

Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters

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Abstract

The uptake of new interface technologies, such as the Oculus Rift, has generated renewed interest in virtual reality. However, the long-standing issue of cybersickness continues to impact on the general use of virtual reality devices, including head mounted displays. This paper contains a discussion of the growing interest, particularly within the gaming and business communities, of virtual reality technologies such as the Oculus Rift. A review of key issues related to cybersickness and their impact on the condition is reported. This includes a discussion of individual, device related and task dependent factors related to cybersickness. We also discuss the underlying theories that are used to explain these conditions and review a number of previous measures, both subjective and objective, that have been used to study cybersickness. We conclude this paper with the outcomes of a preliminary study using the Oculus Rift and comparing two different virtual roller coasters, each with different levels of fidelity. We find that the more realistic roller coaster with higher levels of visual flow has a significantly greater chance of inducing cybersickness.

Keywords: Cybersickness, measures, Oculus Rift, head-mounted display, simulator sickness, motion sickness.

1 Introduction

Virtual reality (VR) is a user interface technology that provides an immersive and realistic, three dimensional

computer simulated world (LaViola Jr. 2000). The ideas associated with VR have been under development since Ivan Sutherland described many of the concepts associated with his “ultimate display” (Sutherland 1965). Recently, VR has begun to move past private and specific industry applications to re-enter the commercial spotlight. This could arguably be attributed to the Oculus Rift, a new head-mounted display that has received considerable interest from the widespread game community.

However, a problem that has been inherent in VR, and devices such as the Oculus Rift is the uncomfortable side effects of cybersickness. Cybersickness can result in a large range of symptoms including nausea, disorientation, tiredness, headaches, sweating and eye-strain (LaViola Jr. 2000). There is still some debate over the underlying causes of cybersickness and a lack of strategies for designing environments that prevent such problems (Kennedy, Lane, Berbaum and Lilienthal 1993). While there is a relationship between motion sickness, simulator sickness and cybersickness, the types of symptoms and perhaps the underlying physiological causes seem to be related (Kennedy et al. 1993). Certainly the issue is complicated as experiences of cybersickness vary greatly between individuals, the technologies being used, the design of the environment and the tasks being performed (Johnson 2005).

As it stands, cybersickness still provides an obstacle to the wide spread adoption and commercial development of technologies associated with virtual reality. If VR is to be the commercially successful technology that companies like Oculus VR, Google, Facebook and Sony are hoping for, further research into cybersickness is required. Of particular advantage would be better quantitative measures for predicting a user’s susceptibility to cybersickness and reliable methods for detecting and measuring symptoms such as the nausea associated with the condition. Previous studies of cybersickness have

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mostly relied on subjective self-reporting of the severity of symptom conditions. Methods to objectively quantify cybersickness symptoms still need to be developed. This situation informs the broader aims of our research which is to develop a physiological measure that quantifies an individual's susceptibility to cybersickness and provides an objective measure of the intensity of the condition. As part of this study we are investigating suitable experiences that might induce cybersickness, so that we can then study these physiological factors in more detail.

The key research questions addressed by this study are: What is the state of previous research in the area of cybersickness? How is cybersickness currently detected and measured in VR? Is there a physiological measure to quantify an individual's susceptibility to cybersickness? Can cybersickness be simply induced to allow more detailed study of the physiological changes that occur?

This paper reports on initial investigations into these research questions. It includes a discussion of the rise of the Oculus Rift and its general place in the history of head-mounted displays. We also review previous work into the area of cybersickness, covering the broad range of symptoms, the factors that impact on the condition, the theories used to explain the phenomenon, the incidence and adaption of cybersickness as well as previous types of measures used in evaluation. Finally we report on an initial investigation into the use of two alternative roller coaster experiences (Murray 2013, *Helix – The NEXT Level* 2014). We find that the more realistic of the two experiences is significantly more likely to induce cybersickness over a short time frame.

2 Head-mounted displays

Virtual environments construct the user interface as a synthetic world where the user can interact with objects and navigate the environment as if they were in the real world. In virtual environments people participate, perform tasks and experience activities within the computer-generated world. The intention is to both "suspend belief" in the person's own reality and "suspend disbelief" of the computer created reality.

VR is not a new phenomenon, indeed many of the ideas associated with virtual environments were first described by Ivan Sutherland as part of his 'ultimate display' (Sutherland 1965). This paper is motivated by anecdotal reports of cybersickness, specifically with head-mounted display technologies like the recently released Oculus Rift (Oculus VR: Oculus Rift 2014). Like VR, head-mounted displays themselves have a long history of development.

The precursor to current head-mounted displays was a stereoscopic television patented by McCollum in 1945 (McCollum 1945). The patent describes the invention as a "stereoscopic television apparatus wherein the image creating mechanism is mounted in a spectacle frame." (McCollum 1945). Heilig also patented a stereoscopic television HMD for individual use in 1960 (Helig 1960). The patent notes that, "by placing one small television tube and peripheral vision lens system before each eye of the user, one ear phone by each ear, and one air duct before each nostril, the spectator is given a complete sensation of reality, i.e., moving three dimensional

images, which may be in color, with 100% peripheral vision, binaural sound, scents and air breezes" (Helig 1960). Philco Corporation designed a helmet, called Headsight in 1961 (Comeau and Bryan 1961). The helmet included a magnetic tracking system that captured head movements for controlling the view of a remote camera. Bell Helicopters also developed a camera-based head-mounted display to provide night vision to helicopter pilots during the 1960s (NRC 1999). Despite this early work in head mounted displays, Ivan Sutherland's "Sword of Damocles" (Sutherland, 1968) is widely regarded as one of the foundational computer-head mounted displays.

During the 1970s, 80s and 90s many further advances were made in head-mounted displays and evaluated for use in military, industrial and entertainment domains (Kiyokawa 2007). See table 1 for examples of the cost and characteristics of commercial head-mounted displays from the 1990s compared with characteristics and costs of the Oculus Rift. Despite this considerable development history of head-mounted displays, the Oculus Rift represents an emerging technology that is still trying to find a place in the mainstream as the "ultimate display".

Product	Resolution (per eye)	Horizontal Field of View	Weight (kgs)	Cost (US \$)
VPL Eyephone 2	360 x 240	90	2.4	11,000
Virtual Research Flight Helmet	320 x 240	100	2	6,000
LEEP Systems Cyberface II	479 x 234	140	1	8,100
Oculus Rift DK 1	640 x 800	110	0.22	\$300
Oculus Rift DK 2	960 x 1080	100	0.32	\$350

Table 1: Characteristics of early commercial HMDs (Burdea and Coiffet 1994; Holloway and Lastra 1993) compared with the Oculus Rift (Antonov, Mitchell, Reisee, Cooper, LaValle and Katsev 2013; Oculus Rift Development Kit 2 2014)

A key feature of head-mounted displays is the ability to provide stereoscopic images. Depth perception is a complex perceptual experience with many of the visual cues, such as brightness, occlusion, shadows, texture gradients and location in the visual field being purely two dimensional in nature (Goldstein 2009). It is only for objects in the one to three metre range that true stereoscopic cues, known as binocular disparity, are perceived (Goldstein 2009). These depth cues rely on the fact our eyes are slightly offset and hence we distinguish close objects from two slightly offset locations. In virtual reality this same effect can be simulated by providing the left and right eye with slightly offset views of the virtual world. Stereoscopic cues can be achieved in a number of ways. For example, by interleaving left and right eye images and using active 'shutter-glass' technology or passive polarization techniques to ensure each eye only sees the intended image. Head-mounted displays, such as the Oculus Rift, achieve this stereoscopic effect by

splitting the screen, dedicating a section of the display for each eye.

To create a true sense of immersion in a head-mounted display the displayed image needs to update so that it matches what the user is looking at in the virtual world. Thus the stereographic image needs to constantly change in direct relation to the wearer's viewpoint. Six degrees of freedom, three for position and three for orientation are required to define this viewpoint. This is achieved by tracking the user's head in real-time and then using the calculated viewpoint for each eye to display the world from the correct perspective. The Oculus Rift features a gyroscope for tracking angular velocity, an accelerometer for tracking accelerations in all directions and a magnetometer for sensing magnetic fields (Antonov et al. 2013). The use of the accelerometer and gyroscope allow for a user's movement and speed to be calculated and tracked in real time and reflected in the virtual environment (Boas). The Oculus Rift also uses algorithms to automatically correct drift from tilt and yaw errors that occur when using accelerometers, gyroscopes and magnetometers to calculate an individual's head position (LaValle 2013a, LaValle 2013b).

One problem with most stereoscopic displays is the accommodation convergence conflict (Durlach and Mavor 1995). In the real world, our eyes converge to look at near objects while also focusing (accommodating) at the same distance on the object. However, in virtual reality, while the eyes will still converge to look at a virtual object, the focus needs to be on the plane of the display itself rather than the object. A number of other key factors that need to be considered when using head-mounted displays are the vertical and horizontal field of view, the resolution, the contrast, the luminance and colour characteristics as well as any flicker or lag in updating the display (Durlach and Mavor 1995). Furthermore, head-mounted displays impact on the normal inertia characteristics of the head, generating unusual forces during head movements that can also directly impact on cybersickness (Durlach and Mavor 1995).

3 The Rise of the Oculus Rift

As of 2012 virtual reality has started to move past private and localized industry applications and into the mainstream commercial spotlight. This shift was arguably due to the Oculus Rift and its broad uptake by game players and developers. Oculus VR, creators of the Oculus Rift head mounted display, had a very successful Kickstarter in 2012, receiving a total of 2.4 million dollars in community funding and raising 974% of its initial monetary goal of 250 thousand dollars. Six months after their Kickstarter campaign, on the 29th March 2013 Oculus VR began shipping the DK1 (Oculus VR 2013).

Oculus VR currently has two iterations of its Oculus Rift device; the Oculus Rift Development Kit 1 (DK1) and the Oculus Rift Development Kit 2 (DK2). Oculus VR announced the second iteration of its development kit, the DK2 on the 19th March 2014 (Oculus VR 2014a). The DK2 features a higher resolution, higher refresh rate, low persistence to remove motion blur, and positional tracking for low latency and precise movements when

compared to its predecessor (see Table 2) (Oculus Rift Development Kit 2 2014). The DK2 represents the next step towards the consumer ready device that is expected to be available before the end of 2015.

Following the announcement of the DK2, Facebook purchased Oculus VR on the 25th March 2014 for \$2 billion (Oculus VR 2014c, Solomon 2014). Facebook CEO Mark Zuckerberg envisions the device as a new communications platform to enhance everyday social experiences (Zuckerberg 2014).

Major technology companies such as Sony, Google and Samsung have seemingly taken notice of the increasing consumer demand. Sony revealed their virtual reality device Project Morpheus in March 2014, a head mounted display for its games console, the PlayStation 4 (Yoshida 2014). On 26th June 2014 Google showed how simple it was to bring VR to mobile devices with an inexpensive build it yourself device dubbed Cardboard (Google Developers 2014). Google's Cardboard is a cardboard enclosure with magnets and lenses that wraps around a mobile device, using the mobile device as the display. Samsung and Oculus VR announced their collaboration, presenting the Samsung Gear VR Innovator Edition. A head mounted device for Samsung's mobile device the Galaxy Note 4 (Oculus VR 2014b). Similar to Google Cardboard, the Gear VR uses a mobile device as a display.

	Oculus Rift DK 1	Oculus Rift DK 2
Resolution	640 x 800 per eye	960 x 1080 per eye
Display	7" LCD at 60Hz	5.7" OLED at 75Hz
Low Persistence	No	Yes (2ms, 3ms, full)
Positional Tracking	No	Yes
Horizontal Field of View	110 degrees	100 degrees
Sensors	Accelerometer, Gyroscope, Magnetometer	Accelerometer, Gyroscope, Magnetometer
Update Rate	1000Hz	1000Hz
Interface	USB 2.0, HDMI 1.3	USB 2.0, HDMI 1.4b
Weight	0.22 kilograms	0.32 kilograms

Table 2: Oculus Rift Technical Specifications (Antonov et al. 2013; DK 2 2014)

At a Steam Dev Days conference in February 2014, Michael Abrash from Valve, a major games developer and digital games distributor, stated that consumer grade virtual reality devices are likely to arrive in two years (Abrash 2014). This is based on their own in house research and development and their collaboration with Oculus VR. Abrash believes that the technology will evolve most rapidly on the PC platform and revolutionize the entire entertainment industry and has indicated that Valve's digital distribution Steam platform will be offering full support (Steamworks Development 2014).

Oculus VR founder Palmer Luckey says there has been more content created for VR in the last year, than the last 20 years combined (Oculus Rift Development Kit 2 2014). Oculus Rift has integrated support for Unity 4, Unreal Engine 4 and the Unreal Development Kit to make development and integration for the Oculus Rift as

simple as possible. Most virtual reality demos and support released so far have focused on first person games. These include games such as *Half-Life 2* (2004), *Team Fortress 2* (2007), *Hawken* (2012), *Garry's Mod* (2004) and *Surgeon Simulator 2013* (2013). There are games such as *Star Citizen* (2015) and *Minecraft* (2009) that are currently implementing Oculus Rift support. Joe Ludwig from Valve is interested in how third person games like *Batman: Arkham Asylum* (2009) and games that use pulled back three quarter views like *Dota 2* (2013) can use head tracking in virtual reality (Ludwig 2013). A full list of supported games and demos is available at The Rift List (2013) and Rift Enabled (2013).

Despite this positive outlook, some developers, such as the team behind the upcoming game *Routine* (2015), have dropped support for the Oculus Rift temporarily as they are experiencing "motion sickness" whilst trying to integrate virtual reality functionality (Foster 2014). Lots of developers are getting on board with virtual reality, specifically support for the Oculus Rift as it has opened up new and exciting ways of interacting and engaging with gamers. However, as evidenced by the reaction of the developers of *Routine*, cybersickness remains an obstacle to longer term usage of these devices. This highlights the potential impact cybersickness can still have on the more general adoption of technologies such as the Oculus Rift. In the next few sections we review significant literature around cybersickness as previously identified in a systematic review (Davis, Nesbitt and Nalivaiko 2014).

4 Cybersickness

Cybersickness can present as a variety of unpleasant symptoms including nausea, stomach awareness/discomfort and sweating as well as disorientation, tiredness, postural instability, headaches, and eye strain (LaViola Jr. 2000). Interestingly there is still some debate over the underlying causes and symptoms associated with cybersickness. Strategies for designing environments are necessary to overcome the likelihood of problems (Kennedy et al. 1993).

Motion sickness, simulator sickness and cybersickness share similar symptoms although the conditions are caused by exposure to slightly different situations. Motion sickness is the unpleasant feeling, accompanied by nausea, dizziness and vomiting that may occur when people travel in moving vehicles. It is also referred to as sea sickness, air sickness and car sickness or more generally as travel sickness as it can be brought on by travelling in any type of moving vehicle including submarines, aircraft and trains. Motion sickness can also be induced on an amusement ride, a spinning chair or simply by using a swing at a playground. Astronauts can also experience a related form of motion sickness, called 'space adaptation syndrome' that occurs in exposure to zero-gravity conditions. Younger children, aged between 4-12 are more prone to motion sickness and indeed susceptibility to the condition in childhood has found to be a good indicator of susceptibility (Golding 1998).

Simulator sickness, as its name implies, was first found in pilots who underwent extended training in flight simulators. Typically these simulators map virtual

movements in the simulator to actual movements of the simulation platform. It is likely the perceived discrepancies between the simulator's motion and that of the virtual vehicle that lead to the condition. This cause differs from the conditions that tend to induce motion sickness. Apathy, sleepiness, disorientation, fatigue, vomiting and general discomfort are typical of the symptoms trainees may experience. These symptoms can reduce the effectiveness of simulators for training and result in decreased simulator use, or the adoption of inappropriate coping mechanisms during training. Furthermore post-training effects can impact on individuals, with effects such as drowsiness or postural instability occurring immediately after training or even many hours later. Compared to motion sickness, simulator sickness tends to be less severe and occurs less frequently. Interestingly studies have found a correlation between the appearance of symptoms and the flight experience of the pilot, with more experienced pilots more likely to develop symptoms (Johnson 2005).

Cybersickness is another subset of motion sickness experienced by users of virtual reality where they appear to be moving in the virtual scene while actually remaining stationary. This stationary reality and the associated compelling experience of self-motion, also calledvection, is believed to underlie the condition. This is in contrast to simulator sickness that is caused by small discrepancies between the user's normal, expected motion and the actual simulator motion. The typical symptoms of cybersickness include nausea, eye strain and dizziness. Stanney et al. (1997) found that cybersickness is three times the severity of simulator sickness. While there are definite relationships between the symptoms experienced in motion sickness, simulator sickness and cybersickness provoke slightly different clusters of symptoms that can be used to differentiate the three conditions (see Table 3) (Kennedy et al. 1993).

In one of the largest studies of simulator sickness, Kennedy et al. (1993) analysed available data from 10 United States Navy flight simulators Using 1,119 pairs of pre-exposure and post-exposure scores from self-reported data on motion sickness symptoms reported by United States Navy personnel. This data was collected using a traditional Pensacola Motion Sickness Survey (Kellogg, Kennedy and Graybiel 1964).

Disorientation Cluster	Nausea Cluster	Oculomotor Cluster
Dizziness Vertigo	Stomach awareness Increased salivation Burping	Eyestrain Difficulty focusing Blurred vision Headache

Table 3: Symptom Clusters

Kennedy et al. (1993) used a series of factor analyses to identify a list of 27 symptoms that were commonly experienced by users. Removing symptoms that had a low rate of occurrence, such as vomiting and symptoms that could contribute ambiguous data, such as boredom Kennedy et al. (1993) developed and validated a new Simulator Sickness Questionnaire that included 16 symptoms. These 16 symptoms were found to cluster into three categories, oculomotor, disorientation and nausea.

The oculomotor cluster included eyestrain, difficulty focusing, blurred vision and headache. The disorientation cluster symptom included dizziness and vertigo. The nausea cluster included stomach awareness, increased salivation and burping.

While the three symptom categories are not orthogonal to one another, they can provide differential information about participants' experience of symptoms and are useful for determining the particular pattern of discomfort produced by a given simulator.

5 Causes and factors

The actual cause of cybersickness is not known and the underlying physiological responses uncertain. The three most prominent theories for the cause of cybersickness are poison theory, postural instability theory and sensory conflict theory (LaViola Jr. 2000).

Poison theory suggests an evolutionary survival mechanism comes in to play when the user experiences sensory hallucinations consistent with ingesting some type of poison (Bouchard, Robillard, Renaud and Bernier 2011). Vomiting and nausea is thus designed to eject any remaining toxic substances in the stomach. However this explanation fails to explain the broader spread of symptoms and varied individual responses and currently there is only limited evidence for this theory (Money 1990). It is suggested that the pattern of stimuli visual and/or vestibular stimuli that trigger motion sickness, accidentally activate brain sensors for detecting toxins (Treisman 1997).

The postural instability theory is based on the idea that the main goal of humans is to maintain postural stability in the environment (Riccio and Stoffregen 1991). Therefore prolonged postural instability results in cybersickness symptoms (LaViola Jr. 2000) and the longer the instability, the more severe the symptoms are likely to be. The suggestion is that whenever the environment changes in an abrupt or significant way, and where postural control strategies have not been learnt the result is postural instability. In many virtual environments visual changes that are unrelated to the normal constraints on body motion lead to a conflict in normal postural control strategies resulting in the symptoms experienced in cybersickness.

However, the most longstanding and popular explanation for cybersickness is known as sensory conflict theory (Cobb, Nichols, Ramsey and Wilson 1999, Kolasinski 1995, LaViola Jr. 2000). This theory describes the conflicts of two key sensory systems engaged in virtual environments namely the visual and vestibular senses (Kolasinski 1995). They provide information about an individual's orientation and perceived motion and it is the mismatch of these senses that can frequently occur in virtual worlds. For example, the vestibular system may be telling the individual that their body is stationary while the visual system is telling them that their body is moving, causing a sensory mismatch (Howarth and Costello 1997). For example, in a driving simulator the user senses the optical flow patterns of the road, buildings, and other parts of the environment as they move in their peripheral vision and this creates the sense of motion. However, the vestibular sense fails to

provide a proportional sense of linear or angular motion and this is in conflict to normal expectations where comparative head movements are registered by both the visual and vestibular senses.

Unfortunately, like the other theories, the sensory conflict theory lacks predictive power in determining how severe the symptoms of cybersickness will be relative to any virtual experience. Furthermore, the theories still fail to explain why, given identical virtual experiences some individuals get sick and others do not.

While the underlying mechanisms that cause cybersickness are still not completely understood there has been more success in identifying some of the many factors known to impact on the likelihood of users developing symptoms. These factors include, individual, device and task differences.

The individual factors include age, gender, race, illness and positioning. Children in the 2-12 age range have the greatest susceptibility to cybersickness and this rapidly decreases from the ages of 12 to 21 and beyond (Kolasinski 1995). Thus older people are less susceptible to symptoms. In regards to gender, women have a wider field of view which increases the likelihood of flicker perception and this in turn increases their susceptibility to cybersickness (LaViola Jr. 2000). Research has also shown that female hormones can affect susceptibility (Kolasinski 1995). For all users, any underlying illness increases an individual's susceptibility to cybersickness. These physical conditions include but are not limited to fatigue, hangovers and the flu (LaViola Jr. 2000). The posture of the individual, possibly related to the postural instability theory, is also important. For example, sitting is a safer posture for users, than standing as this reduces any demand on postural control (Kolasinski 1995).

These individual factors might provide a further barrier to commercialization of virtual reality as there needs to be consideration for a wide range of participants. Furthermore, particular users with health problems or under the influence of drugs and alcohol may have higher susceptibility to cybersickness symptoms (Kruk 1992). This will have implications for how the technology is used and developers should be aware of the variety of conditions under which the technology will function.

The main device factors that technology suppliers need to be aware of include lag, flicker, calibration, field of view and general ergonomics. Lag occurs when there is a delay between an individual's action and the system's reaction; this can contribute to cybersickness symptoms (LaViola Jr. 2000). In terms of lag, efficient tracking of movements that reflect changes of view are critical, as are real time graphical displays that operate at around 50-60Hz. Any errors in tracking can likewise impact on cybersickness. Display flicker, the perception of which differs between individuals is not only distracting but it also causes eye fatigue (Kolasinski 1995). Flicker fusion is an important property of the device and is even more critical for wider fields of view as peripheral vision is more sensitive to flicker (LaViola Jr. 2000). Poor calibration increases cybersickness symptoms due to differences in physical characteristics of humans. For example, interpupillary distance, which is the distance

between the centres of the pupils of both eyes, varies between humans (Kolasinski 1995). As stereoscopic displays requires each eye to receive a slightly offset view of the virtual world this offset needs to correspond as closely as possible to the users own specific interpupillary distance. As such appropriate calibration is required for each individual. Another factor that needs to be considered is general ergonomics. For example, heavy and poor fitting headsets can cause physical discomfort and restricted movement from cables can cause further distractions from the virtual experience (McCauley and Sharkey 1992). McCauley and Sharkey (1992) discuss the effects of poor engineering practices. They further suggest that calibration, head tracking and transport delays may all have a direct impact on the incidence of cybersickness. When referring to calibration the authors feel that correct size, accurate focus and correct alignment will assist in the management of cybersickness. Thus an awareness of these device-related factors are essential in designing commercial virtual technology.

Cybersickness can also be influenced by the specific task the user is performing in the environment. The main task factors include the level of control the user has and the duration of the task. Participants who have good control in a virtual environment can better predict future motion and are found to be less susceptible to cybersickness. Those with no control over the virtual environment lack the same level of predictability about the environment and are thus more prone to cybersickness symptoms (Kolasinski 1995). A similar situation occurs in motion sickness as the passenger of a vehicle is more likely to experience car sickness than the driver. This is because the driver is in control and able to predict motion. Longer exposure times to virtual reality also result in increased episodes of cybersickness and symptom severity, requiring longer adaptation periods. Using brief exposures to virtual environments is one way to improve the speed of adaptation (Kolasinski 1995, McCauley and Sharkey 1992). Therefore task duration is another consideration when designing virtual tasks.

6 Subjective Measures

Previous research has shown that participants experience subjective sensations when subjected to virtual environments (Kennedy et al. 1993). Earlier research has focused on the use of questionnaires as a means of determining participants experience and susceptibility (Cobb et al. 1999, Kennedy et al. 1993; Kim, Kim, Kim, Ko and Kim 2005).

The survey known as the Pensacola Motion Sickness Questionnaire (Kellogg et al. 1964) based on 27 previously identified issues (Hardacre and Kennedy 1963) is recognized as one of the earliest subjective measures designed for assessing motion sickness (Bouchard et al. 2011). This work led to the development of the Pensacola Diagnostic Index (Graybiel, Wood, Miller and Cramer 1968). This is still the most widely used measure in motion sickness studies (Gianaros, Muth, Mordkoff, Levine and Stern 2001). The Pensacola Diagnostic Index score is calculated by summing an individual's ratings on various scales related to the

symptoms of dizziness, headache, warmth, sweating, drowsiness, salivation and nausea.

As simulation technology developed the Pensacola Motion Sickness Questionnaire was modified several times. This was driven by particular interest from the military, marine, and aviation industries. Pre and post questionnaires provided a baseline to determine symptoms experienced by participants during simulation. After a major study analysing the factors relevant to simulator sickness an alternative 16-item Simulator Sickness Questionnaire was developed (Kennedy et al., 1992; Lane and Kennedy, 1993). While correlated with the previous Motion Sickness Survey this new survey also allowed the identification of multivariate measures related to oculomotor effects, disorientation and nausea. This survey has been previously discussed in more detail in section 4.

Another widely used survey instrument is the Nausea Profile (Muth, Stern, Thayer and Koch 1996). It was designed for medical use to try and capture in more detail from patients their complex experiences associated with nausea. The Nausea Profile questionnaire uses a 10 point ranking, from not at all to severely, to rank 17 items. These items relate to how much an individual feels shaky, upset, lightheaded, sick, sweaty, queasy, worried, hopeless, tired, panicked, nervous, scared, ill, aware of their stomach, a need to vomit, weak and warm. These symptoms relate to three subscales related to somatic distress, gastro-intestinal distress and emotional distress (see Table 4).

Somatic distress	Gastrointestinal distress	Emotional distress
Fatigue	Sick	Nervous
Weak	Stomach awareness	Scared
Hot	Might vomit	Worry
Sweaty	Ill	Upset
Lightheaded	Queasy	Panic
Shakiness		Hopelessness

Table 4: Subscales in Nausea Profile (Muth et al. 1996)

Like Kennedy's Simulator Sickness Questionnaire, the Nausea Profile is distinguished from approaches such as the Pensacola Diagnostic Index in that it examines symptoms along multiple dimensions. This is in contrast to other univariate questionnaires that try to measure the experience along a single dimension from not at all to severe. Another multivariate questionnaire was developed to measure the symptoms associated with the subscales of gastrointestinal, central, peripheral, and sopite-related symptoms (Gianaros et al. 2001). Scores from this Motion Sickness Assessment questionnaire were found to correlate with both the Pensacola Diagnostic Index and the Nausea Index. Importantly it introduces a further dimension of motion sickness related to what is known as the 'sopite syndrome' (Lawson and Mead 1998). Sopite symptoms include drowsiness, yawning, disengagement and negative affect (Lawson and Mead 1998).

One potential problem with these more general survey approaches is that they have not been designed to study adverse effects, associated with viewing particular virtual environments. The Virtual Reality Symptom

Questionnaire (Ames, Wolffsohn and McBrien 2005) was developed specifically for investigating symptoms that result from virtual reality viewing using technology such as head-mounted displays. Ames et al. (2005) determined a list of the most frequently reported symptoms following virtual reality viewing by examined previously published studies. From a list of 47 previously used symptom questions, a pilot questionnaire consisting of 12 non-ocular and 11 ocular related questions was devised. In testing only 13 of these questions were found to be reported in more than 20% of participants (see Table 5). Even though this questionnaire was developed more specifically for use with virtual reality and was tested on head-mounted displays it lacks the validation of other approaches and so far has not been as widely adopted (Bouchard et al. 2011).

Nonocular Symptoms	Ocular Symptoms
Fatigue	Tired eyes
Drowsiness	Eyestrain
General discomfort	Vision discomfort
Headache	Difficulty focusing
Difficulty concentrating	Blurred vision
Dizziness	Sore/aching eyes
Boredom	

Table 5: Range of Symptoms reported in at least 20% of participants using Virtual Reality Symptom Questionnaire (Ames et al. 2005). Symptoms ranked in order of occurrence.

While these other survey approaches allow rating of symptoms in terms of susceptibility to motion sickness, Reason and Brand's susceptibility survey (1975) is the most widely used and validated approach (Golding 1998). This was updated in 1998 to simplify the rating and scoring mechanisms (Golding 1998). This newer validated questionnaire captures the individual's travel experiences and their relation to any nausea or vomiting. It records experiences both prior to the age of 12 and in the individual's previous 10 years in a variety of vehicles such as cars, buses, trains, aircraft, boats as well as fairground and playground rides. A susceptibility rating is calculated on the basis of quantified Likert rankings regarding the severity of experiences and the frequency of occurrences.

7 Objective Measures

The most simple and commonly used instrument for studying motion sickness in humans is subjective rating of nausea and other accompanying signs by questionnaires described in the previous section. There has also been some early work reported in using physiological measures to predict motion sickness (Graybiel and Lackner 1980, Lawson, Sunahara and Lackner 1991, Cowings, Naifeh and Toscano 1990, Stern, Koch, Stewart and Linblad 1987) although correlations with measures such as heart rate, peripheral blood flow and gastric activity were found to vary considerably between individuals.

Where questionnaires are of limited value for gaining insights into the neural mechanisms of motion sickness, physiological changes that accompany motion sickness provide more promise and hence have continued to be studied. The key physiological changes include sweating,

alterations in gastric myoelectric activity and in cardiac vagal tone, increase in the delta-power of the EEG and rise of plasma vasopressin (Stern, Koch and Andrews 2011). It is less known but well documented that motion sickness causes disturbances in thermoregulation (Nalivaiko, Rudd and So 2014) that manifest as dilatation in the cutaneous vascular bed and reduction in thermogenesis; it is quite likely that "cold sweating" is a part of this thermoregulatory response. Provocations used in most of these studies were either vestibular (swings or cyclical linear motion) or visual (optokinetic drum).

While subjective signs of cybersickness were initially reported more than two decades ago (Regan and Price 1994), very few studies documented objective symptoms that are associated with this condition. An excellent work addressing this issue was published by Kim et al. in 2005. The authors collected 16 electrophysiological parameters while their subjects were navigating the virtual environment. During this provocation, some parameters increased (gastric tachyarrhythmias, eye blink rate, skin conductance, respiratory sinus arrhythmia and delta-power of the EEG) while other decreased (heart period, fingertip temperature and photoplethysmographic signal, and EEG beta-power). Of those changes, several (gastric tachyarrhythmias, eye blink rate, respiration rate, respiratory sinus arrhythmia and heart rate) had significant positive correlation with the subjective score of cybersickness. In another study Ohyama, Nishiike, Watanabe, Matsuoka, Akizuki, Takeda and Harada (2007) found that VR immersion results in an increase of the low-frequency but not high-frequency components of the heart rate variability; in conjunction with the previously mentioned work, this may indicate that cybersickness is associated with an increase of the cardiac sympathetic outflow.

Two studies reported that virtual reality causes mild and short-lasting (<10 minute) changes in the static postural stability measured by the body sway amplitude (Cobb and Nichols 1998, Cobb 1999). Dynamic postural stability was not affected in these experiments. While postural stability in both studies was measured just before and just after the provocation. Unlike the studies mentioned above, Akiduki, Nishiike, Watanabe, Matsuoka, Kubo and Takeda (2003) performed stability tests during the provocation. Interestingly, they found significant differences only in the data collected immediately after the VR immersion.

It thus appears that overall objective signs of cybersickness resemble those of other types of motion sickness; it is however not known whether subtle differences exist, similar to differences in symptoms between motion sickness and simulator sickness that could be revealed by questionnaires. It is also not known whether and how cybersickness affects thermoregulation. The dilatation of cutaneous vessel during provocative motion has been confirmed in experimental animals (Ngampraman, Cerri, Del Vecchio, Corrigan, Kamphee, Dragic, Rudd, Romanovsky and Nalivaiko 2014) and thus appears to be a cross-species real-time marker of motion sickness (Nalivaiko et al. 2014).

While physiological measures provide more detailed and precise data about the experience of cybersickness,

the equipment can be intrusive in itself. This may be a problem when virtual environments attempt to suspend the user's disbelief in their current reality. There are other trade-offs to consider as the subjective questionnaires with a long history of use and validation have been well evaluated and shown to be reliable. In contrast physiological measures are more expensive to perform and the results are more complex to analyse. Further discussion on some of the limitations of the various subjective and objective methods is available in a previous review (Davis et al. 2014).

8 Preliminary Study

Based on measured disturbances in thermoregulation experienced by animals when motion sickness is induced (Nalivaiko et al. 2014) we would like to study physiological measures such as skin temperature for their potential to objectively measure the severity of cybersickness. However, to perform these studies we need to provide a virtual experience that reliably induces the nausea symptoms associated with cybersickness. In this preliminary study we use the Oculus Rift DK1 and compared two virtual roller coaster experiences developed for this platform, the Parrot Coaster (Murray 2013) (See Figure 1) and the Helix Coaster (*Helix – The NEXT Level* 2014) (see Figure 2).

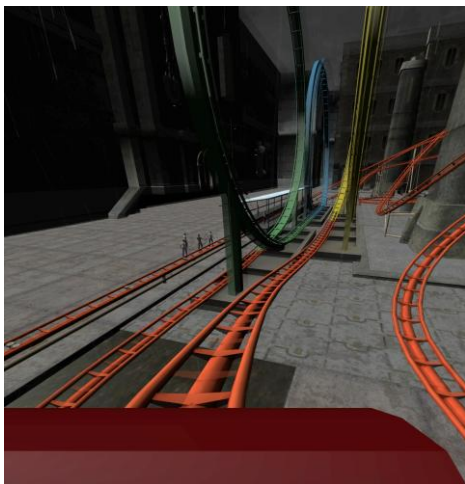


Figure 1: Roller coaster experience – Parrot Coaster (Murray 2013)

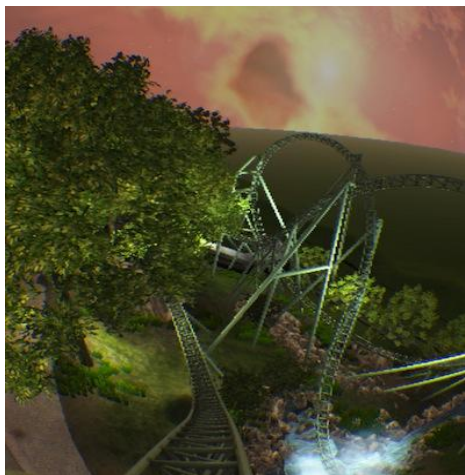


Figure 2: Roller coaster experience – Helix Coaster (*Helix – The NEXT Level* 2014)

8.1 Method

Twenty four subjects, 19 male and 5 female, within the ages of 18-30 were recruited for the study and randomly divided into two groups. The first group (9 males, 3 females) experienced the Parrot Coaster (Murray 2013) and the second group (10 males, 2 females) experienced the Helix Coaster (*Helix – The NEXT Level* 2014). The study was approved by The University of Newcastle Human Research Ethics Committee. Participants were required to have normal or corrected to normal vision and normal vestibular function. Participants were excluded if they were suffering from acute symptoms of cold or flu, pregnancy, or acute eye or ear infection. Participants who might experience vertigo, claustrophobia or conditions, such as epilepsy were also excluded.

Participants were fitted with the Oculus Rift DK1 and asked to rate their nausea level on a subjective scale between “0–no nausea/discomfort” to “10–very nauseous (feeling like vomiting)”. They were informed that the simulated roller coaster experience would last for up to 14 minutes and that they would be asked to rank their nausea every 2 minutes. Participants could choose to stop the experience and remove the Oculus Rift DK1 at any point they felt too nauseous to continue. At completion of the roller coaster experience, the Oculus Rift DK1 was removed and the completion time recorded.

8.2 Results

Of the 12 participants on the Parrot coaster, eight reported mild nausea (subjective rating 1-3), two experienced a moderate level of nausea (subjective rating 4-6) and two reported high levels of nausea (subjective rating 7-10) (see Table 6). This compares with the Helix coaster where no participants reported only mild nausea (subjective rating 1-3), seven experienced a moderate level of nausea (subjective rating 4-6) and five reported high levels of nausea (subjective rating 7-10) (See Table 7). Two of the 12 (17%) participants failed to complete the Parrot coaster as they felt the nausea experience was too great to continue. This compares with the Helix coaster where eight (66%) of the participants were unable to complete the ride.

We compared the average ride time in minutes for participants on both coasters using an independent samples t-test. Assuming equal variance the average ride time was significantly different for Parrot coaster ($M=12.7$, $SD=3.1$) and Helix coaster ($M=8.1$, $SD=4.7$) conditions; $t(22)=2.77$, $p^* = 0.011$.

We also aggregated the 7 subjective ratings from each of the 12 participants ($n=84$) under both coaster conditions. Where participants had to stop before completing the 14 minutes they would have less than 7 ratings and in these cases we used their final subjective rating for the ratings during their unriden time. This is likely a low approximation of their nausea rating which we would expect to increase if they had stayed on the ride. We compared the average nausea rating for participants on both coasters using an independent samples t-test. There was a significant difference in the subjective nausea rating for the Parrot coaster ($M=2.9$,

SD=2.5) and Helix Coaster (M=4.9, SD=2.3) conditions; $t(166)=6.19$, $p^*=4.6E-09$.

n	Time (minutes)							Ride Time
	2	4	6	8	10	12	14	
12	0	0	1	0	1	1	1	14
10	0	1	1	1	1	1	1	14
1	0	1	2.5	2	2	3	2	14
2	0	1	1	2	4	2	2	14
7	0.5	0.5	2	0.5	0	2	3	14
3	0	0	1	1	2	2	3	14
11	1	1	1	2	2	3	3	14
5	2	1	1	1	2	2	3	14
6	2	2	3	3	3	3	4	14
8	1	2	4	4	6	7	7	14
9	5	6	7	10				7
4	1	4	6					5

Table 6: Participant’s subjective nausea ratings after every 2 minutes on the Parrot Coaster (n=12)

n	Time (minutes)							Ride Time
	2	4	6	8	10	12	14	
8	1	1	1	1.5	3	3	4	14
4	3	3	4	5	4	5	4	14
7	0	1	3	4	4	4	4.5	14
11	2	2	3	2	3	4	6	14
1	0	1	4.5	6				8
9	1	3	5	6				7
2	1.5	3	5	6.5				7
3	1	4	5	7				7
6	3	5	7					5
10	5.5	7						3
12	2	7						2.5
5	8							2

Table 7: Participant’s subjective nausea ratings after every 2 minutes on the Helix Coaster (n=12)

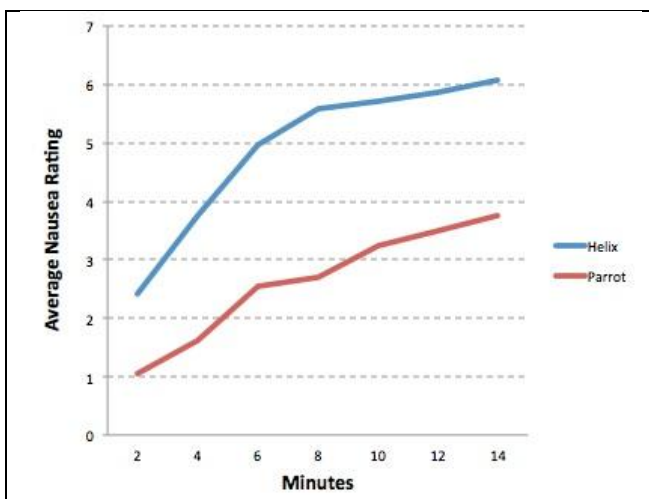


Figure 3: Average nausea ratings for participants in the alternative roller coasters

8.3 Discussion

We found significant differences between the two virtual roller coaster simulators in the extent of their nausea-provoking capacities. The latter was determined both with the time participants could spend in the experiences before developing nausea ($p^*=0.054$) and the average nausea rating ($p^*=0.000003$). In both cases the Helix roller coaster was more likely to induce nausea symptoms. Indeed only 2 (n=12) of the riders on the Parrot coaster were required to stop while 8 (n=12) of the

riders on the Helix requested to stop before the allotted 14 minutes of ride time. For our future studies where we are interested in provoking the fast onset of nausea the Helix coaster is clearly indicated as the best option to use in these studies.

We should note that the results of this study are not intended to identify cybersickness problems with the Oculus Rift specifically or VR technology in general. We deliberately choose the immersive head-mounted display and a provocative roller coaster experience in an effort to provide conditions that would invoke nausea. However, it is interesting to reflect on the design variations between the roller coaster demos and how they might be considered when designing experiences where it is desirable to minimise possible nausea effects. We identified three possible reasons for the differences between the two experiences, fidelity, optical flow and the level of interaction required of the participant.

The Helix roller coaster contains a much greater level of detail and realism than the more abstracted Parrot coaster. Fidelity or graphic realism has previous been highlighted as a factor that can increase simulator sickness (Kennedy, Hettinger and Lilienthal 1990).

In flight simulators flying close to the ground also causes higher incidence of simulator sickness than flying at higher altitudes. This is usually explained in terms of increased visual flow, due to fast changing detail experienced when flying at lower heights above terrain. (Johnson 2005). The level of detail, the placement of scenery in the Helix coaster, the track configuration as well as the higher velocity of this ride when compared to the Parrot coaster suggests a similar cause, that is higher levels of visual flow may be responsible for the increased nausea.

Increased head movements also increase susceptibility to simulator sickness (Kennedy, Fowlkes, Berbaum and Lilienthal 1992, Kolasinski 1995, McCauley and Sharkey 1992, Riccio and Stoffregen 1991). At the end of each loop of the Helix coaster participants have to move their head to the right and pause to restart the rollercoaster. This forced head movement doesn’t occur in the Parrot coaster rollercoaster as it loops continuously.

9 Conclusion

The unique nature of VR technology presents several issues for commercial development. The possibilities for this technology have expanded from training applications to consumer entertainment devices. Unfortunately cybersickness represents an ongoing obstacle for the widespread development and acceptance of VR especially for everyday use.

We believe that an important step in controlling for cybersickness effects is the development of a simple objective measures. Most existing measures either rely on self-reporting or more expensive and complex objective measuring systems. The development of objective measures for cybersickness is an important step in understanding the causes and effects it can have on participants as well as assisting attempts to improve the design of both the technologies involved and the environments being developed. As such there is a need to

develop cost-effective, objective measures for cybersickness as a more precise measurement will aid in all these aspects.

In this paper we reviewed previous work in cybersickness and also compared two virtual roller coaster versions. We found that, based on the time participants were able to remain riding and their average nausea ratings, one roller coaster (Helix) was significantly more likely to cause the onset of nausea symptoms. This suggests the rollercoaster with higher levels of graphic realism and providing greater levels of optical flow is an appropriate stimulus to use in our future studies where we wish to study physiological changes associated with the onset of cybersickness.

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