reflect scenarios that would be encountered in typical VR use, such as first- or third-person gaming experiences where the user is in control of a single player character in a well-designed virtual world.

[24] Basting, Fuhrmann, and Grünvogel. "The effectiveness of changing," 225-226.
[25] Webb and Griffin. "Eye movement, vection, and motion sickness," 622-625.
[26] Palmisano, Mursic, and Kim. "Vection and cyber sickness," 1-8.
[27] Kuiper, Bos, and Diels. "Vection does not necessitate."

Palmisano et al. fail to account for the build-up of symptoms in participants while Webb and Griffin's participant sample did not include any females (who have been found to be more susceptible to symptoms of cybersickness).[28] Research by Basting et al., in particular, is limited by lack of detail, such as information about their participant sample and the data collected. It is difficult to make any comparisons between these studies (or the work conducted by Moss and Muth)[29] because of the different methods used.

While there may have been a failure to assess head movements as a contributing cause of cybersickness, these studies were able to identify other helpful correlations. For example, the fact that differences between various FoV conditions were observed, would suggest that there exists some relationship between FoV and cybersickness. Unfortunately, current research into this area is not sufficient to demonstrate exactly what this relationship is, though it would appear to suggest that a smaller FoV could minimise the severity of cybersickness symptoms.

Given that a wide FoV creates a more immersive experience, this implies there is a trade-off between immersion and cybersickness. While further research might provide a better understanding of this relationship, there is still sufficient evidence for developers to include an adjustable FoV within the VR systems they are currently producing. This would give users the option of either having a more convincing immersive experience with a wide FoV or minimising the severity of cybersickness by using a narrower FoV.

2.2.2 Visual realism

The trade-off between immersion and cybersickness is also relevant to visual realism, another aspect of VR use. Some of the research included in this review has investigated the effect of visual realism on cybersickness.

Davis et al.[30] compared two different virtual roller coaster experiences that participants could view through an Oculus Rift. One of the roller coaster scenes was defined as low fidelity because it included low graphic realism, and minimal visual flow. Visual flow refers to the amount of fast changing detail within a user's view. For example, a pilot flying low to the ground will experience greater visual flow than if they were flying high above the ground because the scenery will appear to be moving faster when the pilot is closer to it. The other roller coaster in this study was defined as high fidelity with greater visual flow.

The low-fidelity roller coaster was viewed as part of an abstract environment which lacked detail, while the high-fidelity roller coaster included a greater level of detail and additional features such as trees and rocks. Participants were exposed to one of the VR roller coasters for 14 minutes and were required to state their level of nausea every two minutes during the virtual experience. They were also given the option to stop the experiment if they felt too nauseous to continue. Those who experienced the high-fidelity roller coaster reported greater levels of nausea, with two thirds of the sample (eight of the twelve participants) choosing to stop the experiment before the end of the allotted time. This was significantly different from those who experienced the low-fidelity roller coaster, who reported less severe nausea, with

[28] Iskenderova, Aliya, Florian Weidner, and Wolfgang Broll. "Drunk Virtual Reality Gaming: Exploring the Influence of Alcohol on Cyber sickness." In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (2017): 561-572; Somrak, Andrej, Iztok Humar, M. Shamim Hossain, Mohammed F. Alhamid, M. Anwar Hossain, and Jože Guna. "Estimating VR Sickness and user experience using different HMD technologies: An evaluation study." *Future Generation Computer Systems* 94 (2019): 302-316; Stanney, Kay M., Robert S. Kennedy, Julie M. Drexler, and Deborah L. Harm. "Motion sickness and proprioceptive aftereffects following virtual environment exposure." *Applied ergonomics* 30, no. 1 (1999): 27-38.
[29] Moss and Muth. "Characteristics of head-mounted displays," 308-319.
[30] Davis, Nesbitt, and Nalivaiko. "Comparing the onset," 30.

only one sixth of the sample (two of the twelve participants) choosing to stop the experiment early. Similar findings were shown in two later studies that used the same methodology.[31] Davis et al.[32] concluded that greater visual realism can lead to cybersickness.

The choice of subject in this study by Davis et al. is a concern that needs highlighting. A virtual roller coaster that features a lot of fast and extreme motion is likely to provoke cybersickness in individuals, regardless of the level of fidelity or visual flow. This response is predicted by sensory conflict theory. Not only is there a great deal of motion shown within the virtual roller coaster experience, but the visual scene will not match up with messages from the vestibular system because the user's body is not actually experiencing any acceleration. The user will be viewing a scene with various changes in motion that, in the real-world, would move their body erratically, but the user is instead absolutely stationary. This mismatch between the systems controlling sight and balance are recognized as leading to cybersickness. With this in mind, it is not clear whether viewing less dynamic virtual scenes (those that do not create so much sensory conflict) with high-visual realism would also prompt greater cybersickness. It is possible that the visual realism of a virtual environment only stimulates more severe cybersickness symptoms in the specific scenarios featured within the study by Davis et al.

Fortunately, work by Tiiro[33] attempts to address this point. The virtual environment in this study featured a small island containing four buildings of different shapes and sizes that participants were able to move through at walking pace. Three different versions of the environment were used, each with a different graphic style. The first had simple lighting and textures (low-realism), the second had dynamic lighting and was detailed (high-realism), and the third featured low detail with simple lighting (abstract and least-realistic).

Data collected included a variety of measures, such as susceptibility to motion sickness, cybersickness, immersion and presence. Sickness scores were found to be consistently highest for participants who viewed the high-realism virtual environment, while the lowest scores were found in the abstract environment. This demonstrates that high-visual realism caused more symptoms of cybersickness than low-visual realism.

Tiiro suggests that sensory mismatch may have been more intense with high-realism graphics, which caused the more severe cybersickness. Findings also showed that the high-realism group felt more presence and immersion in the virtual environment than those who experienced the low-realism conditions. These findings also support the suggested trade-off between immersion and cybersickness outlined above.

[31] Nalivaiko, Eugene, Simon L. Davis, Karen L. Blackmore, Andrew Vakulin, and Keith V. Nesbitt. "Cyber sickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time." *Physiology & Behavior* 151 (2015): 583-590; Nesbitt, Keith, Simon Davis, Karen Blackmore, and Eugene Nalivaiko. "Correlating reaction time and nausea measures with traditional measures of cyber sickness." *Displays* 48 (2017): 1-8.
[32] Davis, Nesbitt, and Nalivaiko. "Comparing the onset," 30.
[33] Tiiro. "Effect of Visual Realism."

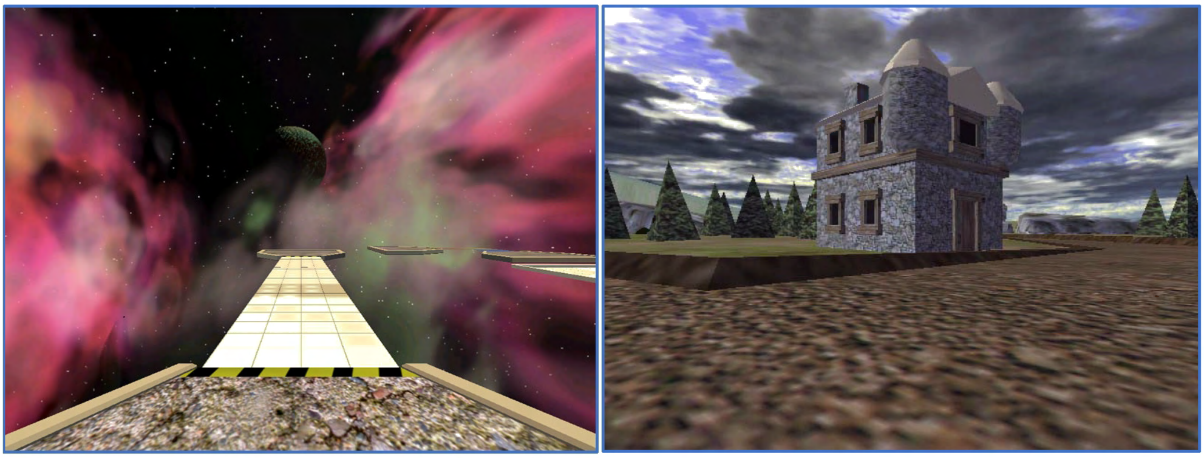


Figure 5: Example environments that can be experienced in VR; one depicting a space scene (left), the other depicting a scene of a building with trees (right).[34]

The work by Davis et al. and Tiiro are particularly important because each makes a good case for the effect of visual realism on stimulating cybersickness and, of all the studies reviewed, they both used current technology and high-quality graphics (examples of graphical quality of VR environments can be seen in Figure 5).

Unfortunately, both studies have limitations. For example, the research carried out by Davis et al. had a small and unrepresentative sample, while Tiiro failed to account for the build-up of symptoms within an experimental session. Despite these criticisms, the argument that they present is still valid: that higher levels of visual realism are more likely to cause more severe cybersickness. As these studies represent only two examples of research into this specific topic, it shows that there is a need for further investigation to support this argument. VR application developers could benefit from considering the trade-off between realism and cybersickness. This might help them to design applications with lower levels of realism to improve accessibility.

2.2.3 Movement options

Sensory conflict theory concerns both the visual and vestibular (balance-related) sensory systems. So far within this section, regarding FoV and visual realism, the focus has been mainly on the visual system. The vestibular system has the purpose of coordinating movement with balance and spatial orientation. This leads on to the question of whether the kind of movement within a virtual space can affect feelings of cybersickness.

Coburn[35] conducted an analysis of different movement options that are available in VR. His study was in an engineering context, where there is an increasing use of virtual environments for the design and analysis of complex 3D models. Typically, a group of engineers each used a VR HMD and associated controllers to work collaboratively in a shared virtual space. As users were in a virtual environment, their movements did not need to be limited to walking or controlled movement (using a joystick), and options were available to warp or fly within the virtual environment. The two options can both be referred to as a ‘visually manipulated still’, as no movement takes place because only the environment changes around the individual. Each of these options presented an opportunity for sensory conflict to occur because of the

[34] Images sourced from Wikimedia Commons and do not contain any copyright-eligible parts or visuals.
[35] Coburn, Joshua Q. "An Analysis of Enabling Techniques for Highly-Accessible Low-Cost Virtual Reality Hardware in the Collaborative Engineering Design Process." (PhD Diss., Brigham Young University, 2017).

likelihood of creating a mismatch between the visual and vestibular (balance and spatial awareness) systems.

Coburn's study intended to identify which movement option was least likely to provoke cybersickness. Two warping options (referred to as teleport and fade): a flight option and manual movement through space were investigated (each controlled using a joystick). The flight option involved the user following a pre-assigned path which lifted them from one position to another, allowing for an aerial view of the virtual environment in the process. The teleport option was able to place the user immediately at an alternative location within the virtual environment without any period of transition. Fade performed along the same lines as the teleport option but took one second to fade the user's view to black before they were relocated to a different position. Participants in this study were positioned in an abstract virtual space with a detailed 3D model of a car and tasked with identifying the location of specific parts of the vehicle. The participants' position was changed using the different movement options during each location task.

Despite the two warping options demonstrating the greatest amount of disorientation and discomfort in participants, the manual movement option was found to be associated with the greatest level of cybersickness. This could be explained by sensory conflict theory because the other movement options (teleport, fade and flight) lack the motion signals that would lead to the mismatch between the visual and vestibular (balance and spatial) sensory systems and cybersickness. Coburn states that these findings underscore a need to include multiple movement options within a VR system. This is supported by qualitative data from his study which showed that for each movement option there were a few people who stated that they would not use a VR system if it was limited to only one of the options included within this study.

2.2.4 Summary

This section has discussed a number of technical aspects of VR systems that developers and manufacturers could consider as part of the design process. This includes: the user's field of view, the graphic realism of the virtual environment and the movement options that are available to navigate virtual space. Although these have been raised as potential factors, further research is required to better understand the full extent of the impact that these factors can have on an individual's experience of VR and the risks they may present. It is likely that there are other factors that have not yet been considered that have the potential to stimulate cybersickness which present opportunities for future research. Additionally, as there are research gaps within the studies discussed here, it is difficult to draw confident conclusions. Where future research can address some of the limitations and errors within current research, this could provide greater understanding of FoV, visual realism and movement options in designing and using VR equipment.

2.3 Approaches to mitigate cybersickness

Summary of findings

• Additional VR system features have been investigated as a means of mitigating cybersickness symptoms, including the use of proprioceptive vibrations, rotational blurring, and an adjustable depth of field.

• The use of vibrations can help better match the sensory inputs, minimising the likelihood of cybersickness occurring.

• Rotational blurring has been shown to have mixed effects on different individuals.

• An adjustable depth of field that changes display sharpness according to the user's gaze can reduce the severity of cybersickness symptoms such as disorientation, nausea and eye strain.

• Some studies have attempted to identify exercises to help the user mitigate cybersickness symptoms. This has included oculomotor and hand-eye coordination exercises. There is some evidence to suggest that oculomotor exercises prior to VR use can help in reducing cybersickness.

• The most effective method of recovering from cybersickness appears to be limiting VR use to short sessions (approximately 15 minutes) and taking sufficient breaks in between sessions.

• There is strong evidence that shows a habituation effect resulting from frequent VR use.

Research gaps

• Further clarification is needed into the effects of VR system features on users' likelihood to experience negative effects.

• Research would be useful that focuses on the identification of additional VR system features that may help improve user experience by minimising negative effects such as cybersickness.

• Further research should seek to compare the effectiveness of user exercises at mitigating negative effects following VR use.

• Additional research might also focus on the identification of further user exercises that can mitigate the negative effects of VR use.

• There is potential for further investigation into the nature of the apparent habituation effect, specifically related to individual differences.

• Studies which have significant limitations (e.g. small sample, outdated technology) would benefit from replication with a more up-to-date and robust method.

Where the previous section has highlighted evidence to suggest specific factors of VR system design that can provoke cybersickness, this section looks at attempts to mitigate these symptoms. In particular, this section includes augmenting the VR system with additional features to reduce sensory conflict and exercises that a user can perform to reduce symptoms of cybersickness.

2.3.1 Additional VR system features

As mentioned in section 2.1, sensory conflict theory is the most longstanding and accepted theory of the three identified in this literature review. It explains cybersickness as a result of the mismatch between the visual, vestibular (balance and spatial awareness) and proprioceptive (position and movement) senses. Plouzeau, Paillot, Chardonnet and Merienne[36] attempted to reduce the degree of sensory conflict by creating artificial 'vibrations' to stimulate and enhance a user's own proprioceptive senses to better reflect the visuals displayed to them by the VR. Proprioceptive receptors within muscles, tendons, joints and the inner ear enable individuals to know the position and movement of their own body. Stimulating muscles via vibrations was thought to induce a convincing if artificial sensation of movement.

This study by Plouzeau et al. featured individuals navigating different virtual environments via a joystick, while vibrations were administered to the upper portions of the thigh in real time to mimic the sensation of walking. Findings demonstrated that the addition of these vibrations resulted in a 47% reduction in feelings of cybersickness.

It is possible that these findings are exaggerated because the study failed to account for other factors that may have led to a reduction in cybersickness. For example, habituation is a factor because those who routinely used VR reported a reduction in associated cybersickness. The rationale of this study is reasonable because proprioceptive vibrations have the potential to minimise sensory conflict and subsequently reduce cybersickness. Further research could attempt to expand upon the approach of Plouzeau et al. by utilising a larger sample, additional stimuli (e.g. various kinds of environments) and further conditions (e.g. individuals seated or standing). In addition, research suggests it is possible for the vestibular system to be stimulated,[37] which presents another opportunity for future study to help inform developers about possible features that would mitigate cybersickness.

Research has also investigated how display settings of HMDs can be adjusted to reduce the occurrence of cybersickness symptoms. Field of view was discussed in the previous section as a factor that can impact on cybersickness. However, two further aspects include rotation blurring and depth of field.

Budhiraja, Miller, Modi and Forsyth[38] applied a blurring effect to a first-person shooter VR game. The effect was only applied during rotational movement in the horizontal plane as this was thought likely to generate the greatest change in VR scenery, and consequently might be expected to provoke the greatest level of cybersickness. The effect was activated by a controller and the amount of blur was directly proportional to the acceleration of the movement. Tracked head movements also resulted in corresponding changes to the user's view, but these were not blurred. Participants did not find the rotational blurring effect to be distracting nor did it detract from the VR experience. While it did not help reduce symptoms of cybersickness in all users – some actually felt a negative effect from the rotational blurring – it did have a strong effect on those who were prone to acute cybersickness. All participants also reported a gentler

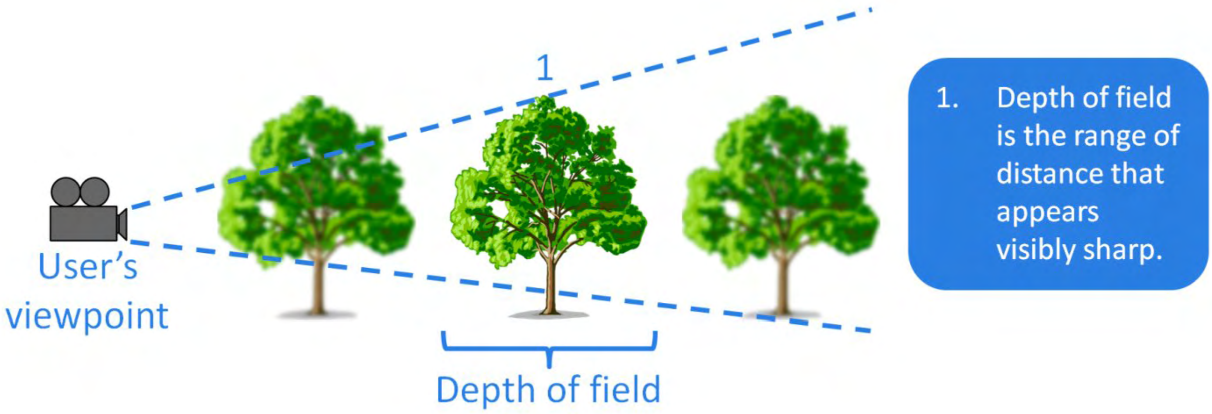
[36] Plouzeau, Jérémy, Damien Paillot, Jean-Rémy Chardonnet, and Frédéric Merienne. "Effect of proprioceptive vibrations on simulator sickness during navigation task in virtual environment." In *International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments* (2015).
[37] Abekawa, Naotoshi, Elisa R. Ferrè, Maria Gallagher, Hiroaki Gomi, and Patrick Haggard. "Disentangling the visual, motor and representational effects of vestibular input." *Cortex* 104 (2018): 46-57.
[38] Budhiraja, Pulkit, Mark Roman Miller, Abhishek K. Modi, and David Forsyth. "Rotation blurring: use of artificial blurring to reduce cyber sickness in virtual reality first person shooters." In *CoRR 2017* (2017).

increase in the level of nausea they experienced over time when rotational blurring was applied.

Further exploration is required to determine the full effect that rotational blurring has on users. Results from this study by Budhiraja et al. suggest that it can be very beneficial to some, while others are affected negatively by it. It could be beneficial to identify what factors determine whether the effect is positive or negative (e.g. susceptibility to cybersickness). However, it would seem reasonable for developers to include an option for rotational blurring in their VR applications where the visual scene is controlled manually. Individual users would then have the ability to turn the feature off or on. The amount of blurring could also be made adjustable to suit users' needs, improving accessibility even further.

Depth of field (DoF) is the range of distance in which an image appears acceptably sharp. When an individual focuses on an object, surrounding objects that are further in the distance or nearer to the individual will appear out of focus and blurred (see Figure 6 illustrating depth of field). This innate human trait does not translate to VR because a virtual environment will be rendered in focus and viewed through a flat display screen. Consequently, when a user attempts to focus on an object in a virtual space and finds that no blurring occurs, it can cause visual fatigue.[39] Carnegie[40] explored using a system that estimated users' DoF and adjusted the sharpness of the display visuals accordingly to determine whether this had any effect on cybersickness symptoms. He found a statistically significant reduction in both disorientation and nausea when the DoF system was enabled; however, all symptoms were still present. This means that this system only reduced the severity of cybersickness symptoms and did not eliminate them entirely.

Figure 6: Diagram showing depth of field



Similar to the research by Budhiraja et al., the findings produced by Carnegie are promising but would benefit from further investigation. There is an opportunity for further study to determine whether a DoF system can be developed to show an even greater reduction of cybersickness symptoms. It is possible that not all users would benefit from such a system. Therefore, there may be scope in the future to design an adjustable option for VR systems so the user has a choice about whether they want to apply and control a simulated DoF.

From research to date, it is apparent any domestic VR system would benefit from the ability to adjust technical settings. Having a range of options that can be adjusted to create a custom VR experience will improve overall accessibility. One user may find having a rotational blurring

[39] Peli, Eli. "Visual and optometric issues with head-mounted displays." *Optics & Imaging in the Information Age* (1996): 364-369.
[40] Carnegie, Kieran. "Mitigating Visual Discomfort on Head Mounted Displays using Estimated Gaze Dependent Depth of Field." (Master's Thesis, Victoria University of Wellington, 2015).

effect to be greatly beneficial, while another may prefer to restrict their field of view. Leaving the choice with the user may be of paramount importance, as the alternative may restrict other users from ever engaging comfortably in VR. Providing a large sample of participants in future research studies could help to inform the most suitable default settings.

2.3.2 User exercises to mitigate cybersickness symptoms

Some of the reviewed studies considered whether there are any exercises that a user can perform to help mitigate cybersickness symptoms. In particular, research included oculo-motor and hand-eye coordination exercises and determined whether performing such tasks can help individuals to physically readapt to the real world following VR use.[41] The research also looked at subsequent reductions in the amount of time it takes for cybersickness symptoms (and other negative effects, such as adaptation and eye strain) to subside.

Park et al.[42] discuss the range of benefits that have been associated with oculo-motor exercises, including improving vision and reducing eye strain. They opted to use a range of oculo-motor exercises prior to participants engaging in VR to mitigate cybersickness symptoms. This study suggested that performing such exercises prior to VR use has benefits that are comparable to performing stretches prior to physical exercise. The exercises involved a programme of slow eye movements: looking in different directions, slowly moving focus to near and far distances, and fixating on newly appearing and slow-moving objects. Participants were required to perform five minutes of oculo-motor exercises before viewing a period of five minutes of VR content. Results from this study indicated that these specific exercises were effective at reducing cybersickness.

Research by Curtis investigated whether performing a hand-eye coordination task following VR use acted as a better means of mitigating cybersickness when compared with letting the symptoms ‘decay’ (or fade) naturally. This study also tested whether these actions could be performed in a virtual environment and still produce comparable results to those performed outside a VR environment. The hand-eye coordination task that Curtis used involved participants placing chopsticks into upright drinking straws. This task was built in the real world and replicated in VR. To fulfil the condition of allowing their symptoms to decay naturally, participants were required to sit quietly, either with the HMD removed or in a virtual environment with an empty landscape. Participants engaged in 15 minutes of VR before being required to complete one of the virtual or physical mitigation exercises. It was found that performing the hand-eye task did not alleviate the symptoms of cybersickness any faster than allowing them to dissipate naturally. In addition, performing the task in VR was not comparable to performing the task in the real world, because when performed in VR, there was a negative impact on the time taken to recover from cybersickness. Therefore, the most effective method of recovery would appear to be removing oneself from the virtual space and resting until symptoms have completely subsided.

These findings support a recommendation to users to take breaks from VR to reduce the build-up of cybersickness symptoms.[43] The Oculus Rift Health and Safety Guide[44] recommends that users should take frequent breaks from VR, ideally a 10 to 15-minute break every 30 minutes. Cybersickness symptoms have been found to emerge within the first 10 to 15 minutes of

---

[41] Curtis, Michael Keneke. "Investigation of visually induced motion sickness: a comparison of mitigation techniques in real and virtual environments." (Master’s Thesis, Iowa State University, 2014).
[42] Park, Won Deok, Seong Wook Jang, Yeol Ho Kim, Gyu Ah Kim, Wookho Son, and Yoon Sang Kim. "A study on cyber sickness reduction by oculo-motor exercise performed immediately prior to viewing virtual reality (VR) content on head mounted display (HMD)." *Vibroengineering Procedia* 14 (2017): 260-264.
[43] Davis, Nesbitt, and Nalivaiko. "Comparing the onset," 30.
[44] https://www.oculus.com/legal/health-and-safety-warnings/

immersion,[45] and longer immersions in VR have been found to demonstrate greater negative effects on sickness and stability.[46] As such, the best approach may be to take a 15 minute break approximately every 15 minutes of use if a user is susceptible to cybersickness. Performing oculo-motor exercises before using a VR system may help in slowing the build-up of cybersickness symptoms[47] and could be encouraged as well.

Further research is recommended to determine when breaks should ideally be taken while taking into account that different people may vary in the frequency and length of breaks they need. Further research might help to identify factors that may be relevant. In addition, further studies might help to identify whether there are any other exercises that can mitigate cybersickness.

2.3.3 Habituation

Habituation refers to the decrease in response to a given stimulus after repeated exposure. Given the known negative effects associated with VR use, habituation is an important area of VR research because it could present a way to reduce adverse after effects from VR use. In particular, does frequent VR use result in fewer episodes of cybersickness?

Some VR research studies have considered users' previous exposure to both VR and gaming. It has been found that those who have more experience with playing video games and using VR systems are typically less prone to cybersickness.[48] This hints at a habituation effect; however, there are other studies that give firmer evidence for the habituation effect using VR. For example, the research of Clemes and Howarth.[49] This study examined symptom reports from users who were immersed in VR at weekly intervals.

Data were collected across four experiments that all featured a similar methodology. Over a five-week period, a pattern of habituation emerged. Malaise ratings and reported nausea were found to decrease consistently on each successive immersion. Symptom onset time was also found to increase at a similar rate. The difference between cybersickness ratings on the first and last session were significantly different. However, the effects of habituation were found to be diminishing by the final session. This is not to suggest that users were immune to symptoms of cybersickness after this five-week period because the symptoms were still present. Instead, Clemes and Howarth suggest that the intervals between VR immersions would have to be less than a week to continue the same trend of habituation.

The findings from Howarth and Hodder's[50] investigation into the characteristics of habituation in VR use suggest that the periods between exposures are not as important as the number of exposures. They note the previous evidence about limiting VR use to short 10 to 15-minute sessions and maintain that repeated exposure to such short sessions is likely to reduce the severity of cybersickness. As a tolerance builds up, individual users should be able to spend

---

[45] Wilson. "Virtual environments and ergonomics," 1057-1077; Lampton, Kolasinski, Knerr, Bliss, Bailey, and Witmer. "Side effects and aftereffects" 1154-1157.

[46] Murata. "Effects of duration of immersion," 463-477; Kennedy, Stanney, and Dunlap. "Duration and exposure to virtual environments, " 463-472.

[47] Park, Jang, Kim, Kim, Son, and Kim. "A study on cyber sickness reduction," 260-264.

[48] Dennison and D'Zmura. "Cyber sickness without the wobble," 215-223; Shafer, Carbonara, and Korpi. "Modern virtual reality technology," 1-13; Somrak, Humar, Hossain, Alhamid, Hossain, and Guna. "Estimating VR Sickness," 302-316; Iskenderova, Weidner, and Broll. "Drunk Virtual Reality Gaming," 561-572.

[49] Clemes, Stacy A., and Peter A. Howarth. "Habituation to virtual simulation sickness when volunteers are tested at weekly intervals." *Human factors in the age of Virtual Reality* (2003): 63-74.

[50] Howarth, Peter A., and Simon G. Hodder. "Characteristics of habituation to motion in a virtual environment." *Displays* 29, no. 2 (2008): 117-123.

longer in VR. This idea has been supported in work by Gavgani et al.,[51] who found participants able to withstand a sickness-inducing VR experience for longer after repeated exposure.

There is clear evidence to show that users of domestic VR systems are likely to become habituated to the negative effects of using VR. However, it cannot be assumed that this effect will occur for all. Within Howarth and Hodder's study, a small portion of individuals (3 out of 70 participants) were found to experience more nausea at the end of the testing period than they reported at the beginning. One of these individuals was found to have become hypersensitive to the stimulus, rather than becoming habituated. Although this result may represent only a small portion of the population, users could benefit from knowing that frequent VR use has the potential to result in greater cybersickness outcomes.

2.3.4 Summary

As cybersickness has been the main focus within the literature reviewed, it is reasonable to regard this as one of the primary concerns associated with VR use. Given this, it is useful that studies outlined in this section have attempted to identify methods of mitigating the symptoms of cybersickness. A number of technical features of VR systems have been raised which can be further explored and developed to improve accessibility. There may also be further exercises or approaches that can be performed by users, either before or after using VR, that can help mitigate cybersickness symptoms. Currently, the evidence supports a requirement to limit VR use to short periods, taking regular breaks in between sessions. Additionally, there is evidence to demonstrate habituation effects from repeated exposure to VR. However, further research could be recommended to better understand the nature of the habituation effect, and who it is most likely to affect.

[51] Gavgani, Alireza Mazloumi, Keith V. Nesbitt, Karen L. Blackmore, and Eugene Nalivaiko. "Profiling subjective symptoms and autonomic changes associated with cyber sickness." *Autonomic Neuroscience* 203 (2017): 41-50.

2.4 Adaptation and other effects resulting from VR use

Summary of findings

• Studies have investigated the effects on vision following VR use, with evidence showing short-term disturbance of eye-movement control.

• ‘Extreme gaze’ angles within VR headsets have been found to be associated with an increased risk of heterophoria (where the eyes point in two different directions when at rest).

• There is some evidence to suggest a negative effect to a user’s balance and coordination following VR use. This presents an increased fall risk to users. There is also a potential risk of serious consequences if an individual were to engage in an activity such as driving or operating machinery immediately following immersion in a virtual environment.

• There was a small amount of evidence demonstrating a negative effect on individual reaction time following exposure to VR. As above, this could also cause concern about the implications for a user driving or performing tasks where precision with hand-eye coordination is necessary, following VR use.

• A number of interviewees reported their avoidance of activities such as driving after using VR.

• Various physiological responses have been observed during VR use, including changes in heart rate, electrodermal activity and levels of perspiration. Of these, electrodermal activity, a term used for defining autonomic changes in the electrical properties of the skin, was measured specifically at a point on the forehead. It has been argued that this approach is the best physiological correlate of nausea resulting from VR immersion. This is an important finding when considering the use of objective measures in future research.

Research gaps

• There is a lack of evidence on any long-term effects to the eyes or visual system following VR use.

• Further research is required to understand the extent of the effect to individual balance, coordination and reaction time; in particular, the duration of the effects, and how they might impact specifically on safety critical tasks (particularly driving and operating machinery). Research that isolates how different performance elements within vehicle driving are influenced by VR is needed.

• Further investigation into physiological responses to VR use could be beneficial in clarifying current evidence.

• Studies which have significant limitations (e.g. small sample, outdated technology) would benefit from replication with a more up-to-date and robust method.

Beyond symptoms of cybersickness, there is concern about adaptation after effects from VR use. These additional effects following VR use include:

- eye strain including problems from extreme gaze, eye movement control, blurred vision and trouble focusing
- impaired balance and loss of balance
- reduced hand-eye coordination
- decreased reaction time
- other physiological changes such as increased heart rate and sweating.

Some researchers[52] have attributed these after effects to physiological ‘rearrangements’ that occur to the visual system and its interaction with other senses after exposure to VR. Understanding these effects becomes important when considering the health and safety of individuals once they have left the virtual environment. For example, should extended immersion in VR result in a detrimental effect on hand-eye coordination then this may present a major safety risk for people then required to operate a vehicle or machine. Changes to reaction time and physiological changes, such as heart rate and sweating during VR immersion, have also been investigated. Identifying physiological responses is important as such responses may provide an objective measure of cybersickness, which could then be utilised in further research.

2.4.1 Effects on vision

Eye strain has already been noted as a symptom of cybersickness and occurs as a result of the eyes being subject to intense use, such as an extended period staring at a computer screen. Vergence-accommodation conflict is another problem that occurs as a result of HMD use. Vergence is a binocular eye-movement that directs the two eyes onto a target: both eyes converge or diverge as the target moves closer or farther away. Accommodation in this context is an adjustment of the focal power of the eye lens to create a clear and sharp retinal image: the focal power increases or decreases as a target moves closer or farther away. Conflict arises because the brain receives mismatching cues between the distance of an object in the virtual space and the focusing distance required for the eyes to focus on that object.[53] In VR, the brain is forced to unnaturally adapt to the mismatched cues, which can contribute to eye strain. Kramida[53] raises some solutions to this issue, namely different screen displays and eye-tracking, that could be explored in future research.

Most HMDs that are used in VR systems consist of screens in which the camera position is displaced around 50 to 70 mm away from the virtual eye position.[54] Consequently, users have to readapt to their original eye position representation after using HMDs. Several authors[55] have reported disturbance in eye-movement control following exposure to VR. Related visual problems were reported among US military helicopter pilots who failed stereoscopic depth

---

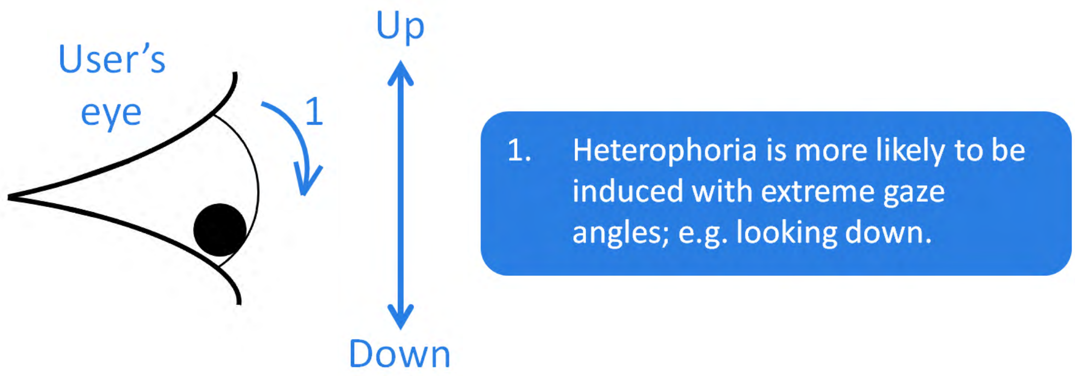
[52] Biocca, Frank A., and Jannick P. Rolland. "Virtual eyes can rearrange your body: Adaptation to visual displacement in see-through, head-mounted displays." *Presence* 7, no. 3 (1998): 262-277; Howarth, P. A., and P. J. Costello. "Visual effects of immersion in virtual environments: Interim results from the UK Health and Safety Executive Study." In *Side International Symposium Digest of technical papers*, vol. 27 (1996): 885-888.
[53] Kramida, Gregory. "Resolving the vergence-accommodation conflict in head-mounted displays." *IEEE Transactions on Visualization and Computer Graphics* 22, no. 7 (2016): 1912-1931.
[54] Howarth, Peter Alan. "Oculomotor changes within virtual environments." *Applied Ergonomics* 30, no. 1 (1999): 59-67.
[55] Hettinger, Lawrence J., Kevin S. Berbaum, Robert S. Kennedy, and Daniel P. Westra. "Human performance issues in the evaluation of a helmet-mounted area-of-interest projector." In *Proceedings of the Image IV Conference* (1987): 320-327; Ebenholtz, Sheldon M. “Sources of asthenopia in navy flight simulators.” Battelle Memorial Inst Columbus OH, (1988); Ebenholtz, Sheldon M. "Motion sickness and oculomotor systems in virtual environments." *Presence: Teleoperators & Virtual Environments* 1, no. 3 (1992): 302-305.

perception tests following prolonged use of night vision goggles. These goggles were of similar design to the VR HMDs.[56]

Mon-Williams, Wann and Rushton[57] conducted an early study into visual deficits following the wearing of a HMD. Specifically, their study was designed to appraise the stress placed on the visual system during a short immersion in VR. This study is now dated and it is likely that current domestic VR systems have advanced significantly since then. With this in mind, following a ten-minute exposure to VR, only a fifth of the sample (4 out of 20 participants) reported a short-term reduction in their binocular vision. In particular, they suffered from blurred vision and difficulty focusing. These effects were found to last up to five minutes after the exposure to VR.

In addition, 'gaze angle' within VR headsets has been found to be associated with an increased risk of heterophoria (see Figure 7). This is a condition where an individual's eyes point in different directions while at rest. As vertical gaze angle is raised or lowered, more demand is placed on the binocular visual system. Mon-Williams, Plooy, Burgess-Limerick and Wann[58] argue that maintaining an 'inappropriate' (when outside natural parameters) gaze angle within a HMD could result in heterophoric changes to the user: where the HMD causes an individual's eyes to point in different directions when relaxed. Howarth[59] found support for this effect. He reported that the optical configuration of VR systems induced significant exophoric changes (eyes turning outwards) and esophoric changes (eyes turning inwards) after the use of stereoscopic and bi-ocular systems, respectively. These induced changes were largely independent of the subjects' interpupillary distance, the distance between an individual's eyes. The heterophoric changes were attributed to prism adaptation caused by an optical mismatch and the possibility that the HMDs induced transient myopia. Transient myopia (temporary short-sightedness where objects appear blurred) can be explained as an accommodation spasm which leads to consequential changes in convergence, and hence heterophoric changes. Current domestic VR systems allow for tracking of head movements which should minimize the risk to users of maintaining extreme gaze angles for long. However, no study appears to have investigated such risks to the visual system using modern VR systems. Even if the risk is minimal, this information should be made available to users.

Figure 7: Diagram showing how vision beyond natural parameters from using VR can induce heterophoric changes to user's individual eye



[56] Sheehy, James B., and Michael Wilkinson. "Depth perception after prolonged usage of night vision goggles." *Aviation, Space, and Environmental Medicine* 60 (1989): 573-579.
[57] Mon-Williams, Mark, John P. Wann, and Simon Rushton. "Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display." *Ophthalmic and Physiological Optics* 13, no. 4 (1993): 387-391.
[58] Mon-Williams, Mark, Anna Plooy, Robin Burgess-Limerick, and John Wann. "Gaze angle: a possible mechanism of visual stress in virtual reality headsets." *Ergonomics* 41, no. 3 (1998): 280-285.
[59] Howarth. "Oculomotor changes," 59-67.

Although exposure to VR for a single, short period is unlikely to be permanently detrimental to a user's vision, the effects of both long-term exposure and repeated exposure are still unknown. Further research would therefore be recommended to determine the full extent of the risks placed on the visual system during longer-term VR use.

2.4.2 Effects on balance and coordination

There is a risk of falling associated with the use of VR HMDs because they intentionally block out all visibility of the real-world. Any attempts to move around in the real world while immersed in VR can result in tripping over household objects, such as chairs and tables. This problem can be subverted by simply engaging in VR while sitting, which has been found to stimulate less cybersickness than standing.[60] However, there is nothing to stop a user from standing while using a VR system and some users are likely to opt to stand to gain a more immersive experience, particularly if the VR scene shows the user standing up and moving around. It has already been highlighted in this report that immersion in VR can result in feelings of vection and postural instability, factors that can result in a loss of balance which can subsequently increase the risk of falling.

Given that the brain prioritises information in a way that minimizes uncertainty in its perceived position,[61] changes may be induced in the coordination between body movements and sensory stimuli that is sent to the central nervous system. During and immediately after these stimulus rearrangements, instability in posture, eye-head coordination and eye-hand coordination can occur. The severity of the instability as well as the recovery time from the after effects typically increases with exposure duration and decreases over time with repeated exposure.[62]

Kennedy and Stanney[63] conducted a basic assessment of individuals' balance following VR exposure. Their approach involved assessing participants' posture and movement while performing a battery of body stances, both before and after VR exposure. Body stances were to be held for 30 seconds and involved such poses as balancing on one leg, with the eyes closed and open. Their assessment was based largely on observation; however, they did find that participants' ability to hold each stance was significantly poorer following VR exposure. Kennedy and Stanney concluded their study by raising the concern that VR-induced postural instability has direct safety implications when considering an individual's ability to operate a vehicle or engage in various activities. While this is a sound conclusion, the overall study is limited. The observational method and dated nature of this study means that the results should be treated with caution.

More recent work by Murata[64] is more convincing. Instead of observational assessments, it used a 'force plate' to conduct tests and collect quantitative data on body movements such as ground reaction forces, postural stability, centre of pressure and displacement, during extended VR immersion. Findings from Murata's study showed that longer periods of VR use

---

[60] Merhi, Omar Ahmad. "Motion sickness, virtual reality and postural Stability." (PhD Diss., University of Minnesota, 2009).
[61] van Beers, Robert J., Daniel M. Wolpert, and Patrick Haggard. "When feeling is more important than seeing in sensorimotor adaptation." *Current biology* 12, no. 10 (2002): 834-837.
[62] Kennedy, Robert S., Kay M. Stanney, and William P. Dunlap. "Duration and exposure to virtual environments: sickness curves during and across sessions." *Presence: Teleoperators & Virtual Environments* 9, no. 5 (2000): 463-472; Kolasinski, Eugenia M. "Simulator Sickness in Virtual Environments." (No. ARI-TR-1027. Army research Inst for the behavioral and social sciences Alexandria VA, 1995); McCauley, Michael E., and Thomas J. Sharkey. "Cyber sickness: Perception of self-motion in virtual environments." *Presence: Teleoperators & Virtual Environments* 1, no. 3 (1992): 311-318.
[63] Kennedy and Stanney. "Postural instability induced by virtual reality exposure," 25-47.
[64] Murata. "Effects of duration of immersion," 463-477.

resulted in a greater decrease in users' ability to keep their balance. This further supports the need to take regular breaks during VR use.

Wright[65] also noted that exposure to VR can cause an unintended postural response leading to instability and sensorimotor adaptation. He argued that even if the virtual environment's spatial resolution, update rates, perspective geometry, monocular and binocular cues, etc. are perfectly programmed to match the natural physical environment, there is still a problem. As found in earlier studies mentioned, the user's body isn't moving when the virtual environments involve movement, so this will still affect how the central nervous system calibrates the combination of motor skills and perceptions via the senses. Wright states "in other words, exposure to a VE (Virtual Environment) will automatically cause sensorimotor adaptation, whether desired or not.' He recognises that short term benefits of using VR may be outweighed by long term deficits. However, Wright trusts that the ability of VR to augment brain function can be "applied in useful ways" such as being used to recover loss of function from neurological damage.

In a study by Biocca and Rolland,[66] the after effects of exposure to VR were investigated using a manual pegboard taskA HMD that displaced the user's natural eye position (making objects appear visually closer and lower down) and a control HMD that featured no displacement were used. After exposure to the VR environment, the HMDs were dismounted and the subjects were tested to see how accurately they could point as requested. Each subject's pointing abilities were investigated in various directions (left-right, up-down, forward-backward). There were fewer errors made with the displacement HMD as opposed to the control HMD and the errors varied depending on the direction. The largest number of errors were made in the forward-backward direction (average of about 35mm). This finding is not surprising as the HMD design displaced the natural eye position in this direction. It is clear from this study that after exposure to the virtual environment, the subjects' visuo-motor systems remained calibrated to the virtual environment and altered their performance in the physical environment. However, the period of time required for the after effects to recede was not investigated. Domestic VR systems such as the Oculus Rift, typically allow individual users to adjust the interpupillary distance of the lenses. This can reduce blurring when users view the display, although no evidence emerged within the study to show whether this can mitigate adaptation effects.

In a similar study, Harm et al.[67] examined the effect of VR exposure on eye-head-hand (EHH) coordination and the ability to maintain visual fixation on eccentric targets (GAZE) i.e. the eccentricity effect is a visual phenomenon that affects target processing. Visual performance is likely to be better (faster and more accurate) when the target is closer and more central to the fovea, and worsens when the target is further in the periphery of the retina). Participants were required to pass a United States Air Force Class III equivalent physical examination. Three experimental sessions were performed with each session separated by a day. On each of the days, subjects performed the EHH and GAZE tasks before, immediately after, and at one-hour, two-hours, four-hours, and six-hours following exposure to VR. The study reported that EHH and GAZE were disrupted by exposure to VR but recovered within six hours. Disruption in EHH was more intense immediately after exposure to VR (0 hour) and approached recovery towards six hours after exposure. The subjects' EHH coordination after VR exposure did not significantly improve across days. There was a significant decline in the ability of the subjects to maintain gaze on horizontal eccentric targets immediately after exposure to VR (at 0 hour)

---

[65] Wright, W. Geoffrey. "Using virtual reality to augment perception, enhance sensorimotor adaptation, and change our minds." *Frontiers in Systems Neuroscience* 8 (2014): 56.
[66] Biocca and Rolland. "Virtual eyes can rearrange your body," 262-277.
[67] Harm, Deborah L., Laura C. Taylor, Millard F. Reschke, Jeffrey T. Somers, and Jacob J. Bloomberg. "Sensorimotor coordination aftereffects of exposure to a virtual environment." *The Visual Computer* 24, no. 11 (2008): 995-999.

which approached recovery by six hours. No significant improvement in this trend was observed across the days of the experiment.

Current evidence is minimal, but it would appear that VR use can negatively impact on users' balance. At this stage it is not yet known how long the effect is likely to last once VR exposure has ended. Murata demonstrates that there is a loss of balance during immersion, and Kennedy and Stanney's results suggest the balance loss is still present immediately after VR exposure. However, evidence would be required to see whether this effect is long-lasting or if it subsides shortly after exposure. This presents a critical area for future research as loss of balance presents a serious safety concern for VR users.

Evidence provided from the interviews suggests that some people are aware of the effect that VR can have on their balance and coordination. Similarly, interviewees reported that certain activities would be best avoided following VR immersion.

Given the apparent risk of falling during VR use, Gonozález, Paganelli and Raposo[68] developed and tested a fall risk warning system. They constructed this system using available technology, specifically an Oculus Rift VR and Microsoft Kinect. Using these two systems, they constructed a feature that applied a red tint over the virtual environment when the user was at a greater risk of falling over. This warning system was received positively by those who tried it and demonstrated a potential means to mitigate the risk of falling during VR use. Such a feature would benefit from further research and development before being fully implemented into VR systems.

2.4.3 Effects on reaction time

Balance loss and a slowing of reaction time are a concerning aftereffects from VR use because of the safety risk in subsequent activities.

Both Nalivaiko et al.[69] and Nesbitt et al.[70] identified that nauseogenic visual stimuli in VR caused a prolongation of simple reaction time. Similar experimental methods were used, where reaction times were measured according to the length of time it took individuals to spot a cross appearing on a computer screen, and to respond by pressing a button. It was found that reaction time was linked to the severity of cybersickness symptoms. In both studies, as measures of cybersickness increased, so too did reaction time. The increase was found to be up to approximately 200 milliseconds.

The extent of effects on reaction time is arguably quite small, being only a fraction of a second. However, in tasks such as operating a vehicle, even a small amount of delay could be critical if the driver was too slow to avert a serious collision. It is possible that reaction time could be slowed even further should a VR user suffer from lingering cybersickness. Additional research could increase knowledge and understanding about the length of reaction time in a sample of VR users and whether it subsides at the same rate as cybersickness symptoms. With the current level of understanding, users could be warned about this possibility and advised to wait for symptoms to subside before engaging in activities that require good balance, quick responses and accurate motor skills, such as driving or operating machinery.

---

[68] González, Armando Martinez, Antonio Iyda Paganelli, and Alberto Raposo. "Analysing Balance Loss in VR Interaction with HMDs." *Journal on Interactive Systems* 9, no. 2 (2018): 68-81.

[69] Nalivaiko, Davis, Blackmore, Vakulin, and Nesbitt. "Cyber sickness provoked by head-mounted display," 583-590.

[70] Nesbitt, Davis, Blackmore, and Nalivaiko. "Correlating reaction time," 1-8.

The ability to drive after using a VR system was an important subject for discussion with interviewees.

2.4.4 Physiological responses

Studies within the literature review, typically relied on subjective measures for responses to VR use. In particular, the Simulator Sickness Questionnaire (SSQ) has been the most commonly used measure for cybersickness. Although it is shown to be a reliable subjective measure, the questionnaire was not specifically designed for gauging cybersickness.[71] Identifying physiological responses to VR exposure, which are objectively measurable factors such as increased heart rate or sweating, could enhance future research studies. Davis et al.[72] state that the development of simple objective methods is integral to quantifying and understanding the causes and effects that cybersickness can have on participants. Furthermore, these can assist attempts to improve the design of both VR system technology and the virtual environments being developed.

Heart rate is a commonly used objective response measure. Research that has investigated how heart rate is affected during VR immersion has shown a mix of findings. In a study by Nalivaiko et al.[73] participants who showed a high nausea response were found to have an increased heart rate. A similar effect was also observed by Cobb, Nichols, Ramsey and Wilson.[74] However, heart rate was found to be virtually unchanged within those who felt minimal nausea. Similar findings were also present in a later study by Gavgani et al.[75] Contrary to these findings, Garcia-Agundez et al.[76] found that individuals with a greater cybersickness response had a lower heart rate, with heart rates as low as 54 beats per minute being reported during the experiment. These inconsistent findings make identifying the exact relationship between heart rate and sickness response difficult, though it would appear that a relationship does exist. This range of findings may be explained from the small sample sizes present in these studies, or the mix of methods used. There is potential that heart rate can be used as an objective measure, but more research would be required.

Aside from heart rate, these same studies also investigated other factors including skin temperature, perspiration and electrodermal[77] activity. Skin temperature was found to increase during VR immersion. This was not found to be associated with nausea or cybersickness;[78] however, a sweating response was.[79] Electrodermal activity, in relation to the forehead, has been found and argued to be the best physiological correlate of nausea resulting from VR immersion.[79] As these findings were drawn from the same studies that also investigated heart activity, the same criticisms can be made. Future research into physiological responses to VR immersion would benefit from sufficient sample sizes and consistent methods. The use of objective physiological measures within research into cybersickness would prove worthwhile.[80]

---

[71] Garcia-Agundez, Augusto, Christian Reuter, Polona Caserman, Robert Konrad, and Stefan Göbel. "Identifying Cyber sickness through Heart Rate Variability alterations." *International Journal of Virtual Reality* 19, no. 1 (2019): 1-10.
[72] Davis, Nesbitt, and Nalivaiko. "Comparing the onset ," 30.
[73] Nalivaiko, Davis, Blackmore, Vakulin, and Nesbitt. "Cyber sickness provoked by head-mounted display," 583-590.
[74] Cobb, Sue VG, Sarah Nichols, Amanda Ramsey, and John R. Wilson. "Virtual reality-induced symptoms and effects (VRISE)." *Presence: Teleoperators & Virtual Environments* 8, no. 2 (1999): 169-186.
[75] Gavgani, Nesbitt, Blackmore, and Nalivaiko. "Profiling subjective symptoms," 41-50.
[76] Garcia-Agundez, Reuter, Caserman, Konrad, and Göbel. "Identifying Cyber sickness," 1-10.
[77] A term used for defining autonomic changes in the electrical properties of the skin.
[78] Davis, Nesbitt, and Nalivaiko. "Comparing the onset," 30.
[79] Cobb et al. "Virtual reality-induced symptoms," 169-186.
[80] Davis, Simon, Keith Nesbitt, and Eugene Nalivaiko. "A systematic review of cyber sickness." In *Proceedings of the 2014 Conference on Interactive Entertainment*, (2014): 1-9.

The results could then inform users of the specific effects. For example, if VR use or cybersickness is found to have a significant impact on heart rate, this may pose a health concern to some individuals who could be advised to avoid VR exposure.

2.5 Interviews

Qualitative research was undertaken with users of VR and VR industry experts to gain insight into the real-world experiences of people who use VR or those who have experience of using or facilitating the use of VR within industry. The experience of interviewees generally confirmed the findings from the literature review:

- Interview participants discussed how the severity of symptoms ranged greatly between users.
- Interviewees raised concerns about general safety while engaging in VR, with one individual reporting that they had experienced a minor injury as a result of being immersed in VR.
- One interviewee believed that preconceptions about VR can impact on one's susceptibility to cybersickness.
- Evidence from the interviews suggests that duration and severity of negative effects following VR use can vary between individuals.

2.6 Summary

As has been mentioned above, research into VR systems appears to have focused mainly on the topic of cybersickness. This section intends to cover other effects that have been found from VR immersion. Of most concern is the potential for adaptation effects to occur. Although evidence is currently minimal within the literature reviewed, extended VR use appears to result in heterophoric changes to the eyes. Further to this, there is some evidence to suggest that balance and coordination can also be affected through adaptation. These negative outcomes from using VR do not present great risk on their own providing that the effects subside over time. However, adaptation can be potentially dangerous if it can adversely impact an individual's ability to safely perform other tasks such as operating a vehicle or using machinery. This same reasoning can be applied when considering the effect on reaction time of using VR systems. Further research into how long adaptation effects are likely to last, and if different individuals are more or less susceptible to the effects, would be particularly useful. Users of domestic VR systems should be made aware of these adaptation effects and encouraged to take regular breaks from VR use in order to mitigate any negative outcomes. Objective physiological responses have also been identified and are recommended to be incorporated into future research into VR, as they present a means of generating more significant research findings.

3 Limitations

There were a number of limitations that were identified during the course of the literature review that should be highlighted. These limitations stem from the literature itself and have a direct impact on the conclusions that can be drawn from this review.

One limitation that was identified concerns the study methods used in the variety of research included within this review. Different studies have used different stimuli in order to induce cybersickness symptoms in participants. For example, Davis et al.'s[81] study used different VR roller coaster experiences, while participants in Curtis'[82] study were required to manually walk around a virtual environment of a cornfield. Although both studies claim that their chosen stimulus was successful in inducing cybersickness symptoms, it cannot be assumed that they were both equal in their ability to do so. This same reasoning can be applied to studies which used different VR systems; for example, the Oculus Rift cannot be assumed to perform equally to the HTC VIVE or Samsung Gear VR. As almost all studies employed different methods while aiming to investigate the effect on cybersickness as a result, it can be hard to compare the results of the different studies.

Research into VR has been undertaken for more than two decades, with the earliest literature included in this review dating back to 1993. Current domestic VR systems have only become available within the past few years.[83] It cannot be assumed that current VR systems perform in a similar way to older systems.

A significant proportion of the studies into cybersickness rely heavily on the use of subjective measures of cybersickness and nausea. The Simulator Sickness Questionnaire (SSQ) is frequently used and has been found to be a reliable measure of cybersickness, featuring subscales that account for oculomotor effects, disorientation and nausea.[78] However, as a subjective measure it is limited by the fact that different individuals may anchor their feelings to different baselines. For example, an individual who is less prone to cybersickness symptoms may rank mild feelings of nausea highly, while someone who is extremely sensitive to severe symptoms may rank equivalent feelings as low. Studies might instead opt for objective measures of cybersickness symptoms such as cardiovascular response and skin conductance. Some research along these lines that was conducted by Nalivaiko et al.,[84] Garcia-Agundez et al.[85] and Gavgani et al.[86] have shown some evidence that heart rate and forehead electrodermal activity indication can be used as objective predictors of cybersickness. However, this research would require further support to reliably demonstrate these as valid objective measures of cybersickness. Also, whichever measures are used, an agreed threshold would be needed (either in terms of rated discomfort, or possibly performance decline) if systems are to be rated fairly.

An individual's experience of VR and their subjective scorings of cybersickness may be influenced by their own preconceptions about VR. This factor could have impacted on past research and should be borne in mind when interpreting findings. It could also be taken into consideration when conducting future research; for example, by including a pre-study

---

[81] Davis, Nesbitt, and Nalivaiko. "Comparing the onset," 30.
[82] Curtis. "Investigation of visually induced motion sickness."
[83] The original Oculus Rift was released in March of 2016.
[84] Nalivaiko, Davis, Blackmore, Vakulin, and Nesbitt. "Cyber sickness provoked by head-mounted display," 583-590.
[85] Garcia-Agundez, Reuter, Caserman, Konrad, and Göbel. "Identifying Cyber sickness," 1-10.
[86] Gavgani, Nesbitt, Blackmore, and Nalivaiko. "Profiling subjective symptoms," 41-50.

questionnaire that collects information regarding participants' own understanding of VR experiences.

Another limitation within the reviewed research concerns the participant samples used within each study. The majority of the studies used a student sample, typically within the 20-30-year-old age range, predominantly male and engaged on a volunteer basis. Males have been found to be less susceptible to the symptoms of cybersickness than females,[87] and as the student sample typically came from a related field of study, many of the volunteer participants had prior experience with video games and VR so they are even less susceptible to such symptoms through habituation.[88]

These limitations should be considered alongside the conclusions drawn from this report.

[87] Iskenderova, Weidner, and Broll. "Drunk Virtual Reality Gaming," 561-572; Somrak, Humar, Hossain, Alhamid, Hossain, and Guna. "Estimating VR Sickness," 302-316.
[88] Hill, K. J., and Peter A. Howarth. "Habituation to the side effects of immersion in a virtual environment." *Displays* 21, no. 1 (2000): 25-30; Clemes and Howarth. "Habituation to virtual simulation sickness," 63-74; Howarth and Hodder. "Characteristics of habituation," 117-123; Gavgani, Nesbitt, Blackmore, and Nalivaiko. "Profiling subjective symptoms," 41-50; Somrak, Humar, Hossain, Alhamid, Hossain, and Guna. "Estimating VR Sickness," 302-316; Nichols, Sarah. "Individual characteristics and experiences of virtual reality induced symptoms and effects (VRISE)." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 44, Los Angeles: SAGE Publications (2000): 538-541.

4 Overall summary

This work aimed to explore the available literature in order to establish the current state of knowledge on the risks to users of domestic VR systems, and to identify ways to mitigate these risks. Consideration was given to additional risks that may affect the user during subsequent use of machinery or driving, with a particular focus on identifying research gaps.

This review has shown that the predominant focus of VR research to date is on the topic of cybersickness, with the review process not identifying any evidence on physical risk factors such as trip hazards or repetitive strain injury. Various theories have been put forward in an attempt to explain the root causes of cybersickness symptoms, with sensory conflict theory showing the most promise. However, further work is needed to more fully understand the root causes of cybersickness.

Various factors of VR systems have been identified that appear to provoke cybersickness occurring. These include:

- the FoV available within the HMD where a narrow FoV can result in more head movements and increased cybersickness,
- the visual realism of the virtual environment where a more realistic experience will increase the likelihood of cybersickness, and
- the movement options available to navigate the virtual space.

The studies reviewed make a compelling argument for a trade-off between the realism of the immersive experience (i.e. one that gives the user a feeling of actually being within a realistic if synthetic environment) and cybersickness. This was also supported by anecdotal evidence provided during interviews. Further research would be useful into this trade-off, and to explore what other factors might provoke cybersickness.

This review also summarises the findings of research studies to identify exercises the user can engage in to lessen the symptoms of cybersickness, including oculomotor and hand-eye coordination exercises.

VR systems can include options to allow users to adjust their own VR experience and thereby reduce the risk of serious cybersickness. Such options can include adjustable depth of field and field of view, rotation blurring, graphic quality and movement options. Current research has raised these as potential areas that present risks to the user; however, much more research is required, in particular to keep pace with the latest technology and developments. Based on current evidence, the most effective means of mitigating cybersickness would be to take regular breaks from using VR. Sessions of VR use should ideally be limited to around 10-20 minutes with breaks sufficiently long enough for any negative symptoms to diminish.

Evidence would also suggest that regular VR use can lead to habituation, which may allow users to extend the time they spend in VR. However, this may put users at risk of adaptation effects, such as a deterioration in a users' eyesight, balance or coordination. These issues present potential health and safety concerns when engaging in other activities immediately following VR exposure; in particular, activities such as operating a vehicle. Although current research has raised the potential for adaptation effects to occur, more research is required to better understand the full risk that adaptation effects present. It was notable that these adaptation effects were not mentioned by any of these interviewees as a concern.

In addition to this summary, Table 1 presents a high-level summary of example VR activities, risks and mitigations. This overview of the key findings from the literature review and interviews helps to identify where the gaps lie in this area of research. Research gaps are outlined in Section 4 and have also been highlighted within the summaries at the beginning of each sub-section of Section **Error! Reference source not found.**.

Table 1: High-level summary of example VR activities, risks and mitigations

Uses of VR – What sort of activities do individuals engage in within VR?
• Video games – Many game developers are creating games specifically designed for VR. • Social media – There are a number of online spaces designed for socialising that support VR; for example, Facebook Spaces and Second Life. • Creative projects – VR is being increasingly used as a tool in fields such as engineering, architecture and the arts. • Therapy – VR can be used as a tool in psychological or occupational therapy, offering a safe virtual environment to treat a specific ailment.

Risks from the use of VR – What risks are present during or following VR immersion?
• Physical injury – While wearing a VR headset, the user is at an increased risk of falling or hitting objects in the real world which they cannot see as a result of wearing the VR headset. • Illness – Cybersickness is a common aftereffect of using VR and is associated with symptoms such as nausea, eyestrain, headaches, and disorientation. • Adaptation – Changes to the body can occur from frequent use of VR, including changes to the visual system (e.g. heterophoria) and postural instability. • Engaging in activities following VR use – if an individual is suffering from any of the above effects, this presents a further risk if an individual engages in another activity immediately following VR use. For example, if an individual is suffering from postural instability, this may have direct safety implications for operate a vehicle safely.

Mitigations from the adverse effects of VR Mitigation – What measures can be taken to minimise risk?
• Short sessions – Limiting VR use to short sessions of around 15 minutes has the potential to mitigate adaptation effects and cybersickness symptoms.

- Take a break – This extends from the previous point in that people should be advised to take a sufficient break following VR use before engaging in any other activity. Rest is advocated until any negative symptoms of VR exposure (e.g. nausea, dizziness) have subsided.
- User exercises – Further research is required to understand the extent of any benefits that user exercises may offer but performing activities such as oculomotor and hand-eye coordination exercises may reduce the severity of symptoms such as eyestrain.
- Apply appropriate settings – Providing the options are available within the VR system, it is advised that each individual adjusts the settings of their VR system to ensure it presents minimal risk to them; for example, adjusting the lenses of the VR headset to improve the sharpness of the display can minimise the risk of headaches and eyestrain.

4 Research Gaps

Findings from the literature review and interviews have highlighted the need for further research into the field of VR. The evidence drawn from the literature does not fully explain the underlying causes of health and safety risks relevant to users of domestic VR systems. This includes the causes of the negative effects experienced by users, individual differences in effects felt, and means to mitigate them. Furthermore, many of the studies can be criticised for their method of study or interpretation of findings. Study methods could be improved to enhance the quality of research and subsequent findings. With these points in mind, several research areas can be identified for further investigation and exploration.

A summary of the research areas and relevant research gaps are shown in Table 2: Summary of evidence review and identified gaps.

Table 2: Summary of evidence review and identified gaps

Research topic	Evidence review – summary
Understanding the cause of cybersickness	
What interactions exist between the various existing theories; specifically sensory conflict and postural instability?	Of the theories that have been raised, none have proven to be sufficient on their own to explain cybersickness in all cases. A combination of sensory conflict and postural instability has the potential to explain root cause of cybersickness following additional research.
What individual factors exist that can impact on cybersickness?	Some evidence shows gender differences in susceptibility to cybersickness; however, this is not well understood. No evidence on factors such as age or visual acuity.
VR system factors that can stimulate cybersickness	
What VR system factors provoke cybersickness?	Some evidence has shown that factors such as greater field of view and graphic realism can cause cybersickness; further evidence would be required to support this. Potential to identify other VR system factors that may arouse cybersickness symptoms (e.g. weight of system).
Does there exist a trade-off between immersion and cybersickness?	Evidence identified from the literature review began to build an argument showing a trade-off between an immersive experience and

	cybersickness; further research should look to clarify and understand this relationship.
Adaptation effects	
What adaptation effects occur as a result of VR use?	Evidence has shown some adaptation effects to vision, balance and coordination. Further research would be required to better understand the exact nature of these effects and whether the effects are present using current VR technology.
Approaches to mitigate cybersickness symptoms and adaptation effects	
What VR system factors can be developed / adapted to mitigate cybersickness symptoms?	Current evidence would suggest that giving the user various options to adjust settings such as field of view and depth of field may improve mitigate cybersickness; however, further evidence is required to support this.
What VR system factors can be developed / adapted to mitigate adaptation effects?	Gap – no evidence found.
What user exercises exist, if any, that can mitigate cybersickness symptoms?	Some evidence was found to suggest oculomotor exercises may be effective in mitigating cybersickness; however, further evidence would be required. Research could also be conducted to identify additional exercises that may help mitigate more specific symptoms (e.g. nausea).
What user exercises exist, if any, that can mitigate adaptation effects?	Gap – no evidence found.
Quantifying the duration of the negative effects	
How long are symptoms of cybersickness likely to last following VR exposure?	Little evidence has effectively shown how long cybersickness is likely to last; further research required to assess this.
How long are adaptation effects likely to last following VR exposure?	Evidence has shown that effects are observable immediately following VR exposure; however, little to no evidence reliably shows when symptoms are likely to subside. Further research required to assess this.

Do longer exposure times increase the recovery period?	Gap – no evidence found.
Are different people more susceptible to lingering effects?	Gap – no evidence found.
Identification and clarification of objective measures of negative effects of VR use	
What physiological response measures are the most robust and reliable for identifying symptoms of cybersickness?	Current evidence would suggest forehead electrodermal activity as a reliable physiological measure; however, further research would be required to provide additional support.
Differences between various VR systems	
Are different VR systems comparable with each other?	Gap – No evidence found.
How do different VR systems impact on cybersickness?	Gap – No evidence found.
How do different VR systems impact on adaptation?	Gap – No evidence found
Do different VR systems provoke additional unidentified effects?	Gap – No evidence found.

Future research should also consider the following factors:

- **The VR system and settings used** –There is insufficient research into the differences between the different models of VR systems and variations in settings on the user. For example, interpupillary distance varies and this has the potential to affect the individual response. Given the rate of advancements in VR technology development, research can quickly become outdated.[89]
- **The intended use of the VR system** – Will the findings of research into the use of VR in a commercial application be reflective of its use in consumer applications? For example, adjusting the field of view of a VR system in a consumer application might negatively impact the effectiveness of a VR training tool.[90]

[89] Costello, Patrick J. “Health and safety issues associated with virtual reality: a review of current literature.” Loughborough, UK: Advisory Group on Computer Graphics, (1997): 1-23.
[90] Nichols, Sarah, and Harshada Patel. "Health and safety implications of virtual reality: a review of empirical evidence." *Applied ergonomics* 33, no. 3 (2002): 251-271.

- **Use of objective measures** – It was highlighted within the literature review findings that current research has had an over-reliance on subjective measures of cybersickness and other negative responses to VR use. Although subjective measures such as questionnaires are accepted methods for gathering material for scientific enquiry, objective measures – such as physiological responses – should provide a greater level of scientific accuracy.

- **Adequate size of sample** – Most of the research studies discussed within the literature review featured noticeably small sample sizes. Future research would benefit from a sufficient sample size to provide representative and reliable research findings, especially where statistical comparisons are required between conditions or systems.

5 References

Abekawa, Naotoshi, Elisa R. Ferrè, Maria Gallagher, Hiroaki Gomi, and Patrick Haggard. "Disentangling the visual, motor and representational effects of vestibular input." *Cortex* 104 (2018): 46-57.

Arcioni, Benjamin, Stephen Palmisano, Deborah Apthorp, and Juno Kim. "Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality." *Displays* (in press).

Barrett, Judy. *Side effects of virtual environments: A review of the literature*. No. DSTO-TR-1419. Defence Science and Technology Organisation Canberra (Australia), 2004.

Basting, Oliver, Arnulph Fuhrmann, and Stefan M. Grünvogel. "The effectiveness of changing the field of view in a HMD on the perceived self-motion." In *2017 IEEE Symposium on 3D User Interfaces* (2017): 225-226.

Biocca, Frank A., and Jannick P. Rolland. "Virtual eyes can rearrange your body: Adaptation to visual displacement in see-through, head-mounted displays." *Presence* 7, no. 3 (1998): 262-277.

Braun, Virginia, Victoria Clarke, Nikki Hayfield, and Gareth Terry. "Thematic analysis." *Handbook of Research Methods in Health Social Sciences* (2019): 843-860.

Budhiraja, Pulkit, Mark Roman Miller, Abhishek K. Modi, and David Forsyth. "Rotation blurring: use of artificial blurring to reduce cybersickness in virtual reality first person shooters." In *CoRR 2017* (2017).

Carnegie, Kieran. "Mitigating Visual Discomfort on Head Mounted Displays using Estimated Gaze Dependent Depth of Field." (Master's Thesis, Victoria University of Wellington, 2015).

Clemes, Stacy A., and Peter A. Howarth. "Habituation to virtual simulation sickness when volunteers are tested at weekly intervals." *Human factors in the age of Virtual Reality* (2003): 63-74.

Cobb, Sue VG, Sarah Nichols, Amanda Ramsey, and John R. Wilson. "Virtual reality-induced symptoms and effects (VRISE)." *Presence: Teleoperators & Virtual Environments* 8, no. 2 (1999): 169-186.

Coburn, Joshua Q. "An Analysis of Enabling Techniques for Highly-Accessible Low-Cost Virtual Reality Hardware in the Collaborative Engineering Design Process." (PhD Diss., Brigham Young University, 2017).

Costello, Patrick J. "Health and safety issues associated with virtual reality: a review of current literature." Loughborough, UK: Advisory Group on Computer Graphics, (1997): 1-23.

Curtis, Michael Keneke. "Investigation of visually induced motion sickness: a comparison of mitigation techniques in real and virtual environments." (Master's Thesis, Iowa State University, 2014).

Davis, Simon, Keith Nesbitt, and Eugene Nalivaiko. "A systematic review of cybersickness." In *Proceedings of the 2014 Conference on Interactive Entertainment* (2014): 1-9.

Davis, Simon, Keith Nesbitt, and Eugene Nalivaiko. "Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters." In *Proceedings of the 11th Australasian Conference on Interactive Entertainment* 27 (2015): 30.

Dennison, Mark Stephen, and Michael D'Zmura. "Cybersickness without the wobble: experimental results speak against postural instability theory." *Applied ergonomics* 58 (2017): 215-223.

Ebenholtz, Sheldon M. "Sources of asthenopia in navy flight simulators." Battelle Memorial Inst Columbus OH (1988).

Ebenholtz, Sheldon M. "Motion sickness and oculomotor systems in virtual environments." *Presence: Teleoperators & Virtual Environments* 1, no. 3 (1992): 302-305.

Garcia-Agundez, Augusto, Christian Reuter, Polona Caserman, Robert Konrad, and Stefan Göbel. "Identifying Cybersickness through Heart Rate Variability alterations." *International Journal of Virtual Reality* 19, no. 1 (2019): 1-10.

Gavgani, Alireza Mazloumi, Keith V. Nesbitt, Karen L. Blackmore, and Eugene Nalivaiko. "Profiling subjective symptoms and autonomic changes associated with cybersickness." *Autonomic Neuroscience* 203 (2017): 41-50.

González, Armando Martinez, Antonio Iyda Paganelli, and Alberto Raposo. "Analysing Balance Loss in VR Interaction with HMDs." *Journal on Interactive Systems* 9, no. 2 (2018): 68-81.

Häkkinen, Jukka, Tero Vuori, and M. Paakka. "Postural stability and sickness symptoms after HMD use." In *IEEE International Conference on Systems, Man and Cybernetics* 1 (2002): 147-152.

Harm, Deborah L., Laura C. Taylor, Millard F. Reschke, Jeffrey T. Somers, and Jacob J. Bloomberg. "Sensorimotor coordination aftereffects of exposure to a virtual environment." *The Visual Computer* 24, no. 11 (2008): 995-999.

Hettinger, Lawrence J., Kevin S. Berbaum, Robert S. Kennedy, and Daniel P. Westra. "Human performance issues in the evaluation of a helmet-mounted area-of-interest projector." In *Proceedings of the IMAGE IV Conference* (1987): 320-327.

Hill, K. J., and Peter A. Howarth. "Habituation to the side effects of immersion in a virtual environment." *Displays* 21, no. 1 (2000): 25-30.

Howarth, Peter A. "Oculomotor changes within virtual environments." *Applied Ergonomics* 30, no. 1 (1999): 59-67.

Howarth, Peter. A., and Patrick. J. Costello. "Visual effects of immersion in virtual environments: Interim results from the UK Health and Safety Executive Study." In *Side International Symposium Digest of technical papers* 27 (1996): 885-888.

Howarth, Peter A., and Simon G. Hodder. "Characteristics of habituation to motion in a virtual environment." *Displays* 29, no. 2 (2008): 117-123.

Iskenderova, Aliya, Florian Weidner, and Wolfgang Broll. "Drunk Virtual Reality Gaming: Exploring the Influence of Alcohol on Cybersickness." In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (2017): 561-572.

Kennedy, Robert S., and Kay M. Stanney. "Postural instability induced by virtual reality exposure: Development of a certification protocol." *International Journal of Human-Computer Interaction* 8, no. 1 (1996): 25-47.

Kennedy, Robert S., Kay M. Stanney, and William P. Dunlap. "Duration and exposure to virtual environments: sickness curves during and across sessions." *Presence: Teleoperators & Virtual Environments* 9, no. 5 (2000): 463-472.

Kolasinski, Eugenia M. "Simulator Sickness in Virtual Environments". (No. ARI-TR-1027. Army research Inst for the behavioral and social sciences Alexandria VA, 1995).

Kramida, Gregory. "Resolving the vergence-accommodation conflict in head-mounted displays." *IEEE Transactions on Visualization and Computer Graphics* 22, no. 7 (2016): 1912-1931.

Kuiper, Ouren X., Jelte E. Bos, and Cyriel Diels. "Vection does not necessitate visually induced motion sickness." *Displays* (in press).

Lampton, Donald R., Eugenia M. Kolasinski, Bruce W. Knerr, James P. Bliss, John H. Bailey, and Bob G. Witmer. "Side effects and aftereffects of immersion in virtual environments." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 38, no. 18, Los Angeles, CA: SAGE Publications, (1994): 1154-1157.

LaViola Jr, Joseph J. "A discussion of cybersickness in virtual environments." *ACM SIGCHI Bulletin* 32, no. 1 (2000): 47-56.

McCauley, Michael E., and Thomas J. Sharkey. "Cybersickness: Perception of self-motion in virtual environments." *Presence: Teleoperators & Virtual Environments* 1, no. 3 (1992): 311-318.

Merhi, Omar Ahmad. "Motion sickness, virtual reality and postural Stability." (PhD Diss., University of Minnesota, 2009).

Mon-Williams, Mark, John P. Wann, and Simon Rushton. "Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display." *Ophthalmic and Physiological Optics* 13, no. 4 (1993): 387-391.

Mon-Williams, Mark, Anna Plooy, Robin Burgess-Limerick, and John Wann. "Gaze angle: a possible mechanism of visual stress in virtual reality headsets." *Ergonomics* 41, no. 3 (1998): 280-285.

Moss, Jason D., and Eric R. Muth. "Characteristics of head-mounted displays and their effects on simulator sickness." *Human factors* 53, no. 3 (2011): 308-319.

Murata, Atsuo. "Effects of duration of immersion in a virtual reality environment on postural stability." *International Journal of Human-Computer Interaction* 17, no. 4 (2004): 463-477.

Nalivaiko, Eugene, Simon L. Davis, Karen L. Blackmore, Andrew Vakulin, and Keith V. Nesbitt. "Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time." *Physiology & Behaviour* 151 (2015): 583-590.

Nesbitt, Keith, Simon Davis, Karen Blackmore, and Eugene Nalivaiko. "Correlating reaction time and nausea measures with traditional measures of cybersickness." *Displays* 48 (2017): 1-8.

Nichols, Sarah. "Individual characteristics and experiences of virtual reality induced symptoms and effects (VRISE)." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 44, no. 5, Los Angeles, CA: SAGE Publications, (2000): 538-541.

Nichols, Sarah, and Harshada Patel. "Health and safety implications of virtual reality: a review of empirical evidence." *Applied ergonomics* 33, no. 3 (2002): 251-271.

Palmisano, Stephen, Rebecca Mursic, and Juno Kim. "Vection and cybersickness generated by head-and-display motion in the Oculus Rift." *Displays* 46 (2017): 1-8.

Park, Won Deok, Seong Wook Jang, Yeol Ho Kim, Gyu Ah Kim, Wookho Son, and Yoon Sang Kim. "A study on cybersickness reduction by oculo-motor exercise performed immediately prior to viewing virtual reality (VR) content on head mounted display (HMD)." *Vibroengineering Procedia* 14 (2017): 260-264.

Peli, Eli. "Visual and optometric issues with head-mounted displays." *Optics & Imaging in the Information Age* (1996): 364-369.

Plouzeau, Jérémy, Damien Paillot, Jean-Rémy Chardonnet, and Frédéric Merienne. "Effect of proprioceptive vibrations on simulator sickness during navigation task in virtual environment." In *International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments* (2015).

Regan, E. C., and K. R. Price. "The frequency of occurrence and severity of side-effects of immersion virtual reality." *Aviation, Space, and Environmental Medicine* (1994): 527-530.

Riccio, Gary E., and Thomas A. Stoffregen. "An ecological theory of motion sickness and postural instability." *Ecological psychology* 3, no. 3 (1991): 195-240.

Shafer, Daniel M., Corey P. Carbonara, and Michael F. Korpi. "Modern virtual reality technology: Cybersickness, sense of presence, and gender." *Media Psychology Review* 11 (2017): 1-13.

Sheehy, James B., and Michael Wilkinson. "Depth perception after prolonged usage of night vision goggles." *Aviation, Space, and Environmental Medicine* 60 (1989): 573-579.

So, Richard HY, and W. T. Lo. "Cybersickness with virtual reality training applications: a claustrophobia phenomenon with head-mounted displays." In *Proceeding of the 1st world congress on ergonomics for global quality and productivity* (1998): 209-212.

Somrak, Andrej, Iztok Humar, M. Shamim Hossain, Mohammed F. Alhamid, M. Anwar Hossain, and Jože Guna. "Estimating VR Sickness and user experience using different HMD technologies: An evaluation study." *Future Generation Computer Systems* 94 (2019): 302-316.

Stanney, Kay M., Robert S. Kennedy, Julie M. Drexler, and Deborah L. Harm. "Motion sickness and proprioceptive aftereffects following virtual environment exposure." *Applied ergonomics* 30, no. 1 (1999): 27-38.

Tiiro, Arttu. "Effect of Visual Realism on Cybersickness in Virtual Reality." (Master’s Thesis, University of Oulu, 2018).

Treisman, Michel. "Motion sickness: an evolutionary hypothesis." *Science* 197, no. 4302 (1977): 493-495.

van Beers, Robert J., Daniel M. Wolpert, and Patrick Haggard. "When feeling is more important than seeing in sensorimotor adaptation." *Current biology* 12, no. 10 (2002): 834-837.

Webb, Nicholas A., and Michael J. Griffin. "Eye movement, vection, and motion sickness with foveal and peripheral vision." *Aviation, space, and environmental medicine* 74, no. 6 (2003): 622-625.

Wright, W. Geoffrey. "Using virtual reality to augment perception, enhance sensorimotor adaptation, and change our minds." *Frontiers in systems neuroscience* 8 (2014): 56.

Appendix A Methodology

A.1 Introduction

BEIS wished to establish the current state of knowledge surrounding risks and hazards associated with the use of domestic VR systems. This section details the in-depth literature review and interview investigation that was conducted in order to address the following objectives:

- Provide an evidence-based understanding of the risks and hazards that a domestic user is exposed to during the use of VR systems.
- Provide an evidence-based understanding of the risks and hazards that a domestic user is exposed to following the use of VR systems; in particular, an analysis of the additional hazards that might occur during subsequent use of machinery or driving.
- Assess possible mitigating measures and their efficacy in protecting the user from harm.
- Identify further research requirements to develop the evidence base of this subject.

A.2 Method

A.2.1 Literature Review

A list of search terms (see Appendix B) relevant to the project objectives was generated to run the literature search. Multiple searches were conducted within a variety of online research databases (Google Scholar, ScienceDirect, PubPsych, TRID,[91] BASE[92] and CORE[93]) through an iterative process, wherein search terms were tested individually and in combination with each other to identify which terms generated relevant results. This process also helped to identify research databases that contained relevant research and exclude those that did not prove to be a useful source of literature. PubPysch and TRID were both excluded as the literature that they generated from the various searches focused predominantly on how VR systems can be used as a therapy or training tool respectively. The remaining research databases were able to provide at least a small selection of relevant texts.

Once the search terms had been tested, those that generated relevant results were merged into a Boolean search expression (an example of which can be seen in **Error! Not a valid bookmark self-reference.**) specific to each database. This allowed the output to be refined to the most manageable number of relevant texts. After conducting and refining the literature search, texts were then compiled in a spreadsheet for a full review. Search output that was clearly irrelevant based on the title was removed at this stage. The completed spreadsheet included 66 pieces of literature. The abstracts of this initial list of literature were reviewed and

[91] Transport Research International Documentation that covers a million records of references to books, technical reports, conference proceedings and journal articles within the field of transport research.
[92] Bielefeld Academic Search Engine is one of the world's most voluminous search engines especially for academic resources, providing more than 120 million documents from more than 6,000 sources.
[93] Connecting Repositories is a research search engine built for the purpose of aggregating all open access research outputs from repositories and journals worldwide.

scored using a set of inclusion criteria (see Appendix C). After scoring, 60 texts were taken forward for full text review.

Literature was reviewed in full with findings recorded systematically in the review spreadsheet. Each individual text was presented in a row, with summaries of the research goals, methods, and findings detailed in columns. Conclusions relating to the objectives of the current project were drawn where possible, from each reference. The five texts that were not taken forward for full text review were reviewed in brief to ensure no major findings had been missed through application of the inclusion criteria. These texts were given a short summary within the review spreadsheet and it was confirmed that no major evidence had been missed.

A.2.2 Interview Investigation

Interviews were conducted with individuals who have personal experience with VR systems, as well as those who work in VR industries or use VR for academic research. These interviews provide insight into the first-hand experiences of individuals when interacting with VR systems.

A qualitative research design was employed to gain further insight into the real-world experiences of people who use VR or those who have experience of using or facilitating the use of VR within industry. Qualitative research is particularly beneficial in understanding how people engage with new technologies as it facilitates open-ended discussion and allows the interview to be guided by the experiences, thoughts, and perceptions of the interviewee.

A.2.2.1 Interviews

Seven one-to-one interviews were undertaken with users of VR and VR industry experts. The interviews:

- Were carried out over the phone at a time that was convenient to interviewees (during working hours)
- Lasted up to 30 minutes
- Were audio-recorded to allow analysis of interview responses
- Were not transcribed, but detailed notes were made of the discussion and verbatim comments were assessed using the audio recordings

In order to guide the discussion, a semi-structured interview guide was developed by the research team. The guide was broken down into a number of subsections, described in Table 3.

Table 3: Interview guide contents

Subsection	Overview	Estimated time
Information and consent	As research undertaken with human participants, this section ensured ethical principles of appropriate information provision and consent was obtained	2-3 minutes
Background	Questions to asses and categorise the type of user being interviewed. This allowed the interviewer to make a decision on the appropriate line of	Up to 5 minutes

	questioning (e.g. personal users or industries)	
[one of] Questions users of VR	Containing a series of questions assessing the experience of using VR, after effects, safety and recommendations	Up to 20 minutes
[one of] Questions for VR industries	Similar to the above line of questions, however with the potential added value of having observed multiple users/ their experiences of VR systems	Up to 20 minutes
Closing	Any last questions and thanking the participant for their time. The opportunity was also taken to ask participants for recommendations on additional interviewees.	2-3 minutes

At the start of the interview, the participants were provided with information about the purpose of the interview, duration and the right to withdraw at any point. Participants were also informed about how the data would be used and safeguarded and explicit consent was sought from participants, before the interview was officially started (this includes the audio recording).

A.2.2.2 Recruitment

Participants were identified from a contact list provided by the client as well as contacts that that the research team have within VR industry and academia. The TRL team then reached out directly to potential participants to provide information about the study and book the interviews. On first contact, participants were sent a letter containing information about the reason for contact and the study.

Because finding relevant contacts proved challenging, the client also supported by establishing contact to secure the necessary interviews.

A.2.2.3 Analysis

Thematic analysis was used to interpret the results from the interviews. Thematic analysis enables the identification of ‘themes’ within the verbatim data. Themes are then grouped and reported on, based on the amount of repetition (or patterns of repetition) observed across interviews.[94]

[94] Braun, Virginia, Victoria Clarke, Nikki Hayfield, and Gareth Terry. "Thematic analysis." Handbook of Research Methods in Health Social Sciences (2019): 843-860.

Appendix B List of search terms

(1st Level)		(2nd Level)		(3rd Level)
"Virtual Reality" OR "VR" OR "Sony PlayStation VR" OR "Oculus" OR "Oculus Rift" OR "HTC Vive" OR "Samsung Gear VR" OR "Lenovo Mirage Solo" OR "Google VR"	AND	Risk* OR Hazard* OR Exposure OR Effect* OR Aftereffect* OR Use* OR Harm* OR Protect* OR Safe* OR Danger* OR Injur* OR Vulnerable OR Mitigat* OR Cybersickness OR "Cyber-sickness" OR Sick* OR Ill* OR Strain* OR Stress* OR Adaptation OR Habituation	NOT	"Augmented Reality" OR "AR" OR Training OR Therapy
Additional search terms identified during the search process				
VRISE (Virtual Reality Induced Symptoms & Effects) OR	AND	Headset OR	NOT	Simulator OR Education OR

"Virtual environment"		"Head mounted display" OR HMD		Treatment OR Surgery

* denotes a wild card operator; e.g. Injur* will capture Injure, Injures, Injury, Injuries, Injurious and Injured.

Example Boolean search expression: ("Virtual Reality" OR "VR" OR "Oculus Rift") AND (risk* OR hazard*) NOT ("Augmented Reality" OR "AR")

Appendix C Inclusion criteria and scoring

	Score = 1	Score = 2	Score = 3
Relevance	Not relevant to the objectives of the project	Some indirect relevance to the objectives of the review	Directly relevant to the objectives of the review
Quality	Non-scientific article (e.g. online source, newspaper or magazine article)	Non-peer reviewed scientific article	Peer-reviewed scientific article (e.g. journal paper or conference procedure)
Timeliness	Older than 10 years	5-10 years old	Less than 5 years old

This publication is available from: www.gov.uk/government/publications/safety-of-domestic-virtual-reality-systems

If you need a version of this document in a more accessible format, please email enquiries@beis.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.