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ORIGINAL ARTICLE

Review on cybersickness in applications and visual displays

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Abstract Cybersickness is an affliction common to users of virtual environments. Similar in symptoms to motion sickness, cybersickness can result in nausea, headaches, and dizziness. With these systems becoming readily available to the general public, reports of cybersickness have increased and there is a growing concern about the safety of these systems. This review presents the current state of research methods, theories, and known aspects associated with cybersickness. Current measurements of incidence of cybersickness are questionnaires, postural sway, and physiological state. Varying effects due to display and rendering modes, such as visual display type and stereoscopic or monoscopic rendering, are compared. The known and suspected application aspects that induce cybersickness are discussed. There are numerous potential contributing application design aspects, many of which have had limited study, but field of view and navigation are strongly correlated with cybersickness. The effect of visual displays is not well understood, and application design may be of greater importance.

Keywords Visually induced motion sickness · Cybersickness · Stereoscopic · Motion sickness · Displays · Head-mounted displays

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1 Introduction

Immersive visual display systems such as stereoscopic displays and systems that track a user's viewpoint to coordinate a virtual scene are becoming more prevalent. Stereoscopic movie availability has grown to the extent that most theaters exhibit several 3D movies at any given time. Stereoscopic television and video games are also more readily available to the public; Facebook has acquired oculus VR for over $2 billion (Parkin 2014), and Google and Microsoft have announced the intent to produce a consumer heads-up augmented reality display (Bilton 2012; Microsoft 2015). However, there have been concerns about the safety of these devices due to eyestrain and feelings of illness. A quick search of "movie theater motion sickness" reveals numerous results from people complaining of illness after attending movies such as "Bourne Ultimatum," "Hunger Games," "Avatar," "The Blair Witch Project," and particularly performances filmed with shaky hand-held cameras. A more notorious event regarding hand-held movies was a movie shown to 294, seventh grade students where 36 became ill enough to warrant treatment in a hospital (Ujike et al. 2008). The symptoms produced in users of these systems mimic motion sickness, but due to the absence of actual physical motion this affliction is considered a distinct condition referred to as cybersickness, visually induced motion sickness (VIMS), virtual simulation sickness, virtual reality-induced symptoms and effects, and other terms.

There is a considerable scope of potential human factors in virtual environments. Cybersickness is one commonly studied issue and is the focus in this review. Studies of these systems have shown the likelihood of symptoms to range from 30 % (Chen et al. 2011) to over 80 % (Kim et al. 2005). However, due to the increased availability of stereoscopic and tracking systems, the problem has become a public issue. Not only cybersickness can impact user comfort, but also it can be a safety issue, leading to injury or decreased capacity. Availability of hardware to track user movement for interaction has been a major development for the gaming industry with the production of the Wii©, the PlayStation Move©, and the Kinect©. Additional tracking systems using face recognition and/or marker tracking with inexpensive web cameras permit coordination of the user's viewpoint with the virtual scene. This provides a foundation for virtual and augmented reality. Since the availability of these systems will almost certainly increase, the occurrence of cybersickness is expected to increase as well. At this time, there is no official standard regarding the safety of such systems.

Cybersickness has been a known issue in virtual and augmented reality systems for decades and in simulators for even longer. Kolasinski (1995) published a list of over two-dozen potential factors in relation to illness exhibited in simulators. Often referred to as *simulator sickness*, the condition is an ongoing concern of the military since symptoms may limit training efficiency. Early studies on simulator sickness largely considered the hardware limitations, believing that symptoms would decrease with hardware improvements, although evidence has indicated otherwise (Kolasinski 1995; Stanney and Salvendy 1998). Mon-Williams et al. (1995) suggested that improving the screen hardware may actually increase symptoms.

There was substantial consideration of lag, tracking accuracy, and flicker as possible sources of simulator sickness (Dizio and Lackner 1997; LaViola 2000). Originally, the intent was to identify what aspects of the hardware would need to be corrected soonest or to improve the efficiency of the actual training applications. Technology improvements have, or likely will in time, rendered some of the hardware issues mute, but not all. There are inherent restraints on virtual environment systems. The tracking position and orientation must be transmitted to the computer, which must then render the scene, resulting in an unavoidable lag time. Contrary to most expectations, simulator sickness estimates have increased with hardware improvements, though this is possibly due to the change of demographics from primarily military to the general public (Stanney and Kennedy 1997).

Prior to 1995, one hardware attribute that was common was that the physical interface for a virtual environment was a constructed mockup of a real-world system. With the development of head-mounted displays and large screens displaying the virtual environment, having a physical interface that resembled the actual object was no longer strictly necessary. No longer requiring a physical mockup greatly increased the flexibility of virtual environments. The applications being studied extended beyond training, and the role of navigation control had to be revised. See-through displays added new aspects to consider since both the physical environment and the computer-generated environment were combined.

With these changes, the removal of the physical basis and the change in application, some researchers began to classify cybersickness and simulator sickness as distinct visual–vestibular malfunctions in the late 1990s. "Cybersickness is not Simulator Sickness" by Stanney et al. (1997) delineated the two afflictions. They reported that the symptom profile of cybersickness was not the same as simulator sickness and that it had higher sickness ratings. They proposed cybersickness and simulator sickness should not be considered the same ailment, although the fields still reference each other due to the same foundational framework. More recently, what would have once been called simulator sickness is now called cybersickness, making the distinction between the two fields ambiguous. Blea et al. (1998), Bos et al. (2008), and Smart et al. (2007) have recommended this distinction to be fully removed by considering postural instability as the sole source of illness in all motion sickness-related ailments.

Cybersickness studies are diverse in that the application, the rendering modes (e.g., stereoscopic, monoscopic), and the display system (e.g., head-mounted display, projection screen) can largely be selected independently of each other, resulting in a combinatorial number of different conditions for a single virtual scene. Due to this and the nature of the ailment, much of cybersickness remains unclear. Out of necessity, many factors posed in the early 1990s have had little exploration. Those with consistent results often do not have a substantial number of studies as there are other factors to examine.

This review discusses the methods of detection and the current knowledge of how rendering modes, visual display systems, and application design affect cybersickness. Hardware-specific factors are not included, although factors such as latency and lag may be well studied. Studies are included if they report results with statistical significance of $p < 0.05$, or are preliminary studies of novel aspects. Search terms included cybersickness, VIMS, virtual reality and environment motion sickness, simulator sickness, theater sickness, and augmented reality motion sickness.

For this review, cybersickness and VIMS will be defined as follows. Cybersickness is the onset of nausea, oculomotor, and/or disorientation while experiencing virtual environments in head-mounted displays, large screens, and curved screen systems. Visually induced motion sickness (VIMS) is nausea, oculomotor, and/or disorientation induced by any visual stimuli. Optokinetic drums, rotating drums with stripes that provide a controlled moving visual field are commonly used in VIMS research and can cause similar symptoms. However, this review focuses on the technological aspects required for cybersickness, as virtual reality permits a greater variety of potential stimuli. Nonetheless, the same visual stimuli in a virtual environment and a real environment can result in very similar symptoms despite significant differences between the environments (e.g., different fields of view and perceived resolution) (Villard et al. 2008; Smart et al. 2002; Yang et al. 2011).

Only studies conducted after 1995 are considered, with the exception of some early theories. While this year is somewhat arbitrary, cybersickness began to gain distinction from simulator sickness and the demographics shifted to a larger non-military population near this time. Any system that entails a specialized moving base or requires a physical mockup of the navigation object (e.g., a cockpit or chair with steering wheel) is considered a simulator, and its symptoms are considered simulator sickness and not included in the main review. However, for interested readers, Sect. 7 presents a selection of moving base articles. General purpose moving bases such as treadmills or walking areas are permitted. Large screens, whether they are curved, projected, or directly displayed, are considered provided they are over 60 inch. This size was selected since screens above this size are less likely to exist in the home, and the user's distance from the screen normally causes the field of view to become large enough to simulate virtual reality.

1.1 Terminology

Virtual reality (VR) refers to a simulated environment whose visual content, and optionally other senses, is entirely produced by a computer and the appearance of the environment alters with the participant's behavior.

Augmented reality (AR) refers to a simulated environment whose visual content, and optionally other senses, is only partially produced by a computer and the appearance of the environment alters with the participant's behavior.

Virtual environments (VE) are the visual stimuli, and optionally other senses, presented by both virtual and augmented reality systems.

Immersion formally refers to the feeling of presence, or the feeling of "being there." Informally, it also includes the time "immersed" inside a virtual environment.

Field of view (FOV) refers to the angular width a screen fills a user's vision. The field of view is measured on the diagonal unless otherwise stated.

A *computer-aided virtual environment* (CAVE) consists of multiple large screens rendered from the point of view of a participant with head tracking. Since what is sometimes called a one-wall CAVE (a single stereographic projection screen) is more similar to a large TV, it will be called a large screen.

Degrees of freedom (DOF) refers to the number of independent axes of translation and rotation when navigating a virtual environment.

The *virtual environment performance assessment battery* (VEPAB) is a set of simple tasks and environments for testing performance and determining the degree of cybersickness (Lampton et al. 1994). VEPAB was developed in 1994, but has not seen widespread usage. The tasks include distance and height estimation, hallway navigation, vertical navigation, and simple control activation.

The *simulator sickness questionnaire* (SSQ) is a standard questionnaire used to determine the impact of cybersickness. SSQ refers to the questionnaire, SSQ-T references the total score, SSQ-N references the questionnaire's nausea category, SSQ-D references the questionnaire's disorientation category, and SSQ-O references the questionnaire's oculomotor category. The SSQ is discussed in more detail in Sect. 3.1.

A *head-mounted display* (HMD) is a visor display that places two small screens, or a single screen that renders two separate images, before the eyes. The screen(s) can either display the same image or can have separate images for stereoscopic viewing.

2 Cybersickness causes and symptoms

Similar to motion sickness, the symptoms of cybersickness are polysymptomatic (many symptoms) and polygenic (symptoms manifested differ from individual to individual) making it a complex illness to understand and describe. In most cases of cybersickness, there is no physical motion so the symptoms are often referred to as being "visually induced." Medically, symptoms include nausea, pale skin, cold sweats, vomiting, dizziness, headache, increased salivation, and fatigue (Ehrlich 2012). Since virtual environments place additional strains on the eyes, eyestrain and difficulty focusing are also included as symptoms.

Despite its similarity to motion sickness, cybersickness has a different symptom profile as shown in Table 1. In cybersickness research, the simulator sickness questionnaire (SSQ) by Kennedy et al. (1993) is often used as a standard measurement. The SSQ asks for the severity of several symptoms on a scale of 0–3. The symptoms are categorized into nausea (e.g., stomach awareness, nausea, etc.), oculomotor (e.g., headache, eyestrain, etc.), and disorientation (e.g., vertigo, dizziness, etc.). In the literature, the categories are often abbreviated as N, O, and D, respectively. Kennedy et al. (2003) and Stanney and Kennedy (1997) indicate that military simulators frequently have a SSQ-O > SSQ-N > SSQ-D symptom

Table 1 Related conditions symptom profiles

	Military simulators	Sea sickness	Space sickness	Cybersickness
Highest rating	Oculomotor	Nauseagenic	Nauseagenic	Disorientation
Middle rating	Nauseagenic	Oculomotor	Disorientation	Nauseagenic
Lowest rating	Disorientation	Disorientation	Oculomotor	Oculomotor

profile (that is, the oculomotor rating is higher than nausea rating, and nausea ratings are higher than disorientation), sea sickness has a SSQ-N > SSQ-O > SSQ-D relationship, and space sickness has a SSQ-N > SSQ-D > SSQ-O relationship. Cybersickness tends to have a SSQ-D > SSQ-N > SSQ-O, although there are exceptions (So et al. 2001b; Cobb 1999; Roberts and Gallimore 2005). It is due to these different profiles that Stanney et al. (1997) recommended they be considered distinct aliments.

More recently, Bos et al. (2008) have proposed that these related illnesses should use postural instability, or the amount of sway when standing, as the sole measurement of severity of symptoms, and therefore, all of these related illnesses should be considered a single ailment. However, the sensitivity of postural instability across different systems and applications and its predictive accuracy have yet to be confirmed. Potentially confounding the studies is that susceptibility varies across demographics. One of the most studied demographic issues is female versus male. Females in virtual environments tend to exhibit more symptoms, though there is some evidence of males under-reporting symptoms so as to not appear weak (Jaeger and Mourant 2001; Stanney et al. 1999a, 2003; Harm et al. 2007). The results are also somewhat contradictory with gender showing no statistical difference in some cases (Harm et al. 2007; Hakkinen et al. 2002). Harm et al. (2007) found that females demonstrate a faster change in symptoms in both onset and recovery, which may explain the differing results. Graeber and Stanney (2002) offers an alternative explanation that females have higher average susceptibility and by holding that factor constant removes the differences between genders.

2.1 Cybersickness effects

Since cybersickness is polygenic, there are studies exploring the symptoms including its effects on the eyes, its symptom profile, and its duration. In stereoscopic systems and HMD's, the environment's virtual camera is usually inexactly aligned with the eyes due to equipment shifts and inaccurate adjustment of the HMD for each participant's interpupillary distance (IPD). Studies on virtual environment's effects on the eyes demonstrate a change in the eye's resting position from before a virtual environment's use. The effects related on the eye are discussed in greater detail in Sect. 5.1.

It is well known that increasing duration also increases the frequency and severity of cybersickness (Jaeger and Mourant 2001; So et al. 2001b; Stanney et al. 2002a, b, 2003; So and Lo 1999; Lo and So 2001). Stanney et al. (1999a, b) reported a 20 % early withdrawal rate with half of participants ending before 30 min. They reported the SSQ-T scores to be significantly different between the groups, and that over 50 % of those that withdrew early did so between 11 and 20 min. Another 20 % withdrew during both the 22–30 and 31–40 min times frames. So et al. (2001b) reported that duration eventually overpowered the effect of their other tested parameters

Emetic responses (vomiting) have drawn some closer inspection. Fortunately, studies have shown that such responses are uncommon in cybersickness, but the causes and relationship with SSQ scores are less certain. Kingdon et al. (2001) sought correlation of sickness ratings and emetic responses with varying scenes and navigation. Of their 1028 participants, 15 individuals had an emetic response. They were paired with another individual, presumably randomly, who had been immersed in the same condition to compare their symptom profiles. Those with an emetic response had significantly higher SSQ-D, SSQ-N, and SSQ-T scores. When comparing symptoms, how the participants are paired may be important. Ehrlich and Kolasinski (1998) conducted a similar study, but paired those with emetic response to those with the highest sickness rating that completed under the same experimental conditions. They only found SSQ-N was significantly higher in the dropouts. Fortunately, emetic responses are rare with an expected incidence of less than 2 % (Stanney et al. 2003; Stanney et al. 2002).

The results reported concerning the duration of symptoms may be the most problematic. While most participants largely recover in an hour, some effects linger for two or more hours. The longest lasting is the SSQ-D score. Stanney and Kennedy (1998) analyzed the effects an hour after immersion and found the SSQ was still twelve times higher than before immersion. (Stanney et al. 2002, 2003). Singer et al. (1998) is in partial agreement with the duration of effects. They considered the sickness ratings 30 min after immersion. In this instance, they only found the difference in the SSQ-D to still be significant. However, their experimental setup was different than most in that it gave frequent 5–15-min breaks. These additional breaks could have impacted symptoms, causing a decrease. Also, the

SSQ-T scores are not calculated linearly, making the actual meaning of some specified percentage drop unclear. Since disorientation affects balance, traveling immediately following immersion is not recommended and waiting approximately an hour appears to be the minimum suggested rest time following long duration immersion.

The side effects of virtual environment exposure can be decreased through habituation (Stanney and Kennedy 1997; Hill and Howarth 2000; Bos 2007; Toet et al. 2008; Howarth and Hodder 2008). Howarth and Hodder (2008) examined the level of habituation with sessions 2–7 days apart. All conditions resulted is a significant decrease in symptoms, and 50 % failed to demonstrate any symptoms by the tenth session. Stanney and Kennedy (1997) suggest sessions every 2–5 days to encourage habituation.

2.2 Theories on the source of cybersickness

The biological causes of cybersickness have not been firmly established, and different theories hypothesize different factors responsible for cybersickness in virtual environments. Table 2 lists common theories that have been proposed: sensory mismatch, postural instability, poison, and rest frame. Sensory mismatch and postural instability are the commonly postulated causes.

Sensory mismatch is the most common theory. It posits that if the stimulus from the outside environment is being perceived differently by different senses, it will induce cybersickness. For example, if a picture has been tilted as shown in Fig. 1, the participant feels gravity as straight down through the vestibular system, but the visual system perceives that gravity is tilted with the picture. Sensory mismatch is often the explanation as to why vection, the perception of the world moving away from the user, is strongly correlated with cybersickness symptoms.

Postural instability posits that if a person is unable to maintain a posture necessary given the stimulus from the outside environment, it will induce cybersickness. Using the picture example, the individual's posture may be slanted as shown in Fig. 1 in an attempt to correct the orientation of the visual stimulus, but since gravity is straight down this posture becomes unstable. The more unstable the posture, the more ill a participant will become. As such, postural instability can be viewed as a more restricted form of sensory mismatch, since it focuses on the vestibular system being unable to cope with the stimulus. It is gaining popularity in the research community because the theory is subject to objective evaluation.

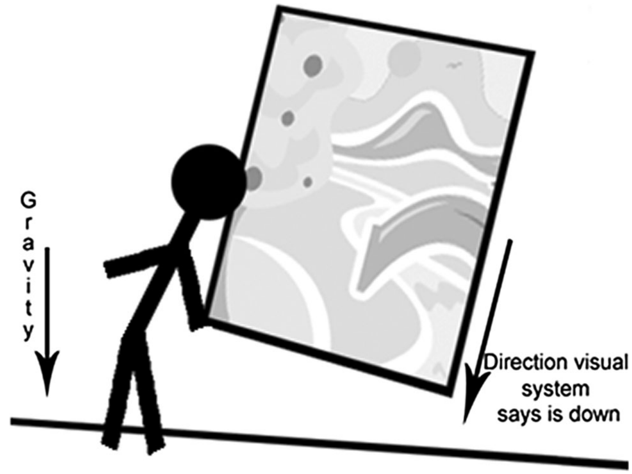

Fig. 1 Example of incorrect visual stimulus

Rest frame theory is based on the direction the user as believes is "up" in relation to the world, and the degree of symptoms theoretically should relate to how discrepant this is from actual gravity. In the sense that symptoms are due to a perceived "up" versus actual gravity, it is similar to postural instability. It has the advantage of being more general, particularly in instances where postural control may not be as much of a factor, such as when seated. For a more through description, see "Virtual Reality and the Vestibular Apparatus" by (Virre 1996) for an explanation of the eyes' delayed adaptation.

Poison theory posits a person feels ill within an incorrectly perceived environment if the perception could have

Table 2 Cybersickness theories

	Posits	Most related virtual aspects
Sensory mismatch	If the stimuli from the outside environment are being perceived differently by different senses, symptoms will occur	Tracking, vection, and navigation
Postural instability	If a person is unable to maintain the posture necessary given the stimuli from the outside environment, symptoms will occur	Orientation cues and position during immersion
Rest frame	If the direction a person perceives as up is difference from the up due to gravity, symptoms will occur	Habituation and orientation cues
Poison	If an incorrectly perceived environment could have been due to effect of poison in the past, symptoms will occur	Realism, tracking, and navigation

been due to the effect of poison in the past (Treisman 1977). Therefore, the nauseagenic symptoms are an incorrect application of a survival mechanism. This theory is not used in cybersickness in practice.

3 Detection measures for cybersickness

With an illness with diverse symptoms, there are also diverse methods of detecting and rating the severity of symptoms. Three measurement mechanisms are common in cybersickness research: questionnaires, postural instability, and physiological state. The questionnaires are the oldest form and owe their provenance to simulator sickness and motion sickness studies. The simulator sickness questionnaire and one-question Likert ratings (the extent of one effect or symptom measured on a numerical scale) are often the *de facto* rating systems of choice. Postural instability detection developed later as robust balance platforms and magnetic sensors became available. Physiological state has only been developed in the last few years. A condensed summary of publications related to detection measures is presented in Online Resource 1.

3.1 Questionnaires

The most common questionnaire in cybersickness studies is the simulator sickness questionnaire (SSQ). The SSQ was developed in 1993 by Kennedy et al. (1993) and was originally designed for a military demographic. Even when postural testing or physiological testing is used, the SSQ is often used as supplementary material or used to determine the accuracy of the alternative method. The SSQ consists of several questions asking for the severity of symptoms on a scale of 0–3. Scores are computed for three categories, each with its own weighting as shown in Table 3. A computed score below 10–15 is considered normal. The three categories are nausea (e.g., general discomfort, stomach awareness, nausea, etc.), oculomotor (e.g., fatigue, headache, eyestrain, etc.), and disorientation (e.g., difficulty focusing, vertigo, dizziness, etc.). The categories in the literature are regularly abbreviated as N, O, and D, respectively.

However, the SSQ does have disadvantages to the extent that some researchers avoid its use entirely. Several symptoms contribute to more than one category, as can be seen in Table 3. Some researchers have expressed concerns of the SSQ's over sensitivity. Merely closing one's eyes for an extended period of time can register on the measurement. In addition, because of the varying levels between the subcategories it should only be used to compare results of motion sickness of the same type. The questionnaire is more appropriate for use in correlation analysis than absolute measurement of illness.

There has also been some concern over its generalization since it was developed for a military demographic, and there is cross-correlation among the categories. Bruck and Watters (2011) calculated the extent of cross-correlation of the SSQ. They proposed four main factor groups of symptoms, each encompassing one to eleven symptoms. They are general cybersickness, vision, arousal (respiration), and fatigue. However, there was overlap of the symptoms in these four groups as well. In 2007, Bouchard et al. (2007) who refer to the redundancy among categories as *loading* attempted to remedy both cross-loading and the possibility of skew due to the original military demographic. They refactored the SSQ using a non-military populace to avoid the cross-loading and created a new questionnaire with two categories: nausea and oculomotor. The participants were 71 % female, a third with anxiety disorders. This demographic is dissimilar from the populations reported in most non-military cybersickness studies, and usage of this refactored SSQ is limited.

Of course, questionnaires are subjective and indirect measurements. Priming and demand characteristics are possible. Young et al. (2007) tested the effect of demand characteristics in the SSQ by considering the post-immersion scores with and without a pre-immersion test. Not surprisingly, the scores of the posttest were higher when a pretest was given, with the nausea category having the largest priming effect with the change of symptoms being a third as high without the pretest. Keshavarz and Hecht (2011b) results are in conflict with Young et al., as they found no statistical significance when participants were given instructions that stated that they should expect good emotions, expect illness, or remain neutral. As the authors mention, there is a difference in how the effect was induced. Young et al. gave their participants a pretest, while Keshavarz and Hecht gave instructions on the expected feelings. Despite these issues, the SSQ has remained the primary reported measure of cybersickness and will be the primary means of comparison in this review.

Following the SSQ in popularity, are numerous verbal single-question rating scale questionnaires to analyze symptom severity through time. They vary from study to study, but normally consist of asking the participant their current level of discomfort at regular intervals as a single number. The reason for this is that longer questionnaires require too much time to administer during immersion and frequent breaks may decrease cybersickness. One such scale is the misery scale (MISC) rating system used employed by Bos et al. (2010) that has a scale of 0–10. "0" represents no symptoms, and "10" is vomiting. Another is the Fast Motion Sickness Scale (FMS) by Keshavarz and

Table 3 Simulator sickness questionnaire symptom categories

SSQ symptom	Weight		
	Nausea	Oculomotor	Disorientation
General discomfort	1	1	0
Fatigue	0	1	0
Headache	0	1	0
Eyestrain	0	1	0
Difficulty focusing	0	1	1
Increased salivation	1	0	0
Sweating	1	0	0
Nausea	1	0	1
Difficulty concentrating	1	1	0
Fullness of head	0	0	1
Blurred vision	0	1	1
Dizzy (eyes open)	0	0	1
Dizzy (eyes closed)	0	0	1
Vertigo	0	0	1
Stomach awareness	1	0	0
Burping	1	0	0
Column weighting for category scores	9.54	7.58	13.92

The total score is the summed symptom scores multiplied by 3.74

Hecht (2011a, b). Their scale ranged from 0 (no sickness) to 20 (frank sickness). They also formally approached the question whether such one-point scales are appropriate to use to monitor symptoms. When comparing to the SSQ, they found a high correlation between the SSQ-N and SSQ-T and the FMS. This implies one-point rating scales are acceptable to monitor symptoms, although they are not as thorough or sensitive.

However, cybersickness studies can be confounded by the susceptibility of the participants. Highly or minimally susceptible participants can skew the results to demonstrate worse or lesser effects, skewing the effects of immersion. To test for the generalization of the results to the normal populace, a susceptible questionnaire is occasionally employed. One is the revised motion sickness susceptibility questionnaire (MSSQ) by *Golding* which shortened and simplified the scoring of the reason and brand motion sickness susceptibility questionnaire (Golding 1998). The MSSQ analyzes the frequency an individual has become ill from motion in the past.

3.2 Postural instability

Postural instability has been gaining popularity as a means of detecting symptoms and relies on the postural instability theory of cybersickness, which states that the more ill someone becomes, the more unstable their postural will be. It is objective, fairly low cost, theoretically yields continuous symptom levels, and does not require disturbance of the participant by asking for a verbal statement of illness every few minutes. In practice, it is neither continuous nor leaves the participant undisturbed. Postural instability measurement typically requires a specific standardized stance to be taken every few minutes, and only position data recorded during the stance are used in analysis. Postural instability measures include time till failure when maintaining a particular stance, stance breaks, velocity of movement, and changes in position of head and/or torso. Stance breaks occur when a participant can no longer maintain a stance and are typically recorded as the number of breaks per minute. Time till failure is the time from first entering a stance to when it breaks.

Before robust methods of detecting postural sway were developed, time till failure maintaining a particular position or the number of stance breaks was employed. As Cobb (1999) explains, there are several flaws with these methods. Cobb analyzed several different stance breaks and time-till-failure measurements and found that many of the definitions of stance breaks were sufficiently vague that the same description could yield different results. For example, “loss of balance” could mean the foot moved from its original position by any measurable amount, the foot moved more than 2 cm from the original position, or several other movements. There is also the possibility of learning effects.

Despite the initial impediments to postural instability, postural sway has been gaining favor as a symptom measurement. Current research typically measures the change in fore-aft and horizontal movement as shown in Fig. 2, and shows a trend of the fore-aft axis being most affected by cybersickness. Standard deviation in postural instability refers to the average amount of variability of movement along a given axis, while velocity refers to the speed of movement along a given axis. Villard et al. (2008) found the standard deviation of head position in the fore-aft and horizontal axes were greater for the participants that stayed well. However, for those that became ill, it was the velocity that had a greater increase in the fore-aft and horizontal directions. Dong and Stoffregen (2010) and Dong et al. (2011) partially agreed with these results. They found those with fewer symptoms displayed a higher horizontal standard deviation, but the remaining participants had a higher fore-aft standard deviation. Bos et al. (2013) instead employed a Nintendo Wii Balance Board© when examining postural instability after watching a stereoscopic movie. They found there was a significant increase on average in standard deviation in both horizontal and fore-aft directions when a low-pass filter of 0.1 Hz was applied to the data. Chardonnet et al. (2015) also considered center of gravity as a means to measure postural instability and cybersickness. They reported that of six out of thirteen postural variables changed significantly with virtual environment exposure. These are area, length, horizontal length, fore-aft length, slope, and speed variance. The amount of variance increases with symptoms.

Although the variables and analysis have yet to be standardized, an overall increase in the standard deviation of motion along an axis is associated with "well" participants, while greater variability with a smaller average motion, particularly in the fore-aft axis, is associated with ill participants. This agrees with concerns in the literature that participants may self-adapt to virtual reality by consciously avoiding head movements when they feel ill.

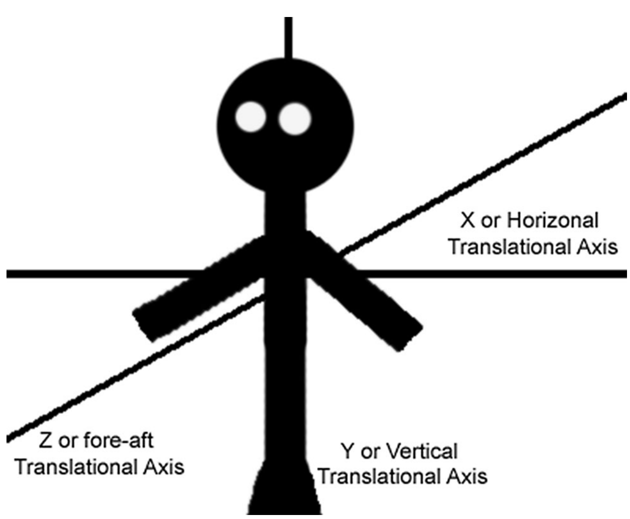

Fig. 2 Translation axis

3.3 Biometric and physiological state

More recently, there is development of a third method of detecting symptom severity using a variety of physiological signals or biometrics. There has been increasing interest likely due to the potential for symptoms to be monitored continuously and without intruding upon the participant by pausing at regular intervals. Physiological signals such as heart rate (also known as the R–R interval) and blood pressure are being analyzed to determine their correlation with cybersickness. The signals are normally detected by sensors attached to the skin. At this time, the choice of physiological signals and the processing of the signals have not been standardized. Some of the more common detection sensors under examination are electrocardiogram (ECG), blood pressure, electrogastrogram (EGG), and respiration (RSP). Two less common options are skin temperature and electroencephalograms (EEG). ECG monitors the heart, EGG monitors stomach movement, and EEG monitors electrical activity due to current flow in the brain.

ECG and blood pressure have shown the best promise thus far. Kiryu et al. (2007) used ECG, blood pressure, and respiration. They split each signal's power spectrum into a lower frequency (LF) range of 0.04–0.15 Hz and high frequency (HF) range of 0.16–0.45 Hz. They reported a correlation with cybersickness and duration using ECG, blood pressure, and respiration LF/HF ratios as the measurement (Kiryu et al. 2007). Watanabe and Ujike (2008) support these earlier findings in that LF/HF ratio obtained from heart rate correlated with duration in virtual environment immersion. The underlying assumption of these studies is that a large LF/HF ratio occurs when the sympathetic nervous system is very active. Biologically, this means the heart beat becomes stronger and/or the blood flow has lower turbulence.

Kim et al. (2005) examined most common signals for correlation with cybersickness with a very provocative stimulus (78.9 % of the participants experienced symptoms after only 9.5 min), but found the most success with EGG. The EGG displayed a gastric tachyarrhythmia increase during the duration of exposure. Roberts and Gallimore (2005) attempted to use the EGG exclusively for detection and found tachygastria (an EGG with a power spectrum of four to nine cycles per minute rather than the normal three cycles per minute) was present during exposure.

4 Display systems

While the effects in one display system are often assumed to apply in other display systems, Sharples et al. (2008) demonstrated that this may not be true. Nonetheless, due to the increased time, participants, and difficultly in experimental design, cross-display system studies are uncommon. Cybersickness research largely consists of HMD and large screens, while other display systems such as domed screens (a semispherical screen that permits up to a 180° × 180° field of view), curved screens, and CAVEs are less common. To provide a broader comparison, a selection of studies within a single display system with reported SSQ scores as a common measurement are included with studies utilizing multiple display systems. Other than studies examining the effect of an independent visual background, cybersickness research employs virtual reality almost exclusively with no external visual input since it provides the greatest control over the environment.

Potentially confounding factors in the comparison of display methods are the presence or absence of head tracking, an option in most virtual environments, and whether the stimulus was meant to deliberately provoke a cybersickness response. This is particularly an issue with detection development studies. Without symptoms, there is nothing to analyze, and thus, these studies typically attempt to be provocative. Since cybersickness is readily apparent in typical environments, the addition of provocative stimuli would increase the difference in symptoms, making the comparisons less reliable. Therefore, developing detection methods are excluded from comparison, with the exception of the study by Stanney et al. (1999a, b) who designed their environment to be a typical virtual environment. One other potential confounding factor is that of duration, which is well known to increase symptoms. However, most studies presented are between 20 and 30 min, thereby lessening duration's influence on the comparison of cybersickness ratings. Lastly, Young et al. (2007) mention the priming or demand characteristics of the SSQ. An administered pretest will affect the post-immersion SSQ score. However, nearly all publications employed a pretest. The publications presented here are available in condensed form in the Online Resource 2.

4.1 Multiple display studies

There is a consistent trend that the incidence of cybersickness increases from desktop to large screen to HMD, but the difference between a large screen and HMD is small, with the exception of the study by Keshavarz et al. (2011). Sharples et al. (2008) showed several significant differences between display systems with virtual reality, as did Liu and Uang (2011). Hakkinen et al. (2002) showed similar effects with stereoscopic movies.

Virtual environments provide greater immersion than typical stereoscopic movies, and therefore, the form of interaction may change between systems. Sharples et al. (2008) compared four display systems: HMD, desktop, projection (large screen), and reality theater (see Fig. 3c) along with lighting (if applicable) and passive/active control. All systems resulted in measureable quantities of cybersickness. They found the HMD produced higher SSQ-N scores than the other three, and its SSQ-T and SSQ-D scores were higher than the desktop. The HMD also had more participants stating sickness at completion than the desktop. The projection screen and reality theater had comparable results and demonstrated a trend of reported symptoms between that of the desktop and HMD. Kim et al. (2014) examined a similar set of displays which included a six-wall CAVE, a HMD, and desktop display. They found significantly more cybersickness in the HMD condition than the CAVE condition and significantly more cybersickness in the CAVE condition than the desktop version. Vlad et al. (2013) found higher cybersickness in a variety of identification tasks with a stereoscopic HMD versus a stereoscopic monitor. Liu and Uang (2011) also compared a standard monitor, a stereoscopic monitor, and an HMD with the addition of varying of depth cues. Depth cues are visual information in the scene that allows participants to determine distance and size of objects. The HMD had higher cybersickness scores than a normal monitor, but the relationship between the HMD and stereoscopic monitor is less clear. There was a significant interaction between the depth cue and display. In the flat object depth condition, the HMD had a higher score, but the stereoscopic monitor had a higher score in the three-dimensional object depth cue condition. As the authors explain, the result may have been affected by the different level of interaction between displays. The relative size of the displays is also unknown, which has shown substantial effects on cybersickness scores (see Sect. 5.3).

Since stereoscopic movies have less interaction than virtual environments, it is possible that there could be different effects, and research demonstrates irregular results. Hakkinen et al. (2002) found postural sway and reported symptoms were higher when playing a stereoscopic HMD game than when passively watching a movie in an HMD or on a monitor. The relationship of viewing the movie in a HMD and on TV is less clear as there were different results across the SSQ categories. The SSQ-T scores were comparable, but the SSQ-N scores were worse for the television, and the SSQ-O and SSQ-D scores were worse for the HMD. They reported an unusual result of the SSQ-N scores decreasing as a result of the movie for both conditions and explain that their participants were stressed before arrival so the relaxing nature of the movie may have masked the effect.

While Smart et al. (2007) did not directly consider the differences between display types, they did report the percentage of participants that became ill in multiple displays. In a moving room 23 % became ill, in a space travel simulator 43 % became ill, in a projector system 17 % became ill,

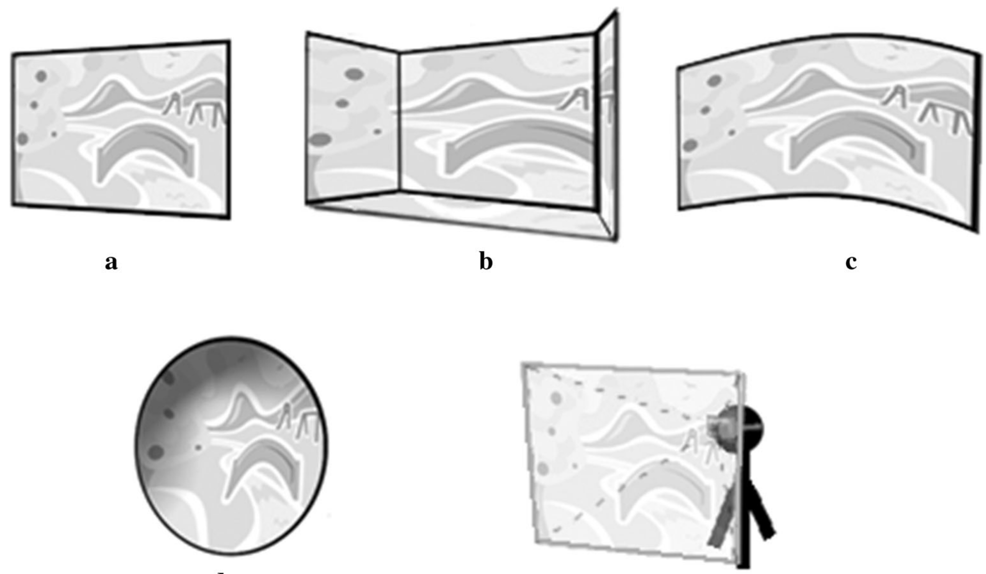

Fig. 3 **a** Large screen, **b** four-wall CAVE, **c** reality theater or curved screen, **d** dome screen, **e** HMD

and in an HMD 42 % became ill. All experiments had the same sinusoidal motion displayed, but the visuals varied.

A difficulty in comparing different systems is the large number of differences in how these systems are designed, work, and are used. A movie is watched while seated with little head movement, while a virtual environment frequently requires movement and a standing posture. The screen size, existence of a headset, distance, resolution, and interaction method can differ. As a result, the cause of differences in symptomology between the displays is not well understood. Keshavarz et al. (2011) attempted to define some of these differences and their potential effects. In their first experiment, participants viewed the same stimuli on an HMD and a large screen. Both conditions had the same visual angles and used a chin rest, but the large screen had higher symptoms than the HMD which is in direct conflict with several studies presented earlier. In another experiment, they masked the view to just the screen, so that the external environment could not be seen, just as in an HMD. This experiment revealed no difference in symptoms between the masked screen and the HMD, which implies the higher cybersickness incidence of an HMD is due to differences in use rather than the display alone. Rebenitsch (2015) also supports this theory by showing normalizing the effects of independent visual backgrounds from Sect. 6.3 there is no longer an effect from the display. Section 6 describes in greater detail the possible differences in use and their effects.

4.2 HMD studies

The majority of cybersickness studies are conducted with HMDs. They offer a guaranteed field of view and higher level of control over the virtual world in comparison with a desktop or a large screen. They also generally have a lower resolution and a smaller field of view than large screens and CAVEs. HMDs generally employ head tracking, though it is not strictly required. Given their smaller fields of view and removal of the outside world, the registration errors can be more or less obvious to participants. These aspects can potentially affect the severity of cybersickness developed in virtual environments.

HMDs anecdotally, and as demonstrated in limited multiple display studies, have the highest incidence of cybersickness of virtual reality systems. The HMD studies presented have average SSQ-T scores that range from 6 to 160 and are presented approximately in order of smallest to largest SSQ-T. Overall, the HMD studies have an average in the upper twenties. Young et al. (2007) developed a simple balloon popping game with very little head movement and found a very low SSQ-T score of six to twelve post-immersion. Stanney et al. (1999a, b) presented a detailed environment to act as an expected virtual environment stimulus to test a spatial discernment sickness detection method. They employed the SSQ for comparison and found their post-immersion SSQ-T to be 19.1. Nichols et al. (2000) compared the amount of *presence*, or the feeling of being “there,” and the SSQ-T scores. They found a negative correlation with the presence and all SSQ categories and the overall score. The SSQ-T was 20, approximated from their graphs. Jaeger and Mourant (2001) examined the effect of the mode of navigation, though how the head tracking was implemented was not specified. A participant could move forward either by using a mouse or walking on a treadmill. They found SSQ-Ts of 15.2 for the treadmill and 23.9 for the mouse navigation. They also considered level of detail and found SSQ-Ts of 16.2 for lower detail and 20.0 for higher detail. Draper et al. (2001) examined the effect of the ratio between the virtual camera field of view and the real HMD field of view in a search and find environment. They demonstrated post-SSQ-T scores of ten when the virtual field of view is equal to the real field of view and 33 when the virtual field of view is greater than the real field of view, with the SSQ-T scores approximated from their graphs. The experiment lacked foreshortening normally created in HMDs when the head is tilted by using a 360° panoramic image to avoid rendering time lag. Lo and So (2001) considered the axis of rotation with no head tracking. They found an SSQ-T score of 37, approximated from their graphs, for all axes after 20 min of immersion. So et al. (2001b) also considered yaw rotation as well as speed in the fore-aft directions. Their reported SSQ-T varied considerably and ranged from 45 to 160 for the speeds of 5.9 m per second and 59.2 m per second, respectively. In general, the scores increased when the speed of navigation was increased.

From the above, albeit diverse studies, cybersickness appears to increase with more in-depth immersion and forced motion. This parallels the effect of shaky handheld movies. Nichols et al. (2000) and Stanney et al. (1999a, b) may be more generally indicative since the visual stimulus presented was designed to be an expected virtual environment immersive experience with no explicit intent to invoke symptoms. These studies had a SSQ-T near 20.

Moss and Muth (2011) explored the consequences of peripheral occlusion. Many HMD have an option to add blinders that block peripheral vision. This lack of peripheral vision is one of the largest differences between HMDs and other displays as it increases the realism of the virtual world by blocking the outside world. They found that when there was peripheral occlusion cybersickness was increased. As mentioned earlier, the Kershavarz et al. results contradict this in that their condition of masking the outside world induced less cybersickness. One of the primary differences in the two studies is that Moss and Muth had their participants move their head while Kershavarz et al. had theirs remain stationary. Another difference was the visual stimulus. Moss and Muth present a room while Kershavarz et al. presented a recording of a car going around a race track. One possible explanation is that decreasing the conflicting information, virtual or real, decreases cybersickness. The car ride in *Kershavarz, Hecht, and Zschutschk* is a well-known stimulus so the stationary room was in conflict, while turning in a virtual room the vestibular system better matched the real room.

4.3 Other display studies

Cybersickness research that employs large screens, domes, CAVES, and curved screens frequently report cybersickness using measures other than the SSQ. Anecdotally, they have lower ratings than the HMD, but higher ratings than a conventional desktop system. Large screen displays are the second most common display system in cybersickness studies. Large screens include projection screens, back-projected screens, and televisions over 60 inch. in size. This size was selected since screens above this size are less likely to exist in the home, and the user's distance from the screen normally causes the field of view to become large enough to simulate virtual reality. Large screens have the advantage of being relatively inexpensive. However, they greatly restrict the range of motion available to view the virtual environment and can have varying fields of view depending on the distance to the screen. To offset this, many studies using large screens do not implement head tracking and have the participants hold their head still. This removes the free angle of viewing in virtual scenes and makes the stimulus closer to a movie. Potentially confounding the comparison is whether or not the visual stimulus was stereoscopic or monoscopic. However, the majority of large screen studies either imply or explicitly state that they are monoscopic.

Villard et al. (2008) employed a large screen to determine whether the cybersickness symptoms are the same in a virtual representation of a stimulus and in its real counterpart. They compared the symptoms of participants in a physically moving room and participants presented a virtual room moving in the same pattern. They found no statistical difference between the two which indicates studies using optokinetic drum-like devices may be generally applicable to cybersickness. Their ill group, which consisted of 46 % of their participants, had an SSQ-T of 100 while the well group had an SSQ-T of 5, approximated from their graphs. Combined, the average SSQ-T is 49, which is higher than most SSQ-T scores published for HMDs. These studies demonstrate that, while anecdotally large screens have less severe effects than HMDs, this may not always be accurate.

To provide clear delineation from large screen, a CAVE is restricted in this review to using three to six screens that creates part to all of a cube that surrounds a participant. The most common is a three-wall CAVE that has a screen in the front, on the left, and on the right. The three-wall CAVE provides a horizontal field of view of 180°–270° depending on the location of the participant, while a six-wall CAVE provides a field of view of 360° by 360°. CAVEs also allow greater motion than a projection or dome screen, albeit less than an HMD. Given their higher level of immersion in comparison with the other display systems, cybersickness effects are liable to be different. However, CAVEs are expensive, difficult to calibrate, and require large rooms to implement. They are also more fragile in terms of maintaining correct calibration since there are multiple screens that must be aligned properly and a slight collision with any one may require recalibration. As such, they are the least common display system and only one cybersickness study using a CAVE was found.

The CAVE used in Watanabe and Ujike (2008) was a four-wall CAVE in the same configuration as shown in Fig. 3b. They considered navigation where the virtual participant's height was determined by the terrain or a planar navigation where the participant's height remained constant. They found an SSQ-T of 45 for height-dependent navigation and 30 for the planar navigation, approximated from their graphs. These studies demonstrate that the display system is only one of the factors contributing to cybersickness and that the scene content may have a greater effect.

Curved screens and domed screens (see Fig. 3c, d, respectively) attempt to improve the field of view provided by a large screen. By wrapping around the participant, these screens can provide a 180° horizontal field of view. Other than the increased field of view, the display systems are similar in both their advantages and disadvantages. However, since peripheral vision provides different cues than focal vision, the effect should not be assumed to be identical to other display systems. There were no studies using curved or domed screens that reported SSQ-T scores, so no direct comparison can be made.

While it is generally assumed that large screens have less severe effects than HMDs, this may not be the case. Possibly, the anecdotal evidence was from early HMDs which had poorer resolution, incorrect eye alignment, and weighed considerably more when compared to screen-based simulators. One likely possibility contributing to the higher cybersickness scores of large screens and CAVEs is the larger field of view. As discussed in Sect. 5.3, a larger field of view tends to increase symptoms. Large screens and CAVEs have larger fields of view than most HMDs.

5 Rendering modes

After the display system is chosen, there is still the option of the number of dimensions to display and the size of the viewing area, or field of view. Screens can display two- or three-dimensional information. The field of view can be either the physical screen or the virtual window that is used when rendering a video frame. The virtual window's size can be readily altered to be relatively smaller or larger than the physical screen. The resulting visual distortions due to differing virtual window and screen sizes have shown an effect on cybersickness.

Stereoscopic displays present two images from different viewpoints so as to simulate binocular disparity (Fig. 4c). HMDs accomplish this by using a display for each eye, each displaying a different image, or a single display and optics to display half of the display to each eye. In non-HMD systems, both images are displayed on the same screen, but the correct image is filtered to each eye by some means. Monoscopic is defined as only having one viewpoint and only one image (Fig. 4a). HMDs such as Google Glass present a monoscopic image to only one eye. Bi-ocular is defined as having a single viewpoint, but breaking the original image into two images by using cropped portions of the image synthesized from that viewpoint and displaying the synthesized image to the corresponding eye. For example, an image can be rendered, with the left 87.5 % of the image displayed to the left eye and right 87.5 % displayed to the right eye, resulting in a 75 % overlap of the full image displayed to both eyes similar to Fig. 4b. This allows for faster rendering time and less specialized hardware. However, often it is the entire image that is displayed to both eyes and thus an overlap of 100 %. While most display systems support all three rendering modes, only HMDs use the bi-ocular rendering mode in practice. There is some ambiguity between monoscopic and 100 % overlap bi-ocular HMD viewing in the literature, and they are regularly used interchangeably. For this review, bi-ocular will refer to 100 % overlap, since less than 100 % overlap studies are very uncommon.

In stereoscopic systems, the images presented are rarely aligned perfectly to the eye due to equipment shifts and inaccurate adjustment of the HMD for each participant's interpupillary distance (IPD). Moreover, the images presented are all at the same distance on one plane. This is in conflict with real life where the eyes both move to focus on the same object (vergence) and adjust the lens's focal length to the perceived distance (accommodation). Since, HMDs place the screen at a constant optical distance, the effect may be particularly aggravating to the eyes. Direct comparison of the impact of rendering modes is limited since the majority of studies are stereoscopic or bi-ocular. Thus, only the studies considering the effects of stereoscopic on the eye and the studies comparing stereoscopic and monoscopic/bi-ocular are presented in this section. The publications presented here are presented in the Online Resource 3 with a summary description of the results.

5.1 Effects on the eye

Stereoscopic, bi-ocular, and monoscopic displays all cause different strains on the eye which may affect the eye's normal function. As such, studies on rendering modes tend to focus

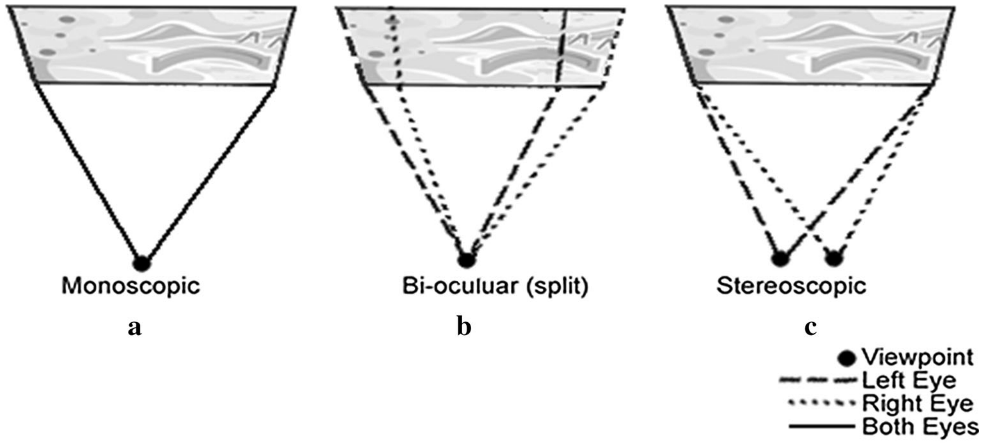

Fig. 4 Viewpoint rendering options

on the eye function itself rather than using the SSQ or postural stability. There are several methods to test for eye function change, the most common being measurement of heterophoria. Heterophoria is defined as a deviation of eye position kept latent with stereo fusion. This means that an eye moves from its resting position if the other eye is covered or stereo fusion has otherwise been inhibited (see Fig. 5).

Heterophoria can be measured by several different methods and often clinically measured with prism and a cover–uncover test. For more detail on the techniques to measure heterophoria, see Rainey et al. (1998). Most individuals have a minor amount of heterophoria, but the amount may be affected by having near or far vision.

The studies employing heterophoria consistently report that HMDs can induce increased heterophoria, but the level of effect for different rendering modes is not known and the exact cause is uncertain since there is high individual variability. The studies presented here measured horizontal heterophoria. Mon-Williams et al. (1998) used this measure to test five different gaze angles, or the vertical angle

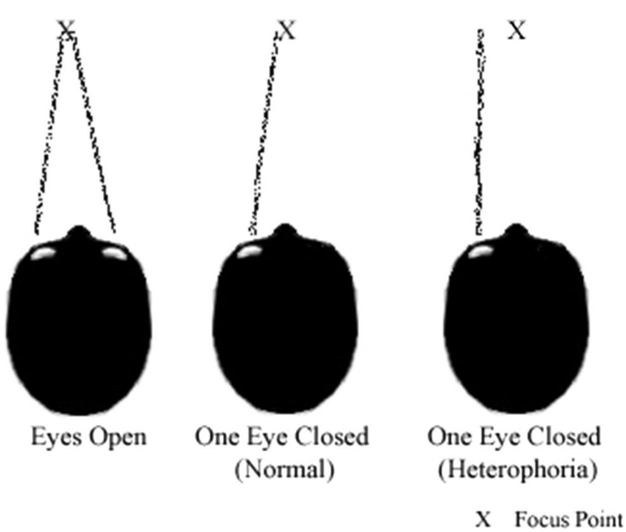

Fig. 5 Horizontal heterophoria

of gaze relative to the ear–eye line (drawn from the center of the ear to the center of the eye: 20° above, and 0°, 20°, 40°, and 60° below ear–eye line in an HMD). They found post-immersion heterophoria varied with gaze angle with the smallest change occurring at 34° below the center ear–eye line on average, which corresponds nearly to looking directly forward. While there is a fair amount of individual variability, in general the further the gaze was from this line, the greater the heterophoria. Howarth (1999) also employed heterophoria when he investigated whether different HMD configurations could cause varying heterophoria effects. Three different HMDs were tested. The first was bi-ocular with a 60 mm interpupillary distance (IPD) and a field of view of $30° \times 23.6°$, the second was bi-ocular with a 70 mm IPD and a field of view of $60° \times 46.8°$, and the third was stereoscopic with an IPD of 64 mm and a field of view of $105° \times 41°$. An IPD of 64 mm is the human average. Each configuration had a significant effect on heterophoria, but they found no correlation between the amount of IPD disparity and the measured heterophoria. The differing display IPDs did show slight trends of inward (first and third HMDs) or outward (second HMD) heterophoria with smaller and larger IPD, respectively.

Combining these results, they imply that correct alignment with the eye and limited movement of the display relative to the eye will decrease the effect on eye function. Kolasinski and Gilson's (1998) study supports this theory when investigating whether the correct alignment of the participant's IPD to the HMD's interpupillary distance had an effect. They measured eyestrain rather than heterophoria and reported the strain on the eye became more severe the farther the display's IPD was from a participant's physical IPD. This implies the display's IPD should be set, at most, as far apart as the participant's IPD.

Another method that measures the effect on the eye directly is the pupillary light reflex, which is defined as how much the pupil diameter changes under lighting changes. Oyamada et al. (2007) examined this effect. They presented three different stereoscopic movies: A (computer-generated random imagery with substantial movement), D (computer-generated story with dinosaur and in which the participant was attacked by a Tyrannosaurus Rex at the end), and R (real imagery of a rollercoaster). They found the reflex was larger for movies A and D only, both of which were computer generated. The nature of the imagery is difficult to quantify, but implies that level of detail and shading may have an effect on cybersickness.

The effectiveness of stereoscopic perception is a third measurement of the effect of virtual environments on the eye. Hale and Stanney (2006) considered if a person's stereoscopic disparity ability (the ability to discern stereoscopic distances in real life) would affect the probability of becoming cybersick in a virtual environment. Perhaps counter-intuitively, while those with poor disparity tended to travel more in virtual environments, they demonstrated no greater illness. This suggests that those with difficulty seeing stereoscopically will not be unduly affected. Stanney et al. (1999a, b) also tested stereoscopic disparity by pointing accuracy. They examined how accurately a person could point to a target immediately after closing their eyes. They found that after virtual environment immersion the accuracy in the vertical direction was significantly worse than before, but not in the horizontal direction. This is a safety concern since cybersickness interferes with distance perception.

5.2 Stereoscopic versus monoscopic versus bi-ocular

There have only been a few studies directly comparing stereoscopic versus other rendering modes in cybersickness. It is often assumed that stereoscopic images and bi-ocular will increase symptoms, but results have been varied. Many studies imply that despite the greater disparity of the visual stimulus presented from real life, bi-ocular displays are gentler on the eyes. In some instances, bi-ocular is equivalent to monoscopic (Keshavarz et al. 2011). Others, such as Seay et al. (2002), had interactions between the independent variables, and thus, the effect of the rendering mode was inconclusive.

In studies using heterophoria, stereoscopic viewing regularly induced strong effects. Hakkinen et al. (2002) reported more postural sway and higher cybersickness scores for a stereoscopic game using an HMD than for a bi-ocular movie using an HMD or a movie with a normal screen. Whether this difference was due to the different visual stimulus of the game or due to the stereoscopic images is unknown. Mon-Williams et al. (1995) used heterophoria to determine the effect of stereoscopic viewing. They found after 10 min of HMD use all, but one of their participants had significant increases in heterophoria, while a bi-ocular display had little effect after 30 min. In contrast, Howarth (1999) demonstrated less heterophoria after using stereoscopic displays than after using bi-ocular displays, although this may be an effect of stereoscopic IPD being set to an average IPD while the bi-ocular displays were set either smaller or larger than the average. Karpicka and Howarth (2013) examined this effect in greater detail. They found statically significant effect in heterophoria with a stereoscopic display, but not in a bi-ocular display. However, those developed heterophoria did not report greater level of discomfort than those that did not.

Studies comparing stereoscopic displays have shown variable results. Ehrlich (1997) examined several factors including stereoscopic versus bi-ocular viewing. The SSQ-N score was higher for stereoscopic than bi-ocular. However, all other SSQ categories followed the same trend. Other studies provide a less clear distinction. Keshavarz and Hecht (2012) examined whether stereoscopic rendering would increase cybersickness during a rollercoaster ride when the head is held stationary. They compared real stereoscopic video of a rollercoaster, stereoscopic rendering of a 3D model of the same rollercoaster, and a monoscopic version of the real and modeled rollercoaster. They found the real stereoscopic rollercoaster cybersickness scores to be higher relative to the other conditions, with no significant differences between each of the others, which suggest increased depth information increases cybersickness. Naqvi et al. (2013) directly compared monoscopic and stereoscopic movies and found stereoscopic movies have higher cybersickness. Rebenitsch (2015) initially showed no effects of rendering mode, but later found that stereoscopic rendering affects the likelihood of becoming cybersick, but not how severe. This means the demographics of the participants could easily mask the effect.

Keshavarz et al. (2011) examined differences in symptoms between an HMD and a large screen, specifically addressing the question of whether the differences reported earlier were due to the large screen being monoscopic while the HMD was bi-ocular. They accomplished this through a device they called a synopter that converted the large screen into a bi-ocular presentation. They found no difference between the monoscopic and bi-ocular conditions.

Differing results in the studies may be partially due to the nature of the application used as stimuli. Mon-Williams and Wann (1998) demonstrated the importance of the specifics of a task when studying the effect of stereoscopic displays. They tested four conditions: bi-ocular, stereoscopic with a small depth range (max change = 5 cm), stereoscopic with a large depth range (max change = 5.5 m), and stereoscopic where the focus point shifted along the fore-aft axis. There were no significant effects between the first three conditions, but a stereoscopic display with a shifting focus point resulted in a significant increase in sickness ratings, visual acuity, and heterophoria when focusing at a distance. This implies that the effect on the eyes is more severe when the vergence of the eye changes frequently while the accommodation of the eye remains identical due to the set screen distance. Wibirama and Hamamoto (2014) also supports this when comparing the effect of having a focus point or allowing the gaze depth to change and showing the same results. Yang and Sheedy (2011) specifically looked at accommodation and vergence as a result of watching stereoscopic movies. A stereoscopic movie produces a greater variance in vergence and accommodation than a monoscopic movie, and the amount of vergence and accommodation is farther from ideal in a stereoscopic setting than in monoscopic setting. The effect on vergence was stronger when viewing far targets while the effect on accommodation was stronger when viewing near targets. Vlad et al. (2013) directly support the effect on task by comparing several different stereoscopic tasks in both stereoscopic televisions and HMDs. By focusing on the realism of an environment, there appears to be increases strain on the eyes which increases cybersickness as does focusing on the depth of an object in an image.

5.3 Field of view

Field of view has been receiving more attention in recent years. In simulators, the field of view may be as much as 360° × 360° in a cockpit mock up, but in most virtual environments, the field of view is more restricted. However, displays with a wider field of view are becoming available. While this increases the realism of the virtual environment, there has been anecdotal evidence that the increase in cybersickness reports is correlated with the increase of field of view for virtual environments. Cybersickness studies involving multiple fields of view strongly support this theory.

The effect of field of view is large. The following studies reported statistically higher cybersickness for small changes. Seay et al. (2002) examined field of view, passive versus active control of the viewpoint, and stereoscopic versus monoscopic viewing. They reported the SSQ-T score was higher for a 180° field of view than for a 60° field of view even when not controlling for level of user control and stereoscopic/monoscopic viewing. Duh et al. (2001c) agreed with these findings when they analyzed the effect of fields of view of 30°, 60°, 90°, 120°, 150°, and 180° for two virtual environment scenes moving in the same pattern (a city and a black and white radial pattern). For the radial pattern, each increase in field of view significantly increased reported symptoms except between 30° and 60°. The largest increase was at the 120°–150° interval. For the city pattern, all intervals were significant except for 30°–60° and 120°–150° with the largest increase at the 90°–120° interval. There was no statistical difference in ratings between the scenes. Harvey and Howarth (2007) examined this effect with the use of different size screens. They considered small (39 inch.), medium (70 inch.), and large (230 inch.) screen sizes with identical luminance in each condition. Sickness ratings increased with screen size. Lin et al. (2002) as reported a steady increase in symptom from 60°, 100°, 140°, and 180°. There was a significant different between 100° and 140°, while the effect largely plateaued between 140° and 180°.

This suggests that field of view is a significant factor in cybersickness, but scene content also contributes. Dizio and Lackner (1997) reported that halving the field of view also halved the symptoms although the exact values were not reported. Examination of the data from Duh et al. (2001c) demonstrates the same level of effect with the ratings approximately doubling from 30° to 60°, from 60° to 120°, and from 90° to 180° for a city scene.

Aside from the physical field of view of the display, there can also be a difference between the physical field of view and the field of view of the rendered scene. The scene may be rendered incorrectly because the display field of view is not known or because the designer has chosen that effect so as to display more content or achieve a specific visual effect. For passive presentations such as motion pictures, the rendered or captured field of view is dependent on the camera placement and the ratio of physical to rendered field of view may vary continuously.

A non-unity ratio between the rendered and physical field of view was not examined until fairly recently as it was assumed the ratio should be one to one. “Virtual field of view” is defined as the field of view of the virtual camera used for rendering the scene, and “real field of view” is defined as the field of view of the actual display. Figure 6 provides an example of how these fields of view may differ. Figure 6b shows a one-to-one ratio, while Fig. 6a shows a one to two magnifying condition (virtual field of view < - real field of view) and Fig. 6c shows a two to one minifying condition (virtual field of view > real field of view).

Toet et al. (2008) demonstrated the possibility that this ratio may be better as something other than one to one. They examined the field of view ratio with a projection screen by altering the viewing distance and found a one-to-one ratio increased cybersickness over differing ratios of the fields of view. They hypothesized that this was due to the visual–vestibular system finding the visual stimulus so unnatural it did not draw upon it to determine which way is “up” which is necessary for cybersickness to occur according to rest frame theory.

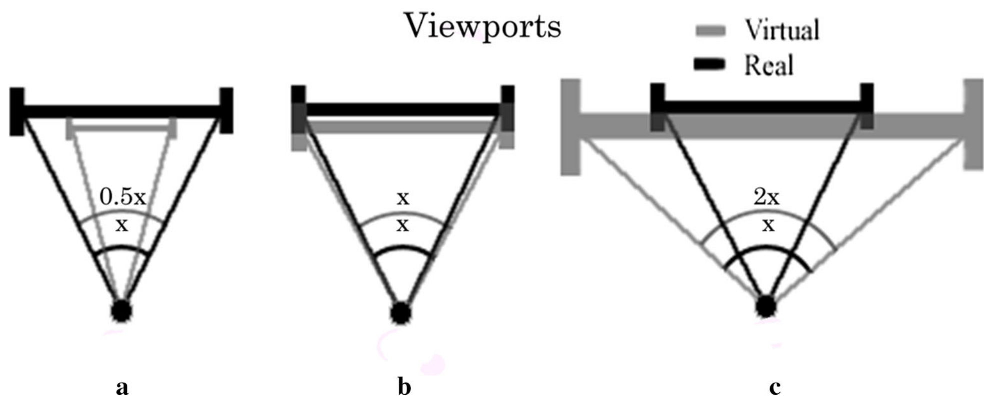

Fig. 6 Virtual field of view and real field of view ratios

Bos et al. (2010) analyzed the effect of both increasing real field of view and increasing ratio of the real to the virtual field of view. They reported the virtual environment demonstrated a strong cybersickness effect. They used regression analysis to determine the size of the effect of the variables and showed a moderate negative effect for the ratio and large positive effect for the real field of view. Their four conditions displayed a significant habituation effect, but the order of the experiments was not specified. van Emmerik et al. (2011) extended this examination with additional real and virtual field of view combinations. Using the five data points from this experiment and the four points from the original experiment (Bos et al. 2010), they applied linear regression to model the effects. The results supported their earlier findings that increasing the ratio between the real and virtual field of view decreases sickness ratings.

Draper et al. (2001) had previously found the reverse was true that a two to one real to virtual field of view ratio increased symptoms. They found a significant increase in sickness ratings in both minifying and magnifying conditions. Conflicting with all four studies is Moss and Muth (2011) who found no effect due to the ratio.

Van Emmerik, *de Vries*, *and Bos* argue that the discrepant results of the correct ratio may be primarily due to the effect of the real field of view. Their study's smallest field of view (40°) was larger than the largest field of view (25°) from Draper et al. Given the demonstrated effect of larger real fields of view and the doubling of symptoms with twice the screen size that *Dizio and Lackner* reported, this explanation is plausible. Draper et al. also used a panorama image for their environment that lacks the foreshortening and object occlusion that exists in most virtual environment experiments. *Moss and Muth* used a field of view of 50°, but the difference between their ratios was smaller than either *Van Emmerik*, *de Vries*, *and Bos* or *Dizio and Lackner* and included different peripheral occlusions. They did not find an interaction between the rendering ratio and peripheral vision, but they reported a high rate of dropouts and a change in procedure midway that could have impacted their results.

6 Application aspects

When implementing a virtual environment, the designer has their choice of software, hardware, participant, application, and interface design. Software and hardware offer some control over the speed and level of detail that may be rendered smoothly in the environment. Researchers may wish to select participants to adjust for susceptibility, but frequently there is limited availability of participants. Application and interface design are less restricted when creating a virtual environment and an effective design can be used long term.

Navigation, scene complexity, and rotation design have received the most attention in cybersickness research as these are part of most virtual environment interfaces. Independent visual backgrounds are a recent development, but show promise in decreasing cybersickness. Most of the factors presented in Kolasinski (1995) under their simulator (display and viewing) and task columns have had one or more studies. A condensed summary of the publications is available in the Online Resource 4.

6.1 Navigation and scene complexity

Most virtual environments provide the participant some form of interaction or navigation with the environment. Those that do not are similar to stereoscopic movies. Two commonly examined aspects in cybersickness are navigation speed and the directions the participants may move. Scene complexity is presented alongside navigation speed since several of the studies on scene complexity are coupled to navigation speed. To increase the optical flow (a measurement of the change of the image over time), and therefore scene complexity, the speed at which the visuals are presented is often increased making the effects of speed and scene complexity correlated. Navigation directions are defined as shown in Fig. 7.

Navigation also presents an unexpected problem associated with the sensory mismatch theory. Participants in a virtual environment tend to identify distances incorrectly, generally underestimating the distance and thus causing a sensory mismatch when moving (Ehrlich 1997). Jaekl et al. (2005) examined the extent participants underestimate distances. Their participants looked left and right, adjusting the movement of the virtual environment until the participant stated it was moving by the same amount as their head. They found that head movement is not equal to the movement of the virtual environment. On average, the gain on rotation was 1.2 for all axes and the gain on translation was 1.4. Sensory mismatch will occur since participants feel as though they have not traveled as far as the actual translation or rotation in the virtual environment. Freitag et al. (2016) later confirmed a similar effect in CAVEs, but only found a trend with cybersickness scores with visual gain. The cause of this effect is currently unknown, but it could partially explain disorientation symptoms in virtual environments.

There was an early effort among some researchers to define a "dose value" for a virtual environment given its optical flow and other factors. So (1999) proposed the cybersickness dose value (CSDV). CSDV is modeled after the motion (sea) sickness dose value's (MSDV) which predicts sea sickness in passengers given the frequency and acceleration in the vertical direction. It is defined as the integral of "spatial velocity" over time multiplied by display, task, and individual scaling factors. So et al. later tested the spatial velocity metric in an attempt to define an objective measure of the visual stimuli in a scene and therefore provide a theory on the relationship between navigation speed, scene content, and cybersickness. They

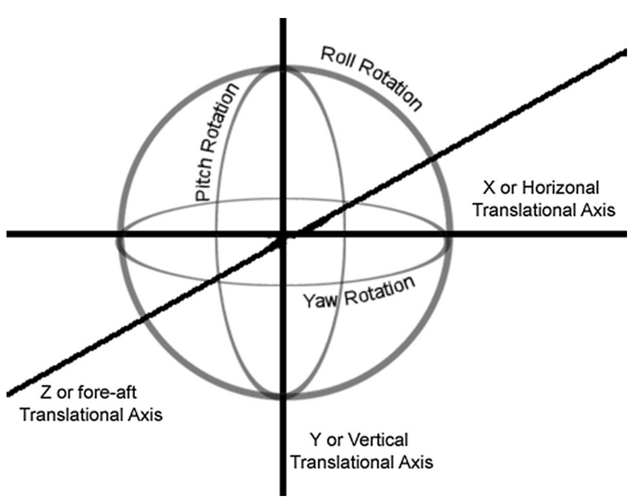

Fig. 7 Translational and rotational axes

defined this measure of scene complexity using the luminance frequency along the horizontal, vertical, and radial axis, and navigation speed (So et al. 2001a, b). They found a correlation with spatial velocity and symptoms when increasing scene velocity in the fore-aft direction and yaw rotation.

Anecdotally, lower observed cybersickness symptoms have been reported if the navigation is very slow or sufficiently fast to blur the scene. Moderate speeds result in significant changes in symptomology. The peak speed is unknown as the effect of navigation speed may vary with the application and other factors can mask its effect. So et al. (2001b) considered the effect of navigation speed in the fore-aft direction and rotation in the yaw axis using a virtual urban scene. They had eight conditions: 3.3, 4.3, 5.9, 7.9, 9.5, 23.5, 29.6, and 59.2 m per second. Initially, they found speed only had an effect on sickness ratings below 9.5 m/s and over 29.6 m/s. At speeds less than 9.5 m/s, the SSQ-T scores ranged from 27 to 47, and from 9.5 to 29.6 m/s the SSQ-T stayed between 45 and 50. They found the time spent in the virtual environment and the number of early withdrawals overshadowed the effect of speed, and concluded navigation speed still has an effect from 10 to 30 m/s. While increasing navigation speed typically increases cybersickness the underlying mechanism and the boundaries where effect slows are less certain. Budhiraja (2015) directly tested the effect motion blur, by applying blur filters on the image if the navigation speed exceeded a threshold. While there was not a significant effect on between subject analysis, within subject analysis presented more hopeful findings with the most cybersickness prone participants showing the most benefit from the mock motion blur.

There is also the possibility that navigation speed and changing scene content are only two factors in a larger issue. The navigation mode and level of control a participant may have can vary, and the literature suggests that smooth navigation with moderate control produces less cybersickness. Dorado and Figueroa (2014) compared stair versus ramps and three different joystick tilt to speed mapping functions. Ramps, which would provide smoother navigation, resulted in less cybersickness than stairs. The effect of the joystick tilt to speed mappings is less clear. Constant velocity and speed proportional to joystick tilt performed marginally better than adding starting and stopping acceleration. While having starting and stopping acceleration better map to real movement, it does not map to how a gamepad typically performs. Stanney and Hash (1998) considered the effect of navigation control with active (six degrees of freedom) control, active–passive control (three degrees of freedom with the chosen axes dependent on the given task), and passive (no) control using tasks from the VEPAB. Although, they used a

15 inch. screen, by using stereoscopic glasses and a distance to the screen of 6.5 inch., the system had a field of view similar in width to other virtual environments and thus is considered appropriate for this review. They reported all SSQ categories for active–passive control were lower than the passive control, and the SSQ-O and SSQ-T for active control were lower than passive control. A later study by Stanney et al. (2002) considered navigation control along with the effects of duration, scene complexity, and performance while holding the navigation speed steady. They found that the level of control (six degrees of freedom or three degrees of freedom) did affect nausea ratings, with the six-degrees-of-freedom condition inducing more sickness. A study by Serge and Moss (2015) compared head tracking with and without translation motion with a joystick. While initially, the translation-free condition did not show a significant effect compared to the joystick condition, the order in which participants use the virtual environment did affect their final sickness ratings. The sickness scores when viewing an environment with the joystick first were higher if participants viewed the translation-free environment immediately prior. Since the conditions were viewed in sequence, this could mean the joystick-free condition, while not statistically significant, was sufficient enough to affect the final scores.

The above studies suggest that restricting degrees of freedom in navigation controls may decrease susceptibility to symptoms. An alternate theory would be that an interface that "matches" the application well is less symptomatic. The research is less clear on the effects of naturalness of the navigation. Watanabe and Ujike (2008) held navigation speed constant, but examined the location of the user in the scene rather than the scene complexity. They compared height-varying navigation versus planar navigation in a hilly virtual environment. In the height-varying environment, the participant walked up and down the hills, while in the planar mode the participant moved over them at a steady absolute height. They found an increase in the SSQ-D score for the height-varying mode over the plane condition, but the SSQ-T scores were statistically the same. Jaeger and Mourant (2001) instead considered the effect of the navigation interface rather than the directions permitted in navigation. They compared forward motion controlled by a treadmill versus a 2D mouse. They reported that walking on a treadmill exhibited lower sickness scores than using the mouse. Similarly, Chen et al. (2013) compared two different six-degree-of-freedom interfaces: a joystick and head/body position. They found that using body position was significantly better in performance and produced less cybersickness than the joystick. Plouzeau et al.'s (2015) study suggests merely adding vibration mimicking walking to a virtual environment may have decrease cybersickness. Lastly, Llorach et al. (2014) also showed decreased cybersickness when participants were permitted to walk rather than use a controller.

The *Watanabe and Ujike* results suggest that navigation should be kept planar even if the environment is not, while *Jaeger and Mourant* and *Chen*, *Plancloulaine* et al. both suggest corresponding movement in the system with the movement in reality. The discrepancy may be due to the different visual stimuli. *Watanabe and Ujike* frequently blocked a large portion of the world from participant's vision when in a valley, while this did not occur in *Jaeger and Mourant* or *Chen*, *Plancloulaine* et al. As discussed in Sect. 6.4.2, flattening the environment decreases cybersickness and the planar condition would have the unintentional effect of flattening the environment when viewing from some fixed distance above the ground.

The studies presented thus far allowed the user to freely view the environment. However, this allows for different visual stimuli to be presented to the individual. One individual may spend time examining the environment, while the next may focus forward. To eliminate this variation, some studies restrict head movement and/or navigation control which guarantees near identical visual stimuli at the cost of a generalization more akin to stereoscopic movies than interactive virtual environments.

When head movement is restricted, it is the nature of visual stimuli relationship to cybersickness that is sought. Chen et al. presented a cave scene to their participants with all four walls textured identically and then translated the scene in the vertical, horizontal, and fore-aft directions. All navigation caused cybersickness, but no one axis was worse than the others (Chen and So 2011). Chen et al. (2012) presented a checker board tunnel to participants and oscillated the scene to imply forward motion at specific luminance frequencies. They tested 0, 0.05, 0.1, 0.2, and 0.8 Hz frequencies with the velocity held constant and found a significant difference between 0.05 and 0.8 Hz for vection ratings with 0.8 Hz having a lower score. These studies indicate that the axis of travel is not a main contributing factor in navigation cybersickness, and instead, the effects likely lie with scene content and navigation control.

6.2 Rotation

Though the ability to turn in an environment is only part of navigation, rotation is often considered independently. This is to limit possible correlation with other navigation modalities and to determine whether there is a specific axis with a higher incidence of cybersickness. Rotation directions are defined as shown in Fig. 7. There are different hypotheses for which axis is the most provocative. Pitch yields a similar visual stimulus as sea sickness, roll is a relatively unusual rotation and the visual/vestibular system may be less developed to handle it, and yaw is the standard rotation for turning, and therefore, the visual/vestibular system may be the most sensitive to discrepancies. In cybersickness research, there is no agreed upon "dominant" single axis of rotation that causes increases in illness.

Studies of rotation frequently indicate that no single rotation axis is worse than others, but there are possible interactions with the environment. So and Lo (1999) considered pitch, yaw, and roll axis rotations. While SSQ-N scores increased for all axes, no one axis was worse than the others

Bonato et al. (2009) instead examined simultaneous multiple axis rotations. A checker board room was presented to their participants along with a stationary virtual frame to give an "up" reference. They then oscillated the room around one axis or two. They found higher cybersickness ratings for the two axis rotation, and the participants were unanimous in their verbal agreement with this result. Keshavarz and Hecht (2011a, b) further explored the effect of multiple rotation axes. They had their participants ride a virtual rollercoaster with pitch, pitch and roll; or yaw, pitch and roll. Symptoms were increasing during the pitch-only condition, but slowed after approximately 5 min. The two axes and three axes condition produces more cybersickness than the pitch axis alone. Occasionally, rotation around a single axis is tested to determine the effect of rotation speed. Duh et al. (2004) examined the roll axis rotation with different oscillating frequencies to determine whether the frequency of rotation change could affect symptoms. They tested the frequencies of 0.8, 0.4, 0.2, 0.1, and 0.05 Hz in two virtual environments scenes: a tropical hillside scene and a black and white radial pattern. The 0.8 Hz rotation symptom ratings showed no statistical difference from the baseline, and the cybersickness score increased as the frequency decreased for both virtual environments. They extended the experiment to include physical motion. In their second experiment, they rotated the individual in the same axis as the visual stimulus, although not at the same frequency. The resulting perceived frequency was 0.2 or 0.06 Hz on average. They found the sickness ratings to be significantly higher for 0.06 Hz average rotation. This is similar to navigation speed in that an excess of movement appears to decrease cybersickness.

Liu and Uang (2012) expanded on effect of rotation speed by proposing a fuzzy warning system based on rotation speed about the vertical axis. They reported a significant difference only between 15 and 60 degrees per second although there was still an increase in symptoms from 15 to 30 and 30–45 degrees per second. Including a pitch inclination did not affect these results.

These results are unlike translational navigation where no particular direction appears to be worse than another. Multiple axes rotations do induce more cybersickness than single axis rotations. That may explain why six-degrees-of-freedom navigation induces more cybersickness than in some three-degrees-of-freedom implementations since the number of rotation axes is often limited.

6.3 Independent visual backgrounds

The use of an independent visual background (IVB) appears promising for cybersickness. Two studies by Duh et al. considered the effect of a grid overlaid on the environment (see Fig. 8a) that never moves relative to the individual, and found similar results in both experiments. Duh et al. (2001b) placed a grid at one of the three different depths in front of the participant and at two different intensities: bight or dim. Having the grid improved symptom ratings, but no one configuration was significantly better than another except for brightness. Duh et al. (2001b) displayed a dim, bright, or invisible grid to their participant along with a rolling virtual environment scene at two different frequencies (Duh et al. 2001d). They found a visible grid decreased cybersickness, but there was significant interaction between the grid and roll frequency. In a separate endeavor, Chang et al. (2013) employed grid lines when examining EEG detection for cybersickness. When using the grid lines, the SSQ-T fell significantly relative to an environment without the grid lines.

An alternative to grid lines is to permit the participant to partially see the real environment behind the virtual environment (see: Fig. 8b). Prothero et al. (1997) used a partially occluded HMD so the virtual room could be seen overlaid on the actual environment in two similar experiments. The primary difference was that the second experiment required focusing on the actual room. Their first experiment reported lower SSQ-T scores and fewer postural stance breaks in the independent visual background condition. The second experiment showed no difference with the condition on the SSQ-T, but fewer stance breaks for the independent visual background condition. The differing results could mean the additional focus on the background or the elimination of a participant from part of the analysis had an effect. The median score on the SSQ-T was identical between the two studies, but the standard deviation was different. Moss and Muth (2011) reported simply removing the peripheral occlusion molding from HMDs decreases cybersickness. These studies imply that even less obtrusive independent visual backgrounds decrease cybersickness.

In one sense, independent visual backgrounds are in conflict with studies that examined the impact of realism.

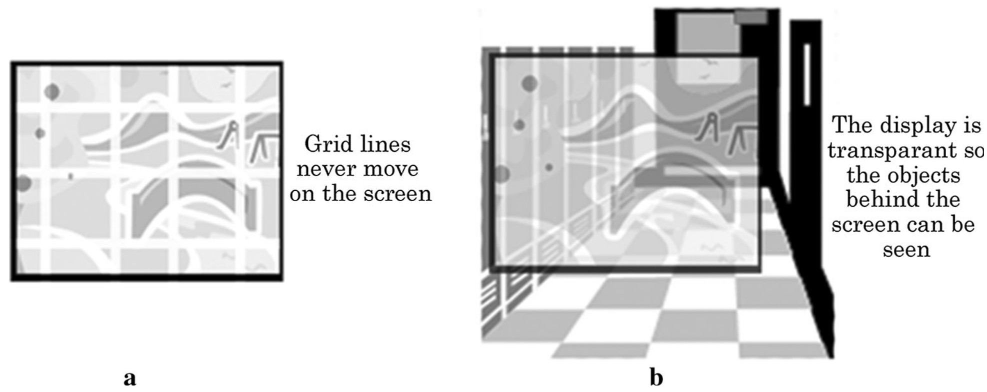

Fig. 8 Two different varieties of independent visual background in cybersickness research; **a** is an example of a grid overlay from Duh et al. (2001a) and **b** is an example of a transparent screen from Prothero et al. (1997)

These studies state than increasing realism, and therefore orientation cues, frequently increases symptoms. The difference lies in which environment's orientation is being emphasized. In realism studies, it is the orientation of the virtual world which is being emphasized, while in independent background studies it is the orientation of the real world.

6.4 Aspects with three or fewer studies

Potential causes of cybersickness extend further than duration, navigation, field of view, and rendering modes. Many of the other aspects have had minimal consideration with fewer than four studies, but each has the potential to further decrease the level of cybersickness. Some poorly understood aspects such as scene content may have large effects on cybersickness.

6.4.1 Tracking and position

Not all cybersickness studies use head tracking so it is reasonable to consider the advantages and disadvantages of head tracking. Howarth and Finch (1999) examined the nauseagenic effects of HMDs with head tracking and without head tracking where the view was altered with a hand-held controller. They found head tracking causes a greater sickness rating within 8 min of exposure, and the gap between the conditions continued to increase with time.

Dong et al. (2011), Chen et al. (2011), and Dong and Stoffregen (2010) also considered control over the environment, i.e., if the participant had any control at all. An HMD offers the advantage of guaranteed identical visual stimuli, so the recorded scenes from a "driver's" game play could be shown to a "passenger" so that they have an identical viewpoint and orientation. The passive participant exhibited higher sickness ratings in all instances. As they explain, this is not surprizing since passengers in a car have a greater incidence of motion sickness, so allowing participants to anticipate their movement decreases cybersickness and may also partially explain the habituation effect.

There is also the issue as to whether the position in which a participant views the virtual environment can contribute to cybersickness. Merhi et al. (2007) investigated whether a participant's posture in the virtual environment could affect the sickness rating. Their participants either stood or sat during the virtual environment immersion. All of those standing withdrew early due to symptoms, and there was no difference in symptom ratings between those that withdrew early while sitting. Therefore, seating participants should lessen the frequency of cybersickness. Increasing the amount of tactile information from reality seems to decrease the incidence of cybersickness, as Moss and Muth (2011) imply. They altered their procedure midway to include a hand rail due to a high dropout rate.

6.4.2 Scene content

Scene content may also affect sickness ratings, but defining how particular content affects cybersickness is poorly understood. Most studies considered one particular aspect without regard to its relation to a larger system. Nichols et al.'s (2000) offers the most general explanation. In their second experiment, they analyzed the correlation of the sense of presence of an "interface" and its effect on cybersickness where the "interface" was defined as: "…whether the interaction devices or display quality interfered with the virtual experience…" They found a negative correlation with the "interface" and all SSQ categories. This may be related to the demand characteristics of the SSQ and suggests that if a participant is sufficiently distracted, they may not notice milder symptoms.

Diels et al. (2007) considered another aspect of the interface design: if the location on the screen on which a person was required to focus could affect symptoms. They displayed a scene consisting of an expanding–contracting random dot pattern oscillating around the center of the screen and along the fore-aft axis. The cybersickness scores were significantly higher with a shifting or off-center focus point. This implies that an application should be designed with its content focused around the center. This is similar to the results presented in the Sect. 5.1, where increased eye movement increases symptoms.

6.4.3 *Realism*

One aspect of most virtual environments is that the implied "up" direction agrees with the visual and vestibular cues. More realistic environments provide more cues as to orientation. Golding et al. (2012) examined the extent that providing "up" visual cues could affect cybersickness. Their pilot experiment showed a panorama that was tilted, inverted, or was abstracted to remove any horizontal or vertical cues. They found no differences among the conditions. They restructured the conditions so that the visuals were that of a real scene from Westminster Bridge rather than a perfectly flat landscape. They found that the upright condition had significantly higher cybersickness than the inverted condition. As they explain, the inverted condition was likely considered so unlikely it was not used to determine the "up" direction. The study also implies that vertical cues are of greater importance than horizontal cues.

Related to orientation of visual cues are the quality and number of the models as they affect the number of cues, but little research has been done on the effect of level of realism on cybersickness. Jaeger and Mourant (2001) considered level of detail directly. They found SSQ-Ts 16.2 for lower detail and 20.0 for higher detail. Liu and Uang (2011) reports similar results. They reported a three-dimensional model condition produces more cybersickness than two-dimensional images.

6.4.4 *Single study aspects*

Lastly, there are several somewhat different studies, each being the only study considering a particular aspect. Clemes and Howarth (2005) decided to consider hormone levels as a possible reason for females having higher sickness ratings in virtual environments. They reported that the hormonal levels of the menstrual cycle do contribute to a participant's susceptibility and are higher on day 12 of a 28-day cycle.

So and Lo (1998) considered if there is a claustrophobia effect that may contribute to symptoms when using an HMD. They found that viewing a yaw axis rotation increased symptoms, but that simply wearing the HMD did not.

Ling et al. (2011) examined the level of effect of anxiety on cybersickness scores since the symptoms overlap. They placed 88 individuals in a neutral room, and those that showed no cybersickness were then placed in a virtual public speaking environment. They found a significant correlation of cybersickness scores with anxiety scores.

7 Where to learn more

Cybersickness has drawn heavily from the related fields of motion sickness, VIMS, and simulator sickness. The research in these fields is largely based on the visual and vestibular systems. (LaViola 2000), Virre (1996), and (Ukai and Howarth 2008) suggest how visual display systems can be better designed to cope with the human vision and vestibular systems. VIMS studies often use moving rooms and optokinetic drums. Studies have shown very similar results with moving rooms or optokinetic drums and virtual representations of these environments (Yang et al. 2011) and (Villard et al. 2008). Simulator sickness is closely related to cybersickness, but the symptom profile is often different and less severe than that of virtual environments. "A Summary of Simulator Sickness Ratings for U.S. Army Aviation Engineering Simulators" offers an overview of current military simulator sickness research (Hicks and Durbin 2011). "Configural Scoring of Simulator Sickness, Cybersickness and Space Adaptation Syndrome: Similarities and Differences?" offers an earlier comparison of different symptom profiles of military simulators, sea sickness, and space sickness (Kennedy et al. 2003).

Studies of these systems include not only application and testing design, but susceptibility, hardware, and other human factors. Kolasinski (1995) listed numerous aspects that may affect cybersickness, some of which have gained considerable attention while others, such as perception style and contrast, lack experimental results. Renkewitz and Alexander (2007) updated this list and the current state of knowledge on some factors not previously included, such as lag. "Postural Instability Induced by Virtual Reality Exposure: Development of a Certification Protocol" provides an explanation of the validity of using postural stability as a measurement of symptoms (Kennedy and Stanney 1996). For a review of earlier studies and an explanation of the social effects these issues may have, see "Effects of Participating in Virtual Environments: A Review of Current Knowledge" (Wilson 1999).

The additional movement in motion base, or dynamic, simulators results in further factors to consider. For readers interested in motion base simulators, Aykent et al. (2013) compared the effect on the inner ear with motion sickness in static and dynamic driving simulators. Dziuda et al. (2014) compared good and bad visibility in static and dynamic driving simulators. Marchal et al. (2011) proposed a tilting platform over a traditional joystick. Bos et al. (2012) present the effects of a naval and air dynamic simulator with anti-motion sickness backgrounds. Quinn (2013) presents a similar study with horizon lines in a 360° field of view dynamic simulator, but also examined the effect of the placement of the screens in a simulator. Benzeroual and Allison (2013) compare a Kinect with traditional controller navigation. Casali (1985) presents an overview of static and dynamic military simulators, while McCauley (2006) presents a more recent overview with emphasis on motion platforms.

Development of general guidelines has proved difficult as precise cybersickness predictive models are lacking. So (1999) proposed the cybersickness dose value which considers scene content and velocity which initially showed good results. However, a later study by So et al. (2001a) expressed their reservation regarding the effectiveness of this model when they found that scene complexity did not significantly affect the level of cybersickness. Kolasinski's (1995) linear model explained 34 % of the variance with several factors. Rebenitsch (2015) recently reported a linear model for predicting cybersickness with an adjusted variance of over 35 % for demographics and 55 % for software and hardware and suggested alternative mathematical models that better fit cybersickness data.

8 Summary

The state of knowledge of cybersickness for application design, display systems, and rendering modes has advanced considerably since 1995. The assumption that simple improvements in technology will eliminate cybersickness is now considered incorrect. Reports of cybersickness have actually increased with improving technology and will likely continue to increase. Cybersickness research efforts decreased for a time in the early 2000s, but has seen renewed interest with the increased production of virtual display technology and stereoscopic movies. There are numerous factors that potentially contribute to cybersickness, and the methods for objective detection are still in development. As such, even the most studied aspects have fewer than six empirical results, with many having fewer than three.

Theoretical foundations to unify the results are lacking. This is a consequence of having a large number of potential factors which have spread experimental results out of necessity. This has limited the ability to create guidelines for any particular virtual environment implementation. Moreover, though there are few cross-display studies, these studies generally report differences among the displays, which results in a broad set of guidelines for virtual environments being unlikely in the near future.

While general guidelines are unavailable, certain aspects have shown consistent, promising results for developing low cybersickness systems. Narrowing the horizontal field of view diminishes cybersickness as does partially limiting the degrees of freedom in control when navigating. Inclusion of the real world and increased tactile feedback appear to decrease symptoms. The ideal speed of navigation is still uncertain, but cybersickness generally increases with increasing speed. Research in other aspects is often in conflict.

Measurement of cybersickness presents its own issues. While the SSQ from Kennedy et al. (1993) is regularly used, the scores are not always reported, making comparison of studies difficult. Moreover, the SSQ has some disadvantages such as administration times and over sensitivity. As a consequence, single-question rating scales are frequently employed, but tend to be study- and researcher-specific. Two potential objective measures show promise. Postural instability is relatively easy to monitor and has been shown to exhibit correlation with subjective scores, although its predictive ability is currently limited. It also often requires a person to stay in one location and results in interruptions during immersion for measurement. More recently, there has been interest in assessing symptoms through physiological signals. Although the sensors tend to be uncomfortable, they do permit a greater range of motion and reduce the requirements for interruptions.

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