A Systematic Review of Cybersickness

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ABSTRACT
The uptake of new interface technologies, such as the Oculus Rift have generated renewed interest in virtual reality especially for private entertainment use. However, long standing issues with unwanted side effects, such as nausea from cybersickness, continue to impact on the general use of devices such as head mounted displays. This in turn has slowed the uptake of more immersive interfaces for computer gaming and indeed more serious applications in training and health. In this paper we report a systematic review in the area of cybersickness with a focus on measuring the diverse symptoms experienced. Indeed the related conditions of simulator sickness and motion sickness have previously been well studied and yet many of the issues are unresolved. Here we report on these issues along with a number of measures, both subjective and objective in nature, using either questionnaires or psychophysiological measures that have been used to study cybersickness. We also report on the factors, individual, device related and task dependent that impact on the condition. We conclude that there remains a need to develop more cost-effective and objective physiological measures of both the impact of cybersickness and a person's susceptibility to the condition.

Categories and Subject Descriptors
H.5.1 Multimedia Information Systems, Artificial, augmented, and virtual realities. H.5.2 User Interfaces, Ergonomics.

General Terms
Design, Human Factors.

Keywords
Cybersickness, simulator sickness, motion sickness, Oculus Rift.

1. INTRODUCTION
Virtual reality is an interactive, immersive and realistic, three dimensional computer simulated world [19,24]. This simulated world is often referred to as a virtual environment [19,24]. Virtual Reality is not a new concept, for example many of the ideas associated with virtual environments were described by Ivan Sutherland as part of his 'ultimate display' (1965). This review is motivated in part by reported issues, such as cybersickness, from one of the new head-mounted display technologies, the Oculus Rift [30]. However, Ivan Sutherland also created what is widely believed to be the first head mounted display in 1968 [38]. Nor is the use of virtual reality for entertainment very new. In 1960, the concept of a multi-sensory theatre was marketed by Morton Heilig. By 1962 this led to the development of a patented virtual reality arcade ride called the Sensorama Simulator. This arcade ride allowed users to ride a motorbike through New York and experience a 3D view with sound, wind, vibration and even aroma [11]. Despite these early beginnings virtual reality is still an emerging technology that is looking for its place as the 'ultimate display'.

Emphasis is sometimes placed on the systems or hardware used to enable virtual environments. High-end graphics computers, 3-D display systems, force feedback devices and systems for tracking body movement are some examples of hardware which often form a critical part of these systems. For applications such as gaming these newer technologies often provide a 'cool' factor. Arguably, however, this technology is not really motivated by new hardware but rather with providing a new style of human-computer interface, the primary goal of which is to significantly increase the communication bandwidth between human and computer.

Virtual environments construct the user interface as a synthetic world. In this computer-synthesized world the user can interact with objects and navigate the environment as if they were in the real world. Virtual environments promote a natural way of interacting with computers using the human body and all its senses. In Virtual environments people participate, perform tasks and experience activities within the computer-generated world. The idea is to immerse a person in an environment that allows natural interaction and participation in order to perform tasks. Thus virtual environments attempt to create a natural way of interacting with computers using the human body and all its senses. In Virtual environments users do not operate computer applications via an interface, rather people participate, they perform tasks and they experience activities within a computer-generated world. The intention is to both "suspend belief" in the person's own reality and "suspend disbelief" of the computer created reality.

There are various devices and technologies that allow a user to experience virtual reality. Such technologies include the Computer Automatic Virtual Environment or CAVE, a room covered in projected images that are viewed using stereoscopic glasses [7]. Relatively recent input devices, such as Nintendo's Wii remote and PlayStation's Move controllers allow users to physically interact in a virtual environment based on device position, rotation and movement. The Microsoft's Kinect allows a user to control or interact with virtual objects using their body [3]. The particular technology focused on in this research will be that of head mounted displays (HMD's) such as the Oculus Rift.

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It should be noted that the various diverse technologies associated with virtual reality bring together many disciplines (electronics, software engineering, computer graphics, human-computer interaction, electro-mechanics, optics and psychology) with this common objective of significantly improving the human computer interface.

Stereoscopic display is one specific technology that has often been a feature of virtual environments. This requires providing the left and right eye with slightly offset views of the generated world. This effect 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 providing small, dedicated monitors for each eye. The position and orientation of the user’s head is tracked and used to update the image from the correct perspective for the user’s viewpoint.

The Oculus Rift head mounted display features a gyroscope for tracking angular velocity, an accelerometer for tracking accelerations in all directions and a magnetometer for sensing magnetic fields [2]. 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 [3]. The Oculus Rift uses software to automatically correct drift from tilt and yaw errors that occur when using accelerometers, gyroscopes and magnetometers to calculate an individual’s head position [22,23].

While the various technologies have found niche applications, for example in military training, the uptake has been delayed both by costs associated with the hardware and software as well as various ergonomic and usability issues. In terms of interactive entertainment it is only recently that there has been a broader uptake of virtual reality technology in applications such as computer gaming and a corresponding desire to investigate the education and training benefits in broader domains [19,24].

Virtual reality is moving past private and localized industry and in to the commercial spotlight, this is arguably thanks to the Oculus Rift. Oculus VR [30], 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. Notable companies such as Facebook, Google, Sony and Samsung have since entered the race and are also in development of consumer grade virtual reality devices.

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). The DK2 is the latest version of the Oculus Rift and 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 1) [32].

Michael Abrash from Valve believes that consumer grade virtual reality devices will probably arrive in two years based on their own in house research and development, and their collaboration with Oculus VR. Michael also believes that the technology will evolve most rapidly on the PC platform and revolutionize the entire entertainment industry and has stated that Valve’s Steam platform will be offering full support [37].

Table 1. Oculus Rift Technical Specifications [2,32]

	Oculus Rift DK 1	Oculus Rift DK 2
Resolution	640x800 per eye	960x1080 per eye
Display	7” LCD at 60Hz	5.7” OLED at 75Hz, 72Hz, 60Hz
Low Persistence	No	Yes (2ms, 3ms, full)
Positional Tracking	No	Yes
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

Oculus VR founder Palmer Luckey says there has been more content created for VR in the last year, than the last 20 years combined [31]. 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, Team Fortress 2, Hawken, Garry’s Mod and Surgeon Simulator 2013. There are games such as Star Citizen and Minecraft that are currently implementing Oculus Rift support with a full list of supported games and demos available at The Rift List [39]. Joe Ludwig from Valve is interested in how third person games like Arkham Asylum and games that use pulled back ¾ views like Dota 2 can use head tracking in virtual reality [26].

Although some developers, such as the team behind the upcoming game Routine, are dropping support for the Oculus Rift temporarily as they are experiencing “motion sickness” whilst trying to integrate virtual reality functionality [34]. 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, cybersickness remains an obstacle to longer term usage of these devices.

2. CYBERSICKNESS

Cybersickness is a problem that has been inherent in virtual reality since its inception. Cybersickness can result in a range of symptoms including nausea, disorientation, headaches, sweating and eye strain [24]. Interestingly there is still some debate over the underlying causes and symptoms associated with cybersickness and strategies for designing environments to overcome the likelihood of problems [17]. 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 but different [17]. 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 [14].

In one study by Cobb, Nichols, Ramsey and Wilson (1999), 80% of participants experienced cybersickness within the first ten minutes of exposure to the virtual environment. This finding demonstrates that, at least in some virtual environments, cybersickness could be a widespread usability issue that could impact on both the broader adoption of the technology but also the continued improvement of the technology. For some applications, such as military training, the cost benefit tradeoffs may arguably outweigh ergonomic issues. However, for more everyday entertainment uses health and safety issues related to cybersickness have the potential to significantly retard the continued development of immersive, virtual reality interfaces.

Thus we believe that understanding the causes, and predicting a user's susceptibility, to cybersickness, especially with new technologies such as the Oculus Rift, is an essential step in removing possible barriers in the use of virtual environments. A more preliminary step is the need to develop reliable objective measures of the symptoms, such as nausea, that are associated with cybersickness. Previous studies of cybersickness have relied on subjective self-reporting of the severity of symptom conditions and methods to objectively quantify cybersickness symptoms still need to be developed. This motivation informs the broader aims of our research which is to develop a cost effective physiological measure that quantifies an individual's susceptibility to cybersickness and also to develop an objective measure of the intensity of the condition.

This paper reports on the first step of this project, whereby we performed a systematic review into the area of cybersickness. This review was intended to be exploratory in nature and thus the following set of research questions were devised for the review:

1. Is there a physiological measure to quantify an individual's susceptibility to cybersickness?
2. How is cybersickness currently detected and measured in virtual reality?
3. Is there a cost effective method of detecting cybersickness in virtual reality?
4. Has previous research utilizing the Oculus Rift been reported?

In the next section of this paper we describe the process we have used for the systematic review and then in subsequent sections we discuss the findings in relation to our overall research objectives, reviewing the multivariate range of symptoms associated with cybersickness, the factors that impact on it, the theories used to explain the phenomenon, previous types of measures and some general methodological considerations when evaluating the symptoms of cybersickness.

3. SYSTEMATIC REVIEW

The aim of this review is to investigate the feasibility of developing a cost-effective physiological measure that quantifies an individual's susceptibility to cybersickness. The review will also examine the possibility of developing an objective measure that can be used to quantify the intensity of the condition. Since we intend to use the Oculus Rift in further investigation the review also looked to see if there were existing studies on the Oculus Rift that report issues related to cybersickness. To begin a systematic review was designed (see Table 2) to gather information relevant to these issues we began with the broader search of 'virtual reality' and 'cybersickness. Key information technology databases were utilized to ensure we accessed the most current and relevant journal and conference papers (see Table 2).

An initial search of 'virtual reality' provided 1.98 million papers with a search of 'cybersickness' providing 1800 papers. A number of relevant journal articles focused on motion sickness, simulator sickness and cybersickness in a range of virtual environments and simulator environments. Clear distinctions had to be made to ensure appropriate search terms due to the difference in definition of cybersickness, simulator sickness and motion sickness. We wanted to reduce the scope of the search and since the most common theory for the cause of cybersickness is a sensory mismatch or conflict between the vestibular and visual senses [5,19,24], the term 'vestibular ocular' was included as a compulsory search term. Terms such as 'sound' and 'mobile' were excluded as they provided irrelevant journal articles (see Table 3). This refined the results by removing 1399 papers. The final systematic review used a refined boolean search string (see Table 4) that produced 171 papers.

Table 2. Search Sources and Parameters

Bibliography Databases	ACM Digital Library, Annual Reviews Journals, EBSCO Megafile Premier, Proquest, ScienceDirect, SCOPUS, SpringerLink
Search Engines	Google and Google Scholar
Article Type	Journal articles and conference papers
Search On	Title, keywords and abstract
Sorting On Returns	Relevance
Language	English
Publication Period	Unlimited

Table 3. Inclusion and Exclusion Criteria

Component 1 (Compulsory Includes)	'virtual reality', 'oculus rift', 'vestibular ocular'
Component 2 (Compulsory Includes)	'cybersickness', 'simulator sickness', 'motion sickness'
Component 3 (Optional Excludes)	-'sound', -'education', -'training', 'acrophobia', -'mobile', -navigation

Table 4. Boolean Search String

("cybersickness" OR "oculus rift") AND ("virtual reality") OR ("vestibular ocular") -sound -training -acrophobia -education -mobile -navigation

4. SYMPTOMS OF CYBERSICKNESS

Motion sickness, simulator sickness and cybersickness share similar symptoms but 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 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 to cybersickness [9].

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 is atypical of 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 occur 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 [14].

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 called vection, 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 different clusters of symptoms can also be found to differentiate the three conditions (see Table 5) [17].

Table 5. Symptom Clusters

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

In one of the largest studies of simulator sickness, Kennedy et al. (1993) analyzed 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 [15].

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 accessed sixteen symptoms (see Table 6). When using the survey each item is rated with the scale of none, slight, moderate or severe. 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.

The Simulator Sickness Questionnaire is a widely applied measurement tool in research studying simulator sickness and cybersickness and has become something of a standard for accessing virtual reality related sickness. Through some calculations, four representative subscores can be found: a Nausea-related subscore (N), an Oculomotor-related subscore (O), a Disorientation-related subscore (D) and the Total Score (TS) representing the overall severity of cybersickness experienced by the users of virtual reality systems.

Table 6. The 16 items of the Simulator Sickness Questionnaire

1. General discomfort	9. Difficulty
2. Fatigue	10. Fullness
3. Headache	11. Blurred vision
4. Eye strain	12. Dizziness with eyes open
5. Difficulty	13. Dizziness with eyes closed
6. Salivation	14. Vertigo
7. Sweating	15. Stomach awareness
8. Nausea	16. Burping

The Simulator Sickness Questionnaire provides straightforward computer or manual scoring, is better able to identify "problem" simulators, and offers an improved diagnostic capability when compared to the original Motions Sickness Survey. The Total Severity score is a composite created from the three subscales. It is the best single measure because it provides an index of the overall symptoms. The three subscales provide diagnostic information about particular symptom categories:

- Nausea subscale is made up of symptoms such as increased salivation, sweating, nausea, stomach awareness, and burping.
- Oculomotor subscale includes symptoms such as fatigue, headache, eyestrain, and difficulty focusing.
- Disorientation subscale is composed of symptoms such as vertigo, dizzy (eyes open), dizzy (eyes closed), and blurred vision.

The three subscales are not orthogonal to one another. There is a general factor common to all of them. Nonetheless, the subscales provide differential information about participants' experience of symptoms and are useful for determining the particular pattern of discomfort produced by a given simulator. All scores have as their lowest level a natural zero (no symptoms) and increase with increasing symptoms reported.

By grouping similar symptoms in to categories, the results provide information about the different processes in the human body affected by motion sickness, simulator sickness and cybersickness. While there are distinctions to be made between the three conditions, an understanding of motion sickness and simulator sickness is required to develop further knowledge of cybersickness and its symptoms. The similarities will also allow existing methods and subjective measurement tools to be reused in this research.

Stanney, Kennedy and Drexler (1997) found that while cybersickness and simulator sickness share similar symptomology, they differed in severity resulting in two separate conditions. The major distinguishing feature for cybersickness is disorientation while the definitive symptoms for simulator sickness are oculomotor in nature [36].

5. THEORIES OF CYBERSICKNESS

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 [24].

Poison theory suggests an evolutionary survival mechanism comes in to play when the user experiences sensory hallucinations consistent with ingesting some type of poison [4]. 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 [28].

The postural instability theory is based on the idea that the main goal of humans is to maintain postural stability in the environment [33]. Therefore prolonged postural instability results in cybersickness symptoms [24] 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 [5,19,24]. This theory describes the conflicts of two key sensory systems engaged in virtual environments namely the visual and vestibular senses [19]. 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 [13]. 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.

6. FACTORS OF CYBERSICKNESS

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 (see Table 7).

The Individual factors include age, gender, 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 [19]. 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 [24]. Research has also shown that female hormones can affect susceptibility [19]. 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 [24]. 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 [19].

Table 7. Factors Effecting Virtual Reality Experience

Individual Factors	Device Factors	Task Factors
Age	Lag	Control
Gender	Flicker	Duration
Illness	Calibration	
Posture	Ergonomics	

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 [20]. 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 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 [24]. 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 [19]. 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 [24]. Poor calibration increases cybersickness symptoms due to differences in physical characteristics of humans. For example, interpupillary distance, which is the distance between the centers of the pupils of both eyes, varies between humans [19]. 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 [27]. 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 [19]. A similar situation occurs in motion sickness as the passenger of a vehicle is more likely to experiences 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 [19,27]. Therefore the duration of a task is another important consideration for the virtual task.

7. MEASURES OF CYBERSICKNESS

Previous research has shown that participants experience a physical response when subject to virtual environments [17]. Earlier research has focused on the use of questionnaires as a means of determining participants experience and susceptibility [5,17,18]. As we have indicated this research is motivated to develop a more objective physiological measure of cybersickness, both as a quantitative indicator of severity and as an indicator of an individual's susceptibility to the condition. In this section we look at previous approaches, both subjective and objective, that have been used to measure cybersickness, simulator sickness and motion sickness.

7.1 Subjective Measures

The survey known as the Pensacola Motion Sickness Questionnaire [15] based on 27 previously identified issues [12] is recognized as one of the earliest subjective measures designed for assessing motion sickness [4]. Indeed this work led to the development of the Pensacola Diagnostic Index [10]. This is still the most widely used measure in motion sickness studies [8]. 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.

Over time the development of simulation technology and driven by particular interest from the military, marine, and aviation industries the Pensacola Motion Sickness Questionnaire was modified several times. Pre and post questionnaires provided a baseline to determine symptoms experienced by participants during simulation. After a major study analyzing the factors relevant to simulator sickness an alternative 16-item Simulator Sickness Questionnaire was developed [16,21]. 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 [29]. 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 8).

Table 8. Subscales in Nausea Profile [29]

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

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 [8]. 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' [25]. The sopite symptoms include drowsiness, yawning, disengagement and negative affect [25].

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 [1] 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 9). 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 [38].

Table 9. Range of Symptoms reported in at least 20% of participants using Virtual Reality Symptom Questionnaire [1]. Symptoms ranked in order of occurrence.

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	

While these other survey approaches allow rating of symptoms in terms of susceptibility to motion sickness, Research and Brand's susceptibility survey (1975) is the most widely used and validated approach [9]. This was updated in 1998 to simplify the rating and scoring mechanisms [9]. 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.

Self-reporting has the advantage of being able to capture the wide range of symptoms experienced with cybersickness. However, it is difficult to compare the various quantitative scales developed and individuals may tend to rank items differently based on their own perceptions of the severity of their symptoms. There is also this inherent issue of subjectivity; when subjects report on their general wellness and previous experiences with motion sickness. In section 8 we return to look at some of the methodological issues that have been reported with previous studies of cybersickness. However, first we examine more objective approaches that have been used to measure and understand the symptoms associated with cybersickness.

7.2 Objective Measures

It might be suggested that to provide a more precise tool for measuring cybersickness it would be good to develop some simple physiological measures of the condition. There are early reports of psychophysiological measures being developed for cybersickness [6], however the underlying physiology symptoms related to cybersickness are not simple and the complication of performing psychophysiological measures in virtual reality are difficult.

One study that used real time physiological data involved nine experiments using participants wearing head-mounted displays [5]. Data measurements were focused on symptoms experienced during the test and any immediate after effects. A total of 148 individuals participated in the study using a variety of virtual environments, tasks and devices. The recording of continuous physiological monitoring allowed for accurate, real time information about participants experience. Results were generalized and varied however indicated that cybersickness is an inherent problem in the technology with 80% of participants experiencing symptoms of cybersickness.

More recent studies have utilized physiological measures for detecting cybersickness such as heart rate, blink rate, electroencephalography and stomach upset [18].

Another example of objective analysis for determining cybersickness symptoms is the work by Kim (2005). In this study participants were exposed to virtual environments to investigate physiological changes. Testing used 61 participants who were in a virtual environment for 9.5 minutes. They were tasked with finding certain items within the environment. The researchers utilized pre and post questionnaires for data collection. During the test data was collected on heart rate, blink rate, electroencephalography (EEG) and stomach upset. Their results concluded that a physiological change occurred when participants experienced cybersickness. These symptoms were measurable by a change in heart rate, blink rate, EEG and stomach upset.

A study by So, Ho and Lo (2001) examined a novel objective way in which cybersickness might be measured utilizing spatial velocity as a proxy measure for predicting whether an individual may experience cybersickness. Two cybersickness experiments were used to measure the relationship between various spatial velocity calculations and symptoms of cybersickness. Spatial velocity was increased either by increasing scene complexity or scene velocity. Both changes resulted in a higher incidence of cybersickness. Therefore suggesting that the use of spatial velocity may provide an objective alternative to self-reporting questionnaires for providing information about cybersickness incidence.

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 users disbelief in their current reality. There are other tradeoffs 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. In the next section we look more closely at some of the methodological issues that have been reported in previous studies of cybersickness.

8. METHODS USED

There are a number of key issues that need to be considered when designing evaluations of cybersickness measures. Self-reporting questionnaires are useful for providing a snapshot of participant experience but are prone to problems, intentional or not, of misreporting. Furthermore they do not provide for uninterrupted real time monitoring information while the participant is in the virtual environment.

The use of pre and post questionnaires can provide data about a participant's wellbeing both before and after the experience. However, these approaches do rely upon the participant's ability to recognise and report changes. Indeed, self-reporting has some inherent subjectivity issues when used to assess both the wellness of the individual, their previous experiences and their current condition. However, it is also a useful way to capture some of the subtle differences in symptoms that can occur in different types of virtual environments and has a long history of usage.

Self-reporting was a large part of data collection within the Stanney et al., (1997) study. The study also uses two different sample participants, military aviators for simulators and university students for virtual environments. However civilian university students may not have had previous virtual environment experience, thus making the university students more self-aware of their symptoms. Both individual differences in experience and the specifics of different types of the platform and tasks can all impact on symptoms being reported. Military aviators were mostly male and due to the nature of their job have previous experience with simulators. Furthermore they are trained to cope with motion sickness. The university part of the study recruited an even spread of male and female participants and again gender is known to impact on symptoms of cybersickness. Disregarding female participants within the study and simply comparing civilian male university students to military male aviators can create unnecessary variability within the data. Thus it is important in any study of cybersickness that a broad population is recruited. It is important to ensure a general age and experience level for studies of virtual environment experience.

Sample size is thus also an important consideration. To enhance data results Kim (2005) utilized a large sample size, a total of 61 participants. Three pre-test questionnaires were used to gain a baseline and each participant provided a pre-immersion rating of themselves. This allowed for more concise representation of participants perceived change in symptomology. Additionally participants also had a time out period before the test that included 10 minutes for instrument correction and five minutes of adjustment to a static virtual environment. Ensuring equipment was correctly calibrated guaranteed accurate data collection. Allowing participants to become familiar with the equipment reduced unnecessary anxiety that could affect results.

Another characteristic problem with previous studies is the self-selection of participants [27]. Due to interest level and the potentially dangerous effects of simulator sickness, many simulator sickness studies focus on military members with previous simulator experience such as aviators [17]. The nature of these jobs and its necessary training requires members to have high tolerance for motion sickness. This means that specific participants have self-selected in to these roles. Anyone experiencing sickness within the simulators might also be excluded from pursuing such a career, and might even attempt to hide any motion-related symptoms.

Ensuring accuracy of objective testing mechanisms is an important step in developing new measurement systems. The use of an objective physiological measure would provide real time, accurate data about the process of cybersickness. To test effectiveness of their tool So, Ho and Lo (2001) used previous experiments focusing on cybersickness. These experiments were re-evaluated through the spatial velocity metric and found to indicate that an increase in spatial velocity resulted in increased likelihood of cybersickness [35]. However, to validate against previous results the study once relied on elements of self-reporting to check the accuracy of their tool.

An evaluation of costs versus necessity may also be required as monitoring equipment for physiological measures can be expensive. One other potential problem with physiological measures is the tendency to collect a vast amount of data that it is hard to analyze, especially as wide differences can occur in individuals [5]. Another recognized limitation of current studies is the focus on short-term results and the inability to measure long-term effects of cybersickness [5].

9. CONCLUSION

The unique nature of virtual environment technology presents several issues for any 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 virtual reality technology.

The importance of appropriately identifying cybersickness is demonstrated through the developments currently being experienced by new virtual reality technology such as the Oculus Rift. 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 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.

10. REFERENCES

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