A Discussion of Cybersickness in Virtual Environments

Joseph J. LaViola Jr.

Abstract

An important and troublesome problem with current virtual environment (VE) technology is the tendency for some users to exhibit symptoms that parallel symptoms of classical motion sickness both during and after the VE experience. This type of sickness, cybersickness, is distinct from motion sickness in that the user is often stationary but has a compelling sense of self motion through moving visual imagery. Unfortunately, there are many factors that can cause cybersickness and there is no foolproof method for eliminating the problem. In this paper, I discuss a number of the primary factors that contribute to the cause of cybersickness, describe three conflicting cybersickness theories that have been postulated, and discuss some possible methods for reducing cybersickness in VEs.

Introduction

Virtual reality[1] (VR) is a promising technology which in recent years has become more and more popuar[33]. The ability to immerse a user in a virtual world through the use of 3D real-time computer graphics and advanced display devices such as head mounted displays (HMDs) or Caves[5] has been shown to be beneficial in a number of applications like education, entertainment, engineering, driving simulation, and flight simulation. However, a troublesome problem with VR is that, in some cases, users develop symptoms that are similar to the common symptoms found when people get motion sick. Users who exhibit these type of motion sickness-like symptoms suffer from a malady called cybersickness.

There are a number of symptoms that can occur due to cybersickness and motion sickness which include:

- Eye strain
- Headache
- Pallor
- Sweating
- Dryness of mouth
- Fullness of stomach
- Disorientation
- Vertigo[2]
- Ataxia[3]
- Nausea
- Vomiting.

Although both motion sickness and cybersickness produce the same types of symptoms, they are not necessarily the same thing. With the former, vestibular stimulation alone can be sufficient to induce motion sickness[24], although vision can also be a contributing factor[17]. With the latter, sickness can occur strictly with visual stimulation and no vestibular stimulation. However, there is no one exact cause

[1]. The terms virtual reality and virtual environments are equivalent for the purposes of this paper and will be used interchangeably.

[2]. Vertigo is a disordered state where the individuals surroundings appear to swirl dizzily.

[3]. 3. Ataxia is postural disequilibrium or a lack of coordination.

for cybersickness and is often described as a polygenic sickness[16].

Consequences and Implications of Cybersickness

There are a number of consequences and implications relating to cybersickness in virtual environments. One of the potentially dangerous problems with cybersickness is the possible after-effects that can develop in the hours following the VE experience. In many cases, symptoms can linger for hours[15] and, in some cases, for days[11]. In one of the more bizarre cases, a pilot had his view of the world invert 180 degrees while driving a car hours after the VE experience[18]. As a result of these types of after-effects, many air force bases have mandatory grounding polices which require that a pilot cannot fly an aircraft from anywhere from 12 to 24 hours after exposure to a VE flight simulator. Also, many VR entertainment centers require that users not drive for at least 30 to 45 minutes after exposure. One could argue that this is not enough time given some of the research results presented above. However, the exposure time for VEs in these entertainment centers is usually only a few minutes while VE flight simulator exposure is usually much longer, and the intensity of the experience is much more severe.

Besides flight and driving safety as a consequence of after-effects, cybersickness implies a decreased amount of VE usage. In general, people try to avoid getting sick, and if a VE experience causes cybersickness then people will just stop using the VE. Another important consequence of cybersickness has to do with compromised training in flight, helicopter, and other VE simulations. First, the training process can be interfered with if users are being distracted by various symptoms. Second, users may adopt behaviors to avoid symptoms in the simulation which would affect the driving/flying of the physical vehicle[19].

Analysis of the Vestibular and Visual Systems

We have seen in the previous section that cybersickness is problematic, and its causes and contributing factors must be understood in order to determine how to develop theories which can predict when cybersickness will occur and how to alleviate it. However, before discussing the three main cybersickness theories and how to alleviate the problem of cybersickness, it is important to understand the underlying physiology of the two main components that relate to self motion, the vestibular system and visual perception. Therefore, in this section, we briefly discuss the vestibular system, the visual perception of self motion, and the important relation between the two.

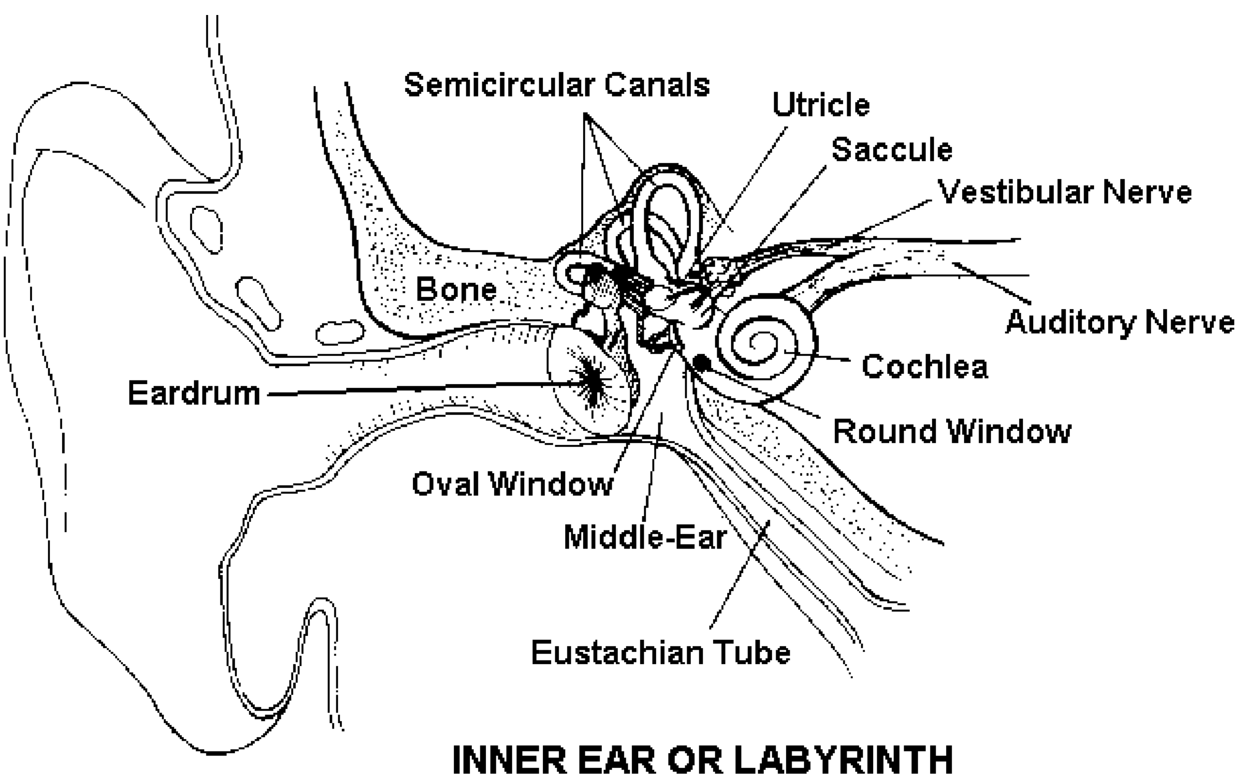

Figure 1: The various components that make up the vestibular system.

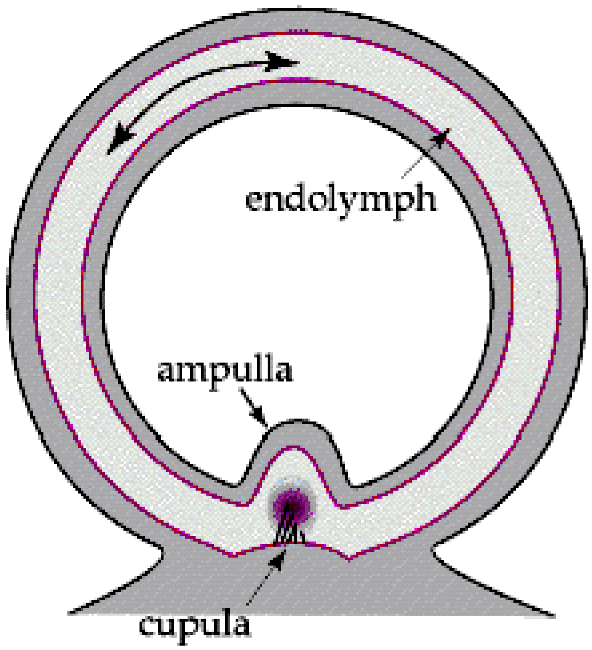

Figure 2: A cross section of a semicircular canal. The cupula sit in a small swelling at the base of the canal called the ampula. The figure is adapted from [22].

The Vestibular System

The Vestibular system, shown in Figure 1, provides information about the movement and orientation of the head in space[10]. It is comprised of the non-acoustic portion of the inner ear which consists of three semicircular canals for detecting angular acceleration and the utricle and saccule which detect linear acceleration.

The three semicircular canals correspond to each of the three dimensions in which human movement can take place. Therefore, each canal detects motion in a single plane. Each canal is filled with a fluid called endolymph, which flows through the canal as the head experiences angular acceleration. As the fluid flows through the canal, it deflects small hair-like cells, called cupula, which send signals to the vestibular receiving areas of the brain[29]. See Figure 2 for a cross section of a semicircular canal. Note that there are two vestibular components, one on each side of the head which mirror each other and act in a push-pull manner. Since each group of hair cells is polarized, they can be either excited (pushed) or inhibited (pulled) based on which direction the cupula move. It is important for both vestibular apparatuses to agree with each other. Under normal operation, one side of the head should push and the other should pull. If both sides are pushed, for example, vertigo will result.

The vestibular system also detects linear acceleration through the utricle and saccule. These two organs have a sheet of hair-like cells, called the macula, whose cilia are embedded in a gelatinous mass. The gelatinous mass has clumps of small crystals, called otolith, which provide the inertia required to drag the hair cells from side to side[22] to provide the perception of motion. Once a constant speed is achieved, the otoliths stabilize and perceived motion disappears with respect to the vestibular system. An example of this phenomena is sitting in a car when it first accelerates and then stabilizes.

As with the semicircular canals, the hair cells in the utricle and saccule are polarized but are arrayed in different directions. Each macula can cover two directions of movement. Since the utricle lies horizontally in the ear, it can detect any motion on the horizontal plane while the saccule is oriented vertically so it can detect up, down, forward and backward motion. Note that a major role for the utricle and saccule is to provide vertical orientation with respect to gravity. As an example, consider the constant small wavers and rocking back and forth when someone is trying to stand still. This is a direct reflection of the utricle and saccule at work.

The Visual Perception of Self Motion

When someone is in a stationary position, they can still get the impression of self motion under certain conditions. This deceptive impression of self motion is called vection[6]. Vection can occur, for example, when someone is in a stationary vehicle while an adjacent vehicle begins to move. Vection can also be produced with wide field-of-view displays (the same displays that are used in virtual environments) of optical flow patterns that are characteristic of self motion[13]. These optical flow patterns provide a temporal change in the structure of the optic array[4]. Optic flow patterns also provide a sense of self motion based on both translational and rotational components about a head-centered axis in three-dimensional space[8]. In standard self motion, these components would be accompanied by vestibular information, but with vection, the vestibular information is either not present or influenced by the optical flow patterns[17]. It is this visual-vestibular relationship which is the foundation for sensory conflict theory (see Section 3.1).

There are a number of important stimulus factors which determine the strength and duration of vection illusions. Field-of-view plays a significant role in causing vection since a larger field-of-view stimulates more of the retinal periphery[17]. The optical flow rate[5] is also a contributing factor to inducing vection since a faster flow rate will increase the perceived motion's speed thus making the illusion more intense. Finally, an important factor in the cause of vection is the apparent depth of the objects in the virtual

4. The optic array is a pattern of light intensities in different visual directions at a moving point of observation[34].

5. The optical flow rate is the perceived forward speed scaled in terms of the height of the eye above the ground surface.

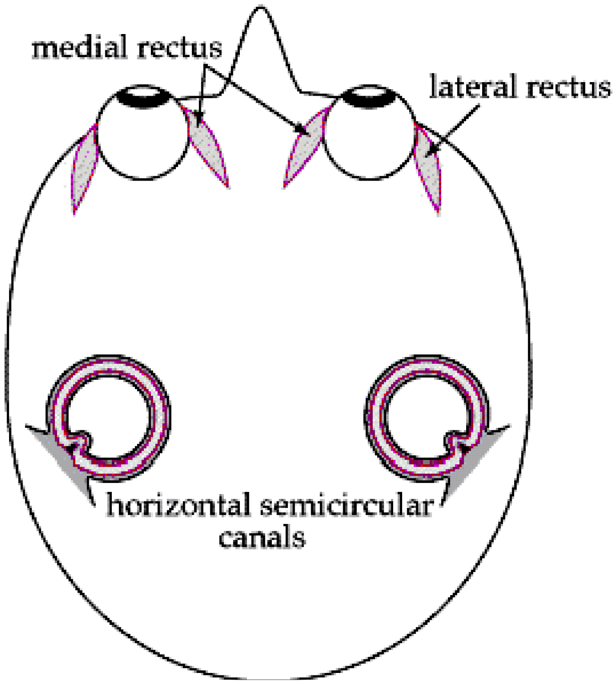

Figure 3: A top down view of a person's head showing the horizontal semicircular canals and the medial and lateral rectus. The figure is adapted from [22].

environment. In applications where the user does not have to perform significant virtual travel techniques and objects are close to the user, such as automotive design or virtual prototyping, vection will be limited. However, with applications such as driving and flight simulation, motion is inherent to the application which will provide more stimulus cues to induce vection[21]. Note that there are more physiological factors dealing with vection due to the complexities of the visual system. A discussion of these factors is beyond the scope of this paper. The interested reader is encouraged to explore both Gleitman[10] and Sekuler[30] for more information.

Relationship Between the Vestibular and Visual Systems

There is an important relationship between the vestibular and visual systems in that the semicircular canals keep the eyes in place when the head moves. The semicircular canals exert control over the eyes so they can compensate for head movements. The eyes are controlled by three pairs of muscles, the medial and lateral rectus, the superior and inferior rectus, and the inferior and superior oblique[30]. Each semicircular canal interacts with a single eye muscle pair. This compensatory reflex is known as the vestibulo-occular reflex[6] .

To describe the vestibulo-occular reflex consider the following example. Figure 3 shows the horizontal semicircular canals and the medial and lateral rectus muscles which will contract or relax the eye in the horizontal plane.

If the head moves to the left and the eyes are to be fixed on a stationary point, then the head motion will excite the left horizontal canal and inhibit the right horizontal canal. The left horizontal canal will send messages to the right lateral rectus and the left medial rectus in order to pull the eyes to the right. Note that since the right horizontal canal is inhibited, it has no effect on the eye muscles. See Figure 4 for more details.

Cybersickness Theories

Now that we have discussed the two most important parts of the body that are associated with cybersickness, the question arises as to why and how does cybersickness occur. There are three main theories as to the cause of cybersickness namely the sensory conflict theory, the poison theory, and the postural instability theory.

Sensory Conflict Theory

The sensory conflict theory is the oldest and most accepted of the theories relating to motion sickness and cybersickness[29]. The theory is based on the premise that discrepancies between the senses which provide information about the body's orientation and motion cause a perceptual conflict which the body does not know how to handle. With cybersickness and motion sickness, the two primary senses that are involved are the vestibular sense and the visual sense. These sensory conflicts arise when the sensory information is not the stimulus that the subject expected based on his/her experience.

In the case of cybersickness, consider a virtual environment driving simulator. As the subject uses the simulation, the optical flow patterns of the road, buildings, and other parts of the environment move past the subject's periphery which gives him/her a sense of vection[7]. The visual system tells the subject a variety of information which includes that he/she is moving in a certain direction, accelerating when pressing the gas pedal and decelerating when pressing the brake. However, since the subject is not actually moving, the vestibular sense provides no sense of linear or angular acceleration or deceleration. Under normal physical driving conditions, the subject has both the vestibular and visual systems providing information and, as a result, this is the perception that the subject expects to have. When the subject does not get the expected response, a conflict occurs and cybersickness may ensue.

6. Note that much of this axon traffic travels via a fiber pathway called the medial longitudinal fasciculus (MLF).

7. The work of Hettinger has shown that, in many cases, vection is required for cybersickness to occur[14].

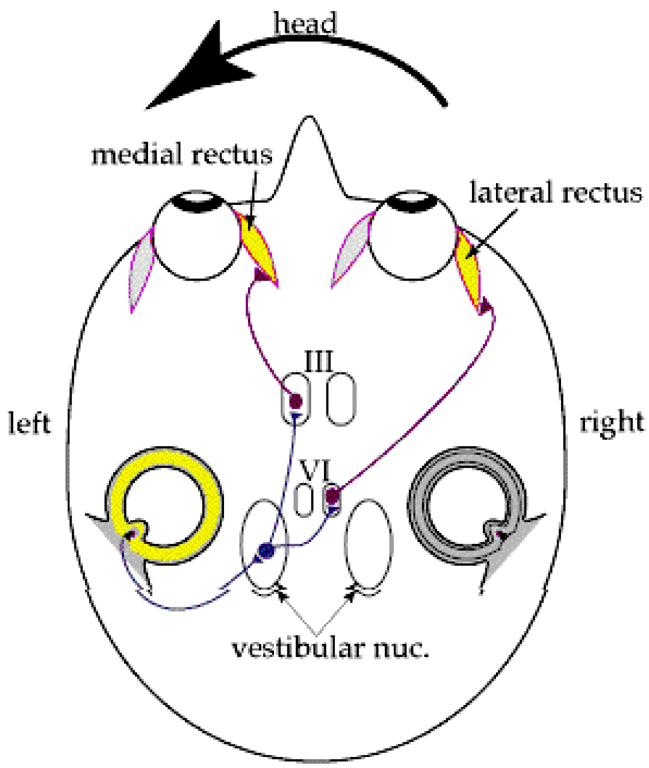

Figure 4: The pathway from semicircular canal to eye muscle is shown. Cells in the vestibular nucleus that received messages from the left horizontal canal are transmitted to an area called the abducens nucleus (VI) to stimulate the right lateral rectus and an area called the oculomotor nucleus (III) to stimulate the left medial rectus. The figure is adapted from[22].

Although the sensory conflict theory is the most widely accepted theory for the cause of cybersickness, there are a number of problems with it. First, it has little, if any, predictive power in determining if cybersickness will occur given a certain situation or how severe it will be, and it does not account for some of the other factors that have been associated with cybersickness (see section 4). Second, although the theory claims a conflict between vestibular and visual cues is a possible cause for cybersickness, it does not account for why some individuals get sick and why others do not given a set of identical stimuli. Finally, the sensory conflict theory claims that a cue conflict can cause cybersickness, but it does not provide an explanation for why such a conflict could make someone sick.

The Poison Theory

The poison theory attempts to provide an explanation for why motion sickness and cybersickness occur from an evolutionary standpoint[32]. The theory suggests that the ingestion of poison causes physiological effects involving the coordination of the visual, vestibular, and other sensory input systems. These physiological effects act as an early warning system which enhances survival by removing the contents of the stomach. The adverse stimulation found in some virtual environments can effect the visual and vestibular system in such a way that the body misreads the information and thinks it has ingested some type of toxic substance thus causing disturbing symptoms which lead to an emetic response.

The poison theory provides an interesting hypothesis for the occurrence of cybersickness and there has been some research that supports the theory[23]. However, it also lacks predictive power and makes no determination for why people who get sick in virtual environments do not always have an emetic response. It also does not provide any explanation for why some people get cybersick in VEs with a given stimuli but others with the same stimuli do not. Unfortunately, it is difficult to verify that this theory is valid.

The Postural Instability Theory

The postural instability theory, developed by Riccio and Stoffregen, is centered on the idea that one of the primary behavioral goals in humans is to maintain postural stability in the environment. In this case, postural stability is defined as the state in which uncontrolled movements of the perception and action systems are minimized[28]. This postural stability is constrained based on the nature of the surrounding environment. For example, consider walking on concrete and walking on ice. In general, people walk on concrete differently than they do on ice, and if someone tries to walk on ice as they do on concrete, they will usually fall down. However, the natural reaction to walking on ice is to change the walking pattern so as to maintain postural stability. Whenever the environment changes in an abrupt or significant way, in many cases, postural control will be lost especially if the control strategies are not available due to lack of experience. Eventually, the control strategy will be learned and postural stability will be attained once again. When someone has either degraded or completely lost postural control, they are in a state of postural instability.

Therefore, the postural instability theory states that the cause of motion sickness and cybersickness is prolonged postural instability[28]. In other words, postural instability precedes and is necessary to produce motion sickness and cybersickness symptoms, and the severity of the symptoms scales directly with the duration of the instability. So, the longer the duration of postural instability, the more severe the symptoms are. Also, symptoms will not occur if postural control is lost completely because the event is usually brief.

Now the question arises as to how the postural instability theory relates exclusively to cybersickness. There are a number of environmental situations that occur which can induce long periods of postural instability. Riccio and Stoffregen classified them into 4 distinct categories which include low-frequency vibration, weightlessness, changing relationships between the gravitoinertial force vector[8] and the surface of support, and altered specificity[28]. Cybersickness falls into the category of altered specificity. Since in many VEs there are optically specified accelerations and rotations that are unrelated to the constraints on control of the body, postural control strategies for gaining postural stability will not work. For example, a subject may use muscular force to resist the tilt of an angular acceleration which is visually perceived. Since there was no physical tilt the subject created an unintended divergence from a stable position causing postural instability. According to Riccio and Stroffregen[28],

Postural instability will result whenever an animal links its control to patterns of stimulation that have ceased to be specific to those environmental conditions for which the control is appropriate.

The postural instability theory was devised in an attempt to refute the sensory conflict theory. It presents a important argument that makes the claim that the cause of cybersickness and motion sickness could not be sensory conflict[31]. The argument states that when the vestibular and visual system are in agreement they are receiving redundant information. So, if the two systems are not in agreement, then there exists a nonredundency of information. In many cases, this nonredundancy does not induce sickness and the sensory conflict theory has no explanation for why. As a result, it is not an adequate theory. However, the interesting thing to note is that the postural instability theory parallels the sensory conflict theory in many ways especially in terms of cybersickness. Whether or not it is a valid theory is uncertain although there has been some evidence to support that the sensory conflict theory is inadequate[27]. More research needs to be conducted to determine the validity of the postural instability theory.

Contributing Factors to Cybersickness in Virtual Environments

There are a number of other factors that have been shown to contribute to cybersickness in virtual environments that are not directly related to any of the three theories discussed in the previous section. In this section, we discuss some of the contributing factors that are associated with technology and with the individual. For a more complete list of reported factors that have caused cybersickness see [19][25].

Display and Technology Issues

The technology used to create virtual environments has come a long way in providing immersive VE experiences. However, due to imperfections in the technology, there are a number of problems (especially with visual displays) which have been associated with inducing cybersickness. Fortunately, with time technology improves so many of these problems could go away in the future.

Position Tracking Error

An important component of virtual environment technology is the ability to track the user's head and possibly limbs in physical space so an accurate representation of the user can be made in the virtual space. Also, the head tracking information gives the user the correct perspective when viewing in the VE. Position trackers are not one hundred percent accurate and depending how inaccurate they are will determine if they will cause cybersickness symptoms. These tracking devices also have a tendency to report slightly unstable information which will cause jitter. As an example, consider a jittery tracker attached to the user's head. If this tracker is used to update the user's view, then the view will be in constant uncontrollable movement even when the user is holding his/her head and body stationary. These types of problems have resulted in symptoms such as dizziness and lack of concentration[1].

Lag

Lag represents the time between the user initiating an action and the action actually occurring in the VE. A very common case of lag in VEs is the time it takes to send information from a head tracker to the computer, have the computer process the information, and then update the visual display. Imagine a user rotating his/her head 30 degrees to watch a passing car in the VE. If lag is significant, the computer will not immediately update the display, and the user will have to wait for the images to appear where they are expected to be. This delay is very unsettling and can cause cybersickness symptoms[25].

Flicker

Flicker is distracting, can cause eye fatigue, and has been shown to be a contributing factor for inducing cybersickness symptoms[12]. The perception of flicker has two interesting properties. First, it differs between individuals and depends on the flicker fusion frequency threshold[9] . Second, the likelihood that flicker will be perceived increases as the field of view increases since the peripheral visual system is more sensitive to flicker than the fovea[2]. One of the goals of virtual reality is to surround the user's field of view with visual stimulation. This goal represents a problem since the wider the field of view the more susceptible humans are to flicker. In order to reduce the possibility of flicker, the refresh rate of the system must be increased. A refresh rate of 30Hz is usually good enough to remove perceived flicker from the fovea[10] . However, for the periphery, refresh rates must be higher. As technology improves, these extremely high refresh rate visual displays should become more common and affordable.

8. Gravitoinertial force is the vector sum of the Earth's gravity and other forces that change a body's linear velocity relative to the Earth[7].

9. The flicker fusion frequency threshold is point at which flicker becomes visually perceptible[25].

10. The reduction of flicker also depends on the temporal characteristics of the display. A slowly decaying phosphor can effectively reduce the flicker fusion frequency threshhold.

Individual Factors

One of the most interesting questions about the causes of cybersickness is why some people get sick in certain situations while other do not. Unfortunately, this question is a rather difficult one to answer due to human complexity. However, there has been some work done in this area which sheds light on a few of these factors.

Gender

As it turns out, women appear to be more susceptible to cybersickness than men[1]. One of the reasons for this is that women generally have wider fields of view than men, and as discussed in the section 4.1.3, a wide field of view increases the likelihood of flicker perception.[19]

Age

Reason and Brand have reported that age differences play a factor in cybersickness susceptibility[29]. They state that susceptibility is greatest between the ages of 2 and 12 years of age. It decreases rapidly from 12 to 21 years and the more slowly thereafter. They claim that around 50 years of age, cybersickness is almost nonexistent.

Illness

Illness has shown to be a contributing factor which increases a person's susceptibility to cybersickness. In fact, Frank et al.[9] claims that someone who is suffering from illness, fatigue, sleep loss, hangover, upset stomach, periods of emotional stress, head colds, flu, ear infection, or upper respiratory illness should avoid using VE simulators.

Position in the Simulator

Positioning the subject in the VE can also play a role in the individual's susceptibility to cybersickness. When people use virtual environments they are usually sitting or standing. Based on the postural instability theory\cite{riccio1}, sitting appears to be the better position in which to reduce cybersickness symptoms since it would reduce the demands on postural control. Another situation in which positioning a user in the virtual environment can increase the susceptibility of cybersickness is in VE simulations where more than one person participates. User's who control the simulation are less susceptible to cybersickness than those who are passive participants[20]. This phenomena is analogous to someone who gets car sick as a passenger but does not get sick as the driver.

Cybersickness Reduction

We have seen that cybersickness is a problem that must be corrected in order for VEs to be usable by anyone who wishes to use them. So the important question arises as to how we can eliminate cybersickness or at least reduce its severity so people who are susceptible to cybersickness can use VEs. In this section, we discuss a number of ways that have been or could be used to reduce cybersickness symptoms.

Motion Platforms

According to the sensory conflict theory, if someone gets sick in a VE, there must be a cue conflict between the visual and vestibular systems. So, one idea for reducing cybersickness was to add motion platforms to the VE simulator[3]. By doing so, the user in the VE would get both vestibular stimulation and visual stimulation. Unfortunately, in many experiments people still got sick with the motion platform added to the VE simulation. Their sickness could be true motion sickness which is a possibility if the motion platform is aligned correctly with the visual input. The other possibility is that the motion platform was not aligned correctly with the visual stimuli and, as a result, there would still be a sensory conflict between the vestibular and visual systems. Research is still being conducted to determine if motion platforms can be used to reduce the severity of cybersickness symptoms.

Direct Vestibular Stimulation

Another possibility for reducing cybersickness is to use direct vestibular stimulation. This idea is similar to the motion platform concept but instead of using a large motion base, the user wears a device which sends electrical signals to the 8th cranial nerve which tricks the vestibular system into believing that there is linear or angular acceleration and deceleration taking place[4]. Using this device with the associated visual stimulation in the VE could reduce cybersickness and possibly eliminate it. However, there are a number of issues that must be considered if this concept is to be applied in practice. The first issue is whether or not the device can be accurate enough to produce fine sensations of motion with respect to the visual stimulation. If the device is not accurate enough, the same types of problems that occur with motion platforms will occur with direct vestibular stimulation. Another issue with this device is how much electrical current is needed to provide a compelling enough vestibular experience to truly induce the vestibular system to provide the brain with self motion information. Currently, no one has attempted to use this device in the context of cybersickness reduction so these questions remain unanswered. This is definitely an area for future research.

Rest Frames

The concept of rest frames is based on the observation that humans have a strong perception for things that are stationary[26]. Therefore, a rest frame is simply the particular frame which a given observer takes to be stationary. The rest frame construct is a way of summarizing much of the literature on spatial perception. It states that

The nervous system has access to many rest frames. Under normal conditions, one of these is selected by the nervous system as the comparator for spatial judgments. In some cases, the nervous system is not able to select a single rest frame.

In terms of cybersickness, if there is difficulty in selecting a consistent rest frame, people are more likely to get cybersick since they will have conflicting information on what is stationary in the VE and what is not. So in order to reduce cybersickness, the discrepancies which indicate conflicting rest frames needs to be removed. Prothero performed two experiments to test this hypothesis and found that creating an independent visual background which is in agreement with inertial cues can reduce cybersickness symptoms[26]. However, subjects were tested with a low-end head mounted display with a limited field of view and simple visual stimulation.

Adaptation

One of the more common approaches that has been developed and used in practice is to provide VE users with some type of adaptation program[21] to the virtual environment. By having users increase their exposure time gradually they can adapt to the virtual environment. Also, tasks that require high rates of linear or rotational acceleration should be gradually worked into the simulation so as to not shock the user's vestibular and visual systems. Unfortunately, using this adaptation scheme does not help the user readapt to the real world once the user is done with the VE. As a result, aftereffects and flashbacks can still occur. However, adaptation strategies still appear to be the best method for cybersickness reduction as long as the participant is willing to take the time to go through the adaptation process.

Conclusions

Cybersickness can present a significant problem for a number of individuals who use virtual environments both during and after the VE experience. It is problematic not just for the number of adverse effects it has but also in that it is difficult to predict on an individual basis and on an overall basis. Cybersickness is also difficult to predict because there are so many factors that can contribute to its cause both from a technological standpoint and an individual standpoint. Although the technological causes may pass with time, those causes based on individuality probably will not. Nevertheless, it is important to understand what the causes for cybersickness are so we can find way to reduce and possibly eliminate it.

A number of theories have been proposed which attempt to explain why cybersickness occurs and where it comes from. The oldest and most prominent is the sensory conflict theory which basically states that conflicts between visual and vestibular systems are the main cause for cybersickness. One of the newer theories to come out is the postural instability theory, a counter to the sensory conflict theory. This theory essentially states that long periods without postural control will cause cybersickness. Finally, a lesser known theory, the poison theory, claims that the cause of cybersickness is based on a maladaptive process which originally used to help the body get rid of toxic substances. All these theories have there pros and cons and it is difficult to choose one to be the true theory for the cause of cybersickness for a number of reasons. First, all three theories present valid arguments for the cause of cybersickness, yet in each theory an example for when the theory does not hold can be found. Another flaw with each theory is that they do not have a firm grasp for why one individual gets sick while another does not in identical conditions. Any complete theory as to the causes of cybersickness should take the individual into account.

Although the current cybersickness theories have flaws, they have been able to help determine the causes for cybersickness in some cases. They also have helped researchers develop some methods with which to reduce cybersickness and its associated symptoms. These cybersickness reduction methods have helped in some cases but not all of them. If a unified and complete theory which can determine the causes of cybersickness on an individual basis and provide the necessary predictive power is found, then perhaps cybersickness could be eliminated completely. Otherwise, just like motion sickness, cybersickness will be with us indefinitely.

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About the Author

Joseph J. LaViola Jr. is currently a Ph.D student in the computer science department at Brown University. He works under the direction of Andries van Dam in the Computer Graphics Group. His primary research interests include multimodal interaction in virtual environments, interaction for large scale scientific visualization, and user interface evaluation.

Author's Address

Joseph J. LaViola Jr.
Brown University
Department of Computer Science
Box 1910
Providence, RI 02912 USA
Phone: 1-401-863-7662
Email: jjl@cs.brown.edu