virtual worlds

Review

Virtual Reality Induced Symptoms and Effects: Concerns, Causes, Assessment & Mitigation

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Abstract: The utilization of commercially available virtual reality (VR) environments has increased over the last decade. Motion sickness that is commonly reported while using VR devices is still prevalent and reported at a higher than acceptable rate. The virtual reality induced symptoms and effects (VRISE) are considered the largest barrier to widespread usage. Current measurement methods have uniform use across studies but are subjective and are not designed for VR. VRISE and other motion sickness symptom profiles are similar but not exactly the same. Common objective physiological and biomechanical as well as subjective perception measures correlated with VRISE should be used instead. Many physiological biomechanical and subjective changes evoked by VRISE have been identified. There is a great difficulty in claiming that these changes are directly caused by VRISE due to numerous other factors that are known to alter these variables resting states. Several theories exist regarding the causation of VRISE. Among these is the sensory conflict theory resulting from differences in expected and actual sensory input. Reducing these conflicts has been shown to decrease VRISE. User characteristics contributing to VRISE severity have shown inconsistent results. Guidelines of field of view (FOV), resolution, and frame rate have been developed to prevent VRISE. Motion-to-photons latency movement also contributes to these symptoms and effects. Intensity of content is positively correlated to VRISE, as is the speed of navigation and oscillatory displays. Duration of immersion shows greater VRISE, though adaptation has been shown to occur from multiple immersions. The duration of post immersion VRISE is related to user history of motion sickness and speed of onset. Cognitive changes from VRISE include decreased reaction time and eye hand coordination. Methods to lower VRISE have shown some success. Postural control presents a potential objective variable for predicting and monitoring VRISE intensity. Further research is needed to lower the rate of VRISE symptom occurrence as a limitation of use.

Keywords: virtual; reality; simulator; sickness; VRISE; immersive; sensory; elderly; HMD; symptoms

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1. Introduction

Motion sickness symptoms have been described throughout history as nausea, seasickness, vomiting, faintness, difficulty concentrating, headache, and other unpleasant noxious stimuli. This description dates to Ancient Greece [1], and this symptom profile is still applicable by today's standards. Motion sickness is seen in many different forms, and each form has its unique differences. Susceptibility to motion sickness depends on a variety of variables. It has been reported that 18% of people are moderately to highly susceptible to motion sickness, with an additional 51% of people that are considered slightly susceptible [2]. Motion sickness can be elicited through many different mediums, including transit vehicles (such as planes, naval ships, and automobiles), optokinetic drum rotation, physical simulators (car cabin driving, flight, surgery, and job simulators), carnival rides, and virtual reality (VR) simulators [2]. In VR environments specifically, symptoms of motion sickness have been seen in over 60% of participants within the first ten minutes of immersion [3,4]. The severity of these symptoms is characterized in a recent systematic review reporting a mean trial dropout rate of 15.6% due to symptoms of motion sickness [5], with a maximum frequency of 67% depending on the content of the virtual environment [6]. VR is becoming increasingly important in the role of rehabilitation, safety, and training. It is used in clinical, elderly, occupational, tactical, and athletic populations. VR has been used to create training programs to decrease falls, increase motor performance after an injury, simulate military and medical scenarios to train in, and many other applications. Accompanying this myriad of applications of VR are attempts to identify and quantify the variables responsible for provoking symptoms. Several studies have been performed with the goal of providing a safer, higher quality and more enjoyable VR experience. The evolution of VR through research has brought with it different styles of immersion including non-immersive, devices such as desktops, television, projections, CAVE systems [7] head mounted devices (HMD). HMDs are head worn visual displays, often including a head tracking system to provide user's head orientation and location information to a computer, that allow users to navigate virtual environments (VE) [8]. VEs are environments in which users can interact in real time with a computer-generated three-dimensional representation of an environment, or interact with elements inside said environment [9]. Even with ample research utilizing head mounted devices (HMD), users still report experiencing symptoms at a higher than acceptable rate. Saredakis [5] reported that pooled mean symptom scores across all studies are above the maximum rating that indicates a flawed simulator. Indeed, virtual reality induced symptoms and effects (VRISE) have been acknowledged as the primary limitation on the widespread utilization of HMD systems [9]. Throughout the literature, there are several different ways of referring to symptoms experienced under the umbrella term of motion sickness. The terminology includes motion sickness, seasickness, simulator sickness, cybersickness, visual induced motion sickness, and others [2,5]. Given the broad range over which motion sickness occurs, it is important to recognize symptoms elicited from VR environments specifically, in order to guide future research toward mitigating this specific motion sickness profile. Identification of such symptoms and the impact of VRISE on an individual can be quantified with subjective, physiological, and biomechanical measures to better understand the holistic behavior with VR immersion and to subsequently minimize these symptoms. While symptoms of motion sickness are similar throughout the different mediums, Cobb [3] and Stanney [10] reported that motion sickness profiles in participants are subjectively different between HMD VR simulators and non-HMD simulators. Specially, disorientation symptoms are more prevalent with HMDs, while more oculomotor disturbance symptoms occur in physical simulators. Given the incongruency of symptomology and terminology, it is important moving forward that like terms be used to increase specificity to the type of symptoms induced by specific simulator devices in order to best prevent or treat these specific profiles. Throughout this review, motion sickness induced by immersive VEs will be referred to as VRISE. The specific symptoms of VRISE are characterized by nausea, pallor, sweating, oculomotor disturbances, disorientation, headache, and fatigue [5,11]. Efforts to identify factors that contribute to VRISE and methods to reduce them through interventions have been tedious but have shown progress [6,12–20]. A significant decrease or elimination of VRISE is vital in moving forward with virtual reality as a tool in rehabilitation and safety training. With that established, the purpose of this review paper is to examine the various factors that can cause VRISE and identify optimum ways to measure VRISE for future research. VR is being utilized more frequently than ever. This is likely due to recent widespread accessibility with certain VR Hardware devices. This gives further justification for research examining the boundaries for optimizing safety, presence, enjoyment, and acceptance in immersive VEs.

2. Concerns for VRISE

There are multiple avenues of concern when it comes to the interaction of VR immersion and VRISE. VR provides virtual access to otherwise hazardous or inaccessible environments. Rehabilitation and memory induction for special populations and the elderly are also supported through VR. Balance training to reduce fall risk and autobiographical memory stimulation to assess/prevent memory loss have been conducted in the elderly population [19,21]. The attitudes of immersive VEs amongst participants aged between 57 and 94, specifically using HMDs, have been reported as neutral prior to exposure to immersive environments [22]. The aforementioned study also examined potential variables contributing to this initial attitude and found no correlations with age, years of formal education, and cognitive ability. However, computer proficiency significantly contributed to the initial attitude of VR. Attitudes toward VR immersion improved to positive after an initial immersion. Suggesting that the most vital barrier to cross when using VEs with older adults is the initial immersion. In addition, Cho [19] found that immersive VR training was safe and economical in older adults. Another study reported that older adults tolerated the use of a HMD devices well, with little to mild discomfort [22,23].

Another spectrum of concern is hardware and software contributions to VRISE. Several contributing factors such as motion-to-photon latency, VE content, field of view, and physical discomfort, among others. For example, Caserman and colleagues [13] reported significant increases in subjectively reported VRISE as motion-to-photon latency increased. Additionally, participants with an HMD developed some motion sickness after the first VR immersion, which was attributed to movement of the visual scene being delayed after the head movement [24]. However, it was revealed that further VR immersion with additional latency did not induce additional motion sickness. A possible explanation for this was that repeated exposure was more effective in developing adaptation as compared to prolonged exposure. This study revealed a negative maximum value for induced VRISE from motion-to-photon latency. This implies that there could be an optimal motion-to-photon latency ratio, which could reduce VRISE to a minimum. Long duration VEs seem to elicit greater VRISE as seen in multiple studies [16]. Naïve duration maximum recommendations have been proposed [25]. However, acclimation guidelines and subsequent duration recommendations need further study to optimize for best use of VR. Furthermore, less detailed and less immersive environments are more highly accepted than fully and semi-immersive environments, based on the lowest symptomatology [23]. This finding presents a contradiction highlighted in Tanaka and Takagi [26], which addresses the paradox of higher quality VR graphics and detailed environments increasing VRISE and the inverse effect of low quality, low VRISE environments. Tanaka and Takagi did not have ideal optimization of the HMD VE on a subject-to-subject basis given individual user characteristics. Cognitive aftereffects of VRISE have also been reported, which potentially adds to the risk undertaken when engaging in certain VR therapies. VRISE effects may be particularly concerning for older adult populations or those who must operate automobiles or heavy machinery post immersion. An additional area of concern that has been debated in recent years is how to appropriately monitor and measure VRISE.

3. VRISE Theory

A multitude of theories and derivatives of such theories exist in attempts to explain the origin of VRISE. These theories include but are not limited to Sensory Conflict Theory, Evolutionary Theory or Poison Theory, Postural Instability Theory, Rest-Frame Theory, Eye Movement Theory, Scene Instability theory, and multisensory re-weighting theory [20,27]. The theories and evidence to support them are discussed in this section.

3.1. Sensory Conflict Theory

The phenomenon referred to as sensory conflict theory has been frequently discussed as a major contributor to VRISE [5,13,23,28–30]. The theory states that conflict between visual, vestibular, and non-vestibular proprioceptive sensory feedback differs from expectations based on previous experience. There are several proposed sensory conflicts that may contribute to VRISE. In HMDs specifically vestibulo-ocular reflex may contribute. This reflex is activated mainly to decrease retinal blur due to vibrations of the body over 1 Hz and consists of the replacement of smooth pursuit tracking with opposite eye movement. In more immersive environments accompanied with simulated vibrations, this reflex can take over smooth pursuit, causing visual fatigue through decreased visual performance and acuity and subsequent strain. This reflex is more often seen in tactical simulations [12,31–34]. Another proposed conflicted reflex arc when experiencing a VE is the optokinetic reflex which consists of symptoms evoked by bending of the head during physical rotation. With HMDs, VRISE may occur with the bending of the head and perceived self-motion without any actual movement. This conflict is referred to as the pseudo-Coriolis effect [35]. This is similar to the concept of vection, which refers to the illusion of self-motion in the opposite direction of moving VR scenery [36]. This concept is commonly used as a subjective measure of presence and VRISE alike and has been reported to be nauseogenic. [36]. Minimization of sensory conflicts should minimize VRISE symptoms. These sensory conflicts can be reduced through alterations to hardware and software (see Sections 4.3 and 4.4).

3.2. Poison Theory

The Poison Theory is a derivative of the Sensory Conflict Theory that seeks to explain how sensory conflicts lead to VRISE. This theory states that certain sensorimotor conflicts are viewed as toxic, and the body acts accordingly to expel these toxins, hence VRISE [20]. It is said, in an evolutionary context, that the function of the brain is information processing in ways that lead to adaptation. Adaptations to these toxins as perceived sensory mismatches provide rationale to the adaptations that occur from repetitive VR exposure. Noting different interparticipant adaptation rates, some individuals may be able to quickly adapt sensorimotor responses to the potential conflicts of VE and reduce or avoid VRISE entirely [37]. The level of adaptation neural adaptation organization is multifocal, with acute and longitudinal adaptation in both the retina and higher cortical systems, and multifocal within higher cortical systems, affecting both sensory and motor processes. [20,38,39].

3.3. Postural Instability Theory

The Postural Instability Theory proposes that postural instability precedes VRISE and that this instability is required to produce this sickness profile [40]. This shifts the focus of motion sickness away from afferent signals to integrational organization of efferent planning and control [41]. Specifically, the theory states that postural precursors of motion sickness are parameters of postural activity that differs between individuals who report being well versus sick or differ in the magnitude of VRISE [20,42]. As these precursors have been demonstrated across many experimental situations and devices including but not limited to: HMD, Desktop VR, Moving Rooms, Ships at sea, during various stances [20]. This theory also contrasts the Sensory Conflict by providing rationale for the inter-intraparticipant differences examined situationally [43], as well as the difference seen in motion sickness profiles between drivers and passengers in vehicles and sex based differences that are examined in VRISE. The specific dependent measures of postural control are discussed in Section 5.3. It is worth noting that differences in spatial magnitudes of postural activity can be both positively and negatively different than baseline. Decreases in magnitude are often mistaken for increased postural control ability. Precursors only need to differ from baseline for prediction of VRISE [42,44].

3.4. Multisensory Re-Weighting Hypothesis

This theory, focuses on the accurate estimation and control of 3-dimensional (3D) orientation of head-and-body [45]. The sensory reweighing process refers to the suggestion that users adapt to conflict between visual and vestibular inputs they are subjected to over a time period [46]. Said inputs are down regulated if they do not contribute to overall perception of the environment. A good example of this is vection, in which visual cues strongly override the vestibular cues, causing the perception of motion based on visual input despite conflicting vestibular input [47]. The recoupling of multimodal cues can be accomplished by either by physically moving an observer along with visual self-motion or sending a mild current through the vestibular senses. The mechanism of which are discussed in Sections 5.3 and 6.

3.5. Rest Frame Hypothesis

Another derivative of sensory conflict theory is the Rest Frame Hypothesis. This hypothesis suggests that a particular rest frame, is selected as the comparator for special judgment. This implies that VRISE should be reducible through a background that matches inertial orientation and motion. Explained simply, it is helpful to envision certain objects are stationary to minimize reference calculations, such as ambulating on Earth's surface. Rest Frame Hypothesis suggests that a coordinate system used to define positions, angular orientation, and motions is this reference frame. In VR, this would suggest the inability to integrate visual and inertial motion cues would be a cause of VRISE [48].

Throughout this review several variables identified to be associated with the various hypotheses are discussed.

4. Causes and Contributing Factors to VRISE

4.1. Vergence Accommodation Conflict

The vergence-accommodation conflict (VAC) has been noted as a significant contributor to the VRISE sickness profile [49]. Vergence is the action of the eyes moving in opposite directions to maintain visual fixation at varying distances. Accommodation is the lens focusing to correct vision. Convergence and increases in focal power are required for images that are near, while divergence and decreased focal power are required for far objects. These coupled actions are driven by sensory input [12]. Inaccurate vergence and accommodation leads to double and blurred vision respectively.

VAC commonly arises in VR using HMDs. Naturally, accommodation and vergence occur simultaneously with the same fixation point. While using HMDs, binocular vision is simulated by displaying distinct left and right images to each eye. Fusion of these images creates perception of one 3D image. Depth is created in this context by altering the offset between images. Disparity being small makes images appear small and vice versa. This allows for vergence to occur in the HMD, but accommodation on the other hand always occurs at screen depth, causing a disparity between the senses which can lead to fatigue, headaches, and other aftereffects [50,51]

4.2. User Characteristics

Individual characteristics of the participants being tested is a factor researchers need to consider when examining VRISE. Certain populations may need specialized equipment to fully address VRISE. The most reported user characteristics that contribute to VRISE are age, gender, and previous VRISE experiences. Mixed findings regarding gender and age have been reported when looking at the likelihood of experiencing VRISE. Many studies have reported that females are more susceptible to VRISE compared to males [5,29]. A study conducted in 2004 reported that females are at higher risk for VRISE compared to males, but many confounding variables were not taken into consideration in this study [52]. Females may also have a smaller interpupillary distance that some head mounted displays may not have the ability to adjust to, thereby creating eye strain and discomfort [5]. However, a study conducted in 2002 reported no significant differences in subjective ratings, Coriolis effect, or blood flow measurements between males and females [53]. Their data also suggested that females may be more likely to admit sickness and/or discomfort according to the contrast between a survey conducted prior to the experiment that examined subjects motion sickness history and their reported symptom measures during immersion; this could be a contributing factor as to why females have been reported to be more likely to experience VRISE. Contrastingly, one study on motion sickness in transportation showed a higher level of vomiting in females than in males, suggesting that subjective bias of male's responses on surveys may not be a valid proposal for differences in susceptibility [54]. Additionally, motion sickness has been shown to fluctuate during different stages of the menstrual cycle, although a previous study only contributes this factor to one third of the overall difference between males and females [55]. With this expressed, we have previously established the differences between VRISE and motion sickness, so these results should be interpreted with caution. Objective physiological measurements of sex-based differences in VRISE should be the focus of future research.

The elderly population has been predicted to be more likely to experience VRISE and have negative attitudes towards virtual reality. However, a study conducted in 2015 revealed no significant VRISE was experienced, and that using virtual reality was well tolerated by the elderly participants [21]. In fact, a recent study found that younger adults subjectively reported a higher frequency of headaches, eyestrain, and cumulative VRISE symptoms than older adults [56]. It is important to consider that most studies performed with elderly samples featured scenic content, which has lower VRISE scores compared to gaming content. It is likely that elderly studies conducted with elderly participants are designed with virtual reality content that reduces the likelihood of experiencing VRISE, which could be the reason for lower VRISE. Overall, VR has shown to have a positive impact on rehabilitation and fall prevention in older adults, with non-immersive VR being the most effective due to higher acceptability and easier access in complex clinical populations [23]. Even with conflicting results in the literature, age and sex have been reported as being the most common user characteristics for VRISE prediction. Additionally, the mixed results brought about by studying user characteristics may be due to differences in hardware and content. Other user specific characteristics such as ethnicity, fitness level, and sensory conflict exposure frequency should be considered to develop a more specific approach to decreasing VRISE based on user characteristics.

4.3. Head Mounted Display and Associated Hardware Contributions to VRISE

Field of view (FOV), resolution, framerate, and ergonomic advances in head mounted display technology have been shown to reduce VRISE and increase presence in immersions in some cases, and increase VRISE in others [25,26,57,58]. With new HMD technology, participants are experiencing high levels of immersion and realism. There is mixed research as to whether the increased immersion elicits VRISE or reduces it [26,57]. Clear imaging and movement tracking accuracy could reduce VRISE due to fewer sensory conflicts; while an increase in the field of view and may increase VRISE [59,60]. This implies that the more realistic and high quality a VR environment, the stronger the symptoms. Tanaka and Takagi [26] attempted to optimize this trade-off by establishing minimized VRISE and maximized presence. They found optimal values for HMD metrics including angular velocity of view and visual angle, but when participants were exposed to the VE at their customized values, symptoms became worse. Since then, guidelines have been developed suggesting a diagonal threshold of 110 degrees FOV [61]. Additionally, studies have shown that head mounted displays elicit greater VRISE compared to reality theatre, projection screens, and desktop computers [16,62]. While Liquid Crystal Display (LCD) screens were used in HMD up until recently, newer commercial versions of HMDs use Organic Light Emitting Diode (OLED) screens, which have noted higher quality and decrease the likelihood of VRISE [63]. The pros and cons of each respective display type (LCD and OLED) on immersion quality has been recently discussed by Hsiang et al. [64] with respect to form factor, color purity, out-coupling efficiency, angular color shift, color contrast and cost. In addition, the refresh rate and resolution of the display influence VRISE, with recommended values of 75 Hz or greater and over 960 × 1080 pixels per eye, respectively [65]. These requirements in turn set the requirements of the computer system [66]. Having an adequate processor, graphics card, and sound card that can support newly commercial HMDs is vital to produce the desired content and minimize VRISE [67].

Another head mounted display characteristic to consider when looking at VRISE is the potential delay between physical movement and display movement. However, there are discrepancies in published findings; one study found that a latency above 63 ms induced significant cybersickness symptoms and decreased performance while another found a latency of 200 ms did not induce sickness compared to no delay [13,68]. Akizuki and colleagues [24] found in 2005 that different levels of latency (0.0–0.8 s) did not induce apparent motion sickness or body sway within conditions. Another result found in this study is a progressively significant increase in body sway from baseline (no HMD) to a transparent HMD without immersion, and then immersed condition. However, the only significant finding regarding postural control was that the ratio of sway from eyes closed to eyes open decreased from pre- to post-immersion. Indicating that VR immersion may lower dependency on the visual system after VR exposure. Another interesting variable to consider is access to peripheral vision of the natural environment with an HMD equipped. Moss and Muth [68] found that by occluding participants' peripheral vision, there was an increase in VRISE compared to when the peripheral vision of the external environment was available. Some environmental factors, including spatial resolution and illumination levels, which may cause resting level accommodation, are not related to VRISE [69,70]. Regarding device ergonomics, Hoshino et al. [71] and Nichols [72] found that the weight and fitting of HMDs can also contribute to VRISE. Keyboards, controllers, and joysticks may all contribute to VRISE if used as a method of navigation in VE [57]. Subsequently, there is a need to continue to research the effects of the characteristics of the head mounted displays on VRISE, to determine optimal HMD design.

4.4. Types of Content in VRISE

The content used in a virtual environment also plays a vital role in the occurrence of VRISE. More specifically, content with plentiful rapid movements will likely induce greater VRISE compared to content with little movement. A systematic review paper recently examined the levels of VRISE experienced in four different content conditions [5]. This systematic review found that simulator sickness questionnaire (SSQ) (see Section 4) scores were significantly higher in studies that used gaming content, followed by 360-degree videos, minimalist content, and ending scenic content. The SSQ subscale symptoms of nausea, oculomotor, and disorientation had the same results.

Additionally, the movement of the content within the environment plays a role in the levels of VRISE experienced. It has been reported that content with higher visual stimulation experienced significantly higher SSQ scores compared to content with low visual stimulation [5]. Further, rapid changes in stimulus distance have been shown to increase visual discomfort, thereby increasing VRISE. Kim and colleagues [14] also noted a significant difference in target size and VRISE levels in target selection tasks while immersed. Different movement speeds throughout VEs have also been shown to have a significant effect on the onset times of vection and nausea. However, they did not affect rates of increase with duration of exposure [36]. In research regarding oscillations of each axes of rotations in HMD VEs [73], it was found that oscillations in yaw pitch and roll axes showed significantly higher VRISE than the control group. This supported one of their hypotheses; the absence of scene movement can reduce VRISE. They showed that some participants are more susceptible to VRISE in a particular axis than others. No variables were found that could explain this individual axis susceptibility.

The Virtual Reality Neuroscience Questionnaire (VRNQ) was established from this list of established variables. This Questionnaire was created to assess the quality of VR software in terms of user experience, game mechanics, in-game assistance, and level of VRISE. User experience is based on the intensity of immersion, enjoyment, graphic quality, sound, and VR tech. Game mechanics measured on navigation ease, and in-game assistance appraises the quality of tutorials, prompts, and instructions. VRISE evaluated nausea, disorientation, dizziness, fatigue, and instability intensity. All rankings were done on a 7-point Likert scale (5–7 positive results). This study suggests minimum cut-offs for adequacy to be a total score of 100; this is the VRISE threshold score for software. Regression analysis revealed the five best variables predicting VNRQ VRISE scores: immersion, graphics, sound, instruction, and prompts [25]. These variables are not commonly studied for contribution to VRISE and should be studied directly soon. The type of content used for a particular population should be considered based on the levels of VRISE one might experience in the specific virtual environment.

4.5. Temporal Affects and Adaptability in Virtual Reality

The amount of time spent in a VE before significant VRISE occurs has long been studied and shows varying results. Most studies report that VRISE tends to increase as exposure time increases, with the most severe symptoms being after the last trial, while some studies have shown that participants can adapt to being in a VE during a single session. In 1999, four participants spent one to two hours in an immersive VE where their VRISE was monitored with an SSQ [30]. All four participants reported VRISE increasing up to one hour after exposure, with two participants withdrawing after one hour due to the severity of their symptoms. The remaining participants were able to complete the two-hour immersion and, in fact, reported their symptoms decreased after 75 min of exposure. Another study reported participants showing significant symptoms just 10 min after the beginning of the trial [74]. More specifically, symptoms of nausea and disorientation appeared after 10 min, and symptoms of oculomotor disturbance appeared after 25 min supporting the hypothesis that VRISE increases with time spent in a VE. Similarly, other studies found that the nausea severity increased linearly with time after a 20-min and 30-min exposure time [36,73]. In 2014, Lui and colleagues [74] found participants' VRISE more severe as exposure duration increased from 5 to 15 min. These findings are congruent with many studies [25,68,75–79]. Other studies have found no differences in VRISE between after-acclimation and post-exposure scores, indicating peak VRISE severity may occur early in the study and then remain approximately the same as participants adapt to the environment [80,81].

A recent study examined the relationship between exposure duration and VRISE during a 7.5-h immersion, which was the first report of VRISE during such a long duration of VR exposure [16]. The participants completed 4 90-min trials with 5 to 10 min in between consisting of an SSQ administration. Each trial consisted of an office task that lasted 40 min. Participants completed 4 simple office tasks arranged in order, including finding wrong-written words, searching for specified content, creating PowerPoint slides, and classifying images. The results indicated a significant positive linear relationship between VRISE level and duration of exposure. Another interesting finding was that VRISE levels quickly increased as exposure increased from 0 to 1.5 h, then gradually became slower, leading to no significant difference between trials 1, 2, and 3. This implies that during the first 4.5-h immersion, participants' symptoms were severe, to begin with, then they were able to adjust to the environment, and sickness adaptation was seen. This finding supports previously mentioned studies which also found an adaptation to the environment. However, as exposure time increased past 4.5 h, VRISE began to increase again, with trial four scores being significantly higher than trial 1, indicating a break in the sickness adaptation. Long-duration immersions of this nature are limited due to dropout rates, hence the inclusion of a 4-subject sample in this review.

Another VRISE acclimation study [82] found that centrifuge-induced symptom severity only increased in one condition in a two-day trial to examine acclimation. If these symptoms induced via centrifuge indicate acclimation, we can infer those similar effects might be seen in VRISE. In addition, Sinitski and colleagues [80] found in 2018 that a 15-min acclimation immersion prior to a 45-min immersion found an increase in disorientation symptoms at first with a decrease by the end of the exposure, which suggests acclimation. In a more traditional learning, methodological setup, Cobb et al. [3] ran three identical trials using within participants measures with one week break between each trial. Results showed that after each consecutive VR exposure, SSQ scores significantly decreased. Results were especially strong for disorientation symptoms. From this limited data, there seems to be a plateau effect for VRISE symptoms, in which the initial severity of VRISE is a sharp increase at onset, followed by a leveling or short decrease in symptom profile, and a subsequent increase in VRISE again once the exposure reaches unpractically long lengths. VRISE ratings seem to decrease with repetitive exposure, which should be further investigated as a primary method of preemptively lowering VRISE prior to exposure.

4.6. Persistence of VRISE

Previous literature has reported [26] that not only does VRISE occur during VR exposure and immediately following, but that VRISE can persist for a period even after immersion. It was also simultaneously discovered that the length of recovery time depends on initial VRISE severity. Severe symptoms in this study required 30 min of recovery time, while slight symptoms required only 5 min of recovery time. The severity in this study was characterized by the SSQ. Keshavarz and colleagues [29] found that participants who had to drop out of their study early due to VRISE severity experienced longer recovery periods than those who completed the study. Furthermore, only five of their participants did not fully recover in 15 min, and for all the participants, there was a significant decrease in symptoms between immediately following exposure and 3 min post-exposure. Another study also confirmed that virtual reality sickness persisted for some time after exposure. Still, most of the participants returned to baseline within an hour following the end of VR exposure [83]. Moss and Muth have seen conflicting results; in 2011, they found that at 10 min post immersion, VRISE ratings were still significantly higher than baseline ratings [76]. In a subsequent study by the pair, all participants returned to baseline VRISE levels within ten minutes. This indicates that variables of the immersion also affect the post immersion duration of VRISE [68]. Other studies reported sickness persisting for 10 min, 30 min, or even more than 4 h following virtual reality exposure [30]. Various factors may determine these potential recovery periods, such as the length of time spent in the virtual reality environment and the severity of symptoms initially experienced. The VRISE profile between immersion and post immersion should be evaluated to gain insight into potential differences in these conditions. This would help minimize the risk of post-immersive symptoms, which is dire in acceptance.

4.7. Cognitive Performance in Virtual Reality

Alterations to cognition from immersions in VE have been noted and studied frequently. Decreased eye-hand coordination, auditory working memory, and visual search are common performance measures examined in cognitive performance. Reaction time (RT) is the most consistent cognitive measure examined in the literature. (RT increases refers to slowing the maximum speed an individual can respond to a stimulus). RTs have been reported to increase post immersion in most studies that examine it as a variable [15], although there have been studies which have reported decreased RT [84]. It was unclear whether VRISE's impact on reaction times resulted from affected cognitive function, motor mechanisms, or a combination of both. Szpak and colleagues [50] attempted to examine the difference between motor and cognitive performances post immersion. The researchers used a decision-making choice RT task and rapid visual processing task to examine the cognitive effects. The results revealed slower cognitive processing speeds on the reaction time task after virtual reality and they were slower compared to the control group. However, the group that used virtual reality was only slower in the cognitive component, not the motor component of the task. Based on the data, the authors suggest that the factors driving the response time effects are more likely related to attentional resources rather than motor performance. Most but not all participants experienced slower RT after virtual reality in this study as well, whereas some participants' RT decreased after virtual reality exposure. Other researchers suggest increased RT may result from VRISE and not impaired cognitive function, meaning participants who did not feel well performed worse because of symptoms, not from what provoked them [84].

Research specifically on the cognitive effects of VRISE is seldom performed. The inconsistencies in content, device, and results across studies were addressed in 2019 by Mittelstaedt and colleagues [15]. They examined different display (HMD and TV screen) conditions and navigation methods (bike ergometer and gamepad), forming 4 groups. They tested simple RT, two-choice RT measures, mental rotation, visual search, and spatial memory before and immediately after immersion in conjunction with an SSQ evaluation. After a ten-minute immersion, significant increases in pre- to post-choice RT tasks, but no differences in any other variable were examined. The choice reaction time tests were performed first and last in the pre- and post-immersion test battery, suggesting post-immersion acclimation was not a factor. VRISE was significantly correlated with both choice reaction tests, and no other measure of cognitive performance was correlated with VRISE.

Another cognitive effect examined is a decrease in hand-eye coordination, which may result from adaptation to the VE in which participants are placed. Studies suggest visual fatigue and attentional resources being used to address conflicts in a virtual environment are potential reasons for decreased cognitive function [6,12]. Understanding what drives the cognitive aftereffects can provide information on how VRISE should be handled post immersion. Further, the literature on the effect of VRISE on cognitive performance is minimal and inconsistent; hence, further research is needed to determine the driving effects on cognitive and motor functioning in virtual reality.

5. Methods to Monitor VRISE

5.1. Subjective Measures

Measuring and monitoring fluctuations in VRISE severity is fundamentally important to ensure the health and safety of diverse populations using VR in the field and research. Many subjective methods are used to measure VRISE. The most frequently utilized item is the SSQ. The SSQ was developed in 1993 and was originally used for motion sickness in physical simulators [85]. The SSQ consists of 16 symptoms, of which users rank on a 0–3 scale in terms of severity. Each of these 16 symptoms belongs to 1 or 2 SSQ subscales. These categories include nausea, oculomotor disturbance, and disorientation. Subscale scores are then multiplied by a constant representing a contribution to VRISE and summed to obtain SSQ total score. This method is commonplace in the literature [50,68,70,80,86–88]. However, several technological advancements since the development of the SSQ have taken place, and the level of immersion seen in newer HMD systems scarcely resembles the training simulators in the early 1990's. Despite its origin and noted differences in simulator sickness and VRISE, the SSQ is still widely used as a method of standard subjective reporting in HMD immersion. Multiple attempts have been to correct this oversight, and authors have attempted to refurbish the SSQ into something more applicable to current simulator designs. The Virtual Reality Symptom Questionnaire developed specifically for HMDs and the Virtual Reality Sickness Questionnaire are alternate measures that can quantify virtual reality sickness but have not yet been widely adopted [5,28,89]. The Misery Scale (MISC) is another self-report measurement used to assess VRISE. This is an 11-point scale that captures the quantitative and qualitative degree of sickness within one combined rating [83]. This scale was developed in a seasickness ship bridge simulator. One major issue with subjectively reporting VRISE is that the self-perceived level of sickness is relative to the individual reporting it.

Incrementally measuring VRISE during exposure is important for tracking the relationship between time and symptom intensity. During early VR research, this was a significant problem. Stopping the direction to complete a questionnaire disrupted the experiment flow, allowing participants to reacclimate to natural conditions and skew data. The development of the Fast Motion Sickness (FMS) scale allowed for a single item, the verbal response from 0–20, for participants to report their VRISE. While subjective, administration of the FMS is easy and can be done during virtual reality exposure; the FMS Scale scores were validated because of their positive correlation with SSQ scores [56]. This means researchers could use the FMS Scale to quantify sickness during virtual reality exposure and the SSQ to comprehensively quantify sickness pre- and post-VR exposure, giving a complete subjective report of the before, during, and after immersion VRISE timeline. Additionally subjective measures also include different nausea scales such as the 7-point and 11-point nausea scale, Bagshaw and Stott's sickness scale, and nausea visual analog scale (VAS) and different sickness scales such as sickness rating scale, discomfort score, subjective symptoms of motion sickness (SSMS), and verbal sickness rating scales. [90].

The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ), developed by Keshavarz and colleagues [29], is an adjusted and simplified version of the original Motion Sickness Susceptibility Questionnaire (MSSQ) designed by Reason and Brand [91]. The VIMSSQ is designed to predict susceptibility of motion sickness provoked by visual displays. Visual acuity is an attribute that is not included in the original MSSQ and necessary for assessing susceptibility in situations involving VR and HMDs. The VIMSSQ is designed to measure how often an individual experienced VRISE symptoms whilst using visual displays in the past. Specifically visual displays include 2D movies, 3D movies, IMAX theaters, Smartphone dynamic content, Tablet dynamic content, Television, HMD VR, Video Games, stationary simulators, moving simulators, and large public moving displays. Correlations (which were moderate to strong) between the VIMSSQ and VRISE (as measured by SSQ) provoked in their study exceed the correlation between induced VRISE and the MSSQ which validates VIMSSQ as the most relevant susceptibility questionnaire for VRISE to date. However, this is a relatively new questionnaire that has not been utilized in a widespread manner. Moving forward, the VIMSSQ could be the preferred questionnaire for assessing experience of VRISE symptoms.

5.2. Physiological Measures

Individual differences in tolerance to motion sickness are widely noted [37]. Individuals also differ in pain and discomfort tolerances. Among actual tolerances, individuals may feel the need to suppress or exaggerate their VRISE due to social norms or alternative agendas. With this established, it is evident that subjective reporting of levels of VRISE is inappropriate and should be replaced with more objective measures. The development of a reliable and valid physiological measurement method would remove any internal bias about VRISE levels. Investigators have attempted this. Evaluating factors such as heart rate (HR), R-R interval, eye blink rate, skin conductance, Electroencephalogram (EEG), electrogastrogram, and skin temperature, among others. [5,17,18,75]. Min [75] originally discovered that theta waves of an EEG could be used to measure VRISE objectively. Kim et al. verified that theta EEG waves could predict VRISE and additionally found that electrocardiogram R-R intervals could be used as a physiological measure of VRISE. Dennison et al. [18] found several significant effects between physiological measures and duration of exposure, including tachy and brady gastrogram activity, blinking rate, skin conductivity, R-R interval and HR, respiration rate, and head rotation rate. They also developed a regression analysis correlating SSQ scores with physiological measures taken during immersion. The explained variance of physiological traits (R^2) was up to 74%. Linear discriminant analysis was also conducted for prediction between monitor and HMD displays based on physiological measures taken in the immersion. The correct prediction rate was high at 77.8%, though the sample was egregiously small ($n = 9$). The mentioned physiological objective measures of VRISE need to be interpreted with caution. Often times these measures are invasive and are easily manipulated by variables other than the VR immersion itself. Moving toward objectivity and away from subjectivity is a common goal in science and should be practiced in VRISE research. It should be noted; however, that subjective measures should be updated as opposed to eliminated. Acceptability of VR is based on a subject's tolerance and resistance to noxious stimuli, in this case, VRISE. The technology will only be utilized if the user finds the immersion personally (subjectively) tolerable.

5.3. Biomechanical Measures

Kinematic variables, namely postural control changes, can also be used to measure VRISE. Postural control alterations from VR immersions have been seen repeatedly in the literature [24,42,92–95]. As discussed in Section 3.3, postural instability has been proposed to be a significant precursor to VRISE. The dependent variables that have been shown to precede postural instability include but are not limited to sway magnitude in anteroposterior, mediolateral, ellipse area, sway velocity, along with head and body positions. [20,80]. In a recent study conducted by Weech [42], the investigators evaluated the effects of vection strength, vestibular thresholds, and excursions of the body center-of-pressure. After elimination of collinearity of predictors and computing unique variances, a model was created that could significantly predict later VRISE magnitude ($R^2 = 0.37$, $p = 0.018$). Of this model, the most predominant predictor of VRISE was visual motion-induced postural sway. It shared an association with lower levels of VRISE. ($r(28) = -0.53$, $p = 0.002$). This study provides an objective measured that could quantitatively measure VRISE severity that does not share the limitations of the physiological objective measurements.

6. Methods to Reduce VRISE

The underlying method to optimize VR HMD immersion comes through minimizing sensory conflicts. Previously discussed in this review (Section 3.5) the Multisensory Reweighing Hypothesis has led to attempts to resynchronize multimodal cues via noisy Galvanic Vestibular Stimulation (noisy GVS), or mastoid bone-conducted vibration (BCV). In a recent study, BVC yielded reductions of VRISE compared to a control group, both groups were immersed, piloting spacecraft through virtual space [45]. Tonic GVS has also been shown to reduce VRISE [42]. These methods of sensory re-weighing show significant promise for mitigating VRISE.

In one of the most progressive studies, Carnegie and Rhee [87] purposefully attempted to reduce vergence-accommodation mismatches discussed earlier by blurring content appropriately, lowering the accommodation mismatch and subsequent visual strain. Within subjects' designs showed a significant decrease in VRISE when dynamic blurring was enabled. Another study showed that the speed at which the vergence-accommodation compensation occurs has a significant effect on VRISE and was found to be the highest at the fastest occurrence of 25 Hz [14]. In 2019, Kourtesis and colleagues [25] conducted a study that answered several open-ended questions left by previous research. While the main study objective was to validate the VRNQ, they had significant secondary findings. Using a commercially available HMD, they exposed participants to three different immersion sessions. Participants rated these sessions on the VRNQ, and each session was rated higher than the previous. This denotes higher quality and lower VRISE experience from one session to the next. The experimenters noted that the intensity of immersion and quality of graphics were increased progressively. The session's length was determined entirely by the participant. There was a significant correlation between the duration of the session and VRISE scores per usual. They concluded that the max duration of VR sessions should be between 55 and 70 min. They found that gaming experience, age, and education do not affect this recommendation. It was also found that significantly more time was spent in each subsequent session despite increasing content intensity. Thus, one of two conclusions can be made. Either the intensity of the immersion contributed to the enjoyment of the experience, which prompted increased duration of the trial, or the acclimation from repetitive exposure significantly lowered VRISE. as opposed to long-duration exposure has given us loose evidence that it may lower VRISE. Future studies should address this directly to confirm this as a method of reducing VRISE.

Another important finding from Kourtesis [25] was that the five best models to predict VRISE susceptibility included immersion intensity, graphics quality, sound, instructions, and in-game prompts. This suggests that improved graphics, realistic sound, quality instruction, and in-game prompts can prevent VRISE. They also noted that the quality of the software as measured by the VRNQ substantially modulates maximum recovery speed. Reducing the intensity of content and speed of navigation while improving the graphics, optimizing FOV, and minimizing latency reduces VRISE [5,24,36,57,68]. However, graphic quality should be investigated further, given the mixed results in the literature [6,57,84,87]. A representation of the natural environment can also reduce VRISE, like that seen in Moss and Muth [68] when they did not occlude peripheral vision during immersion. Minimizing oscillatory movements within VEs should be commonly practiced as well [73].

The development of better travel techniques through the user's point of view to navigate through VE is also a proposed method of minimizing VRISE. Limiting the conflict between visual and vestibular or proprioceptive feedback through more realistic movement should lower VRISE and increase presence. Current techniques to minimize these conflicts in HMDs include controller-based, motion-based, teleportation-based, and room scale-based movement [96]. It has been noted that using movements as similar as possible to natural environmental movements (6 degree of freedom wands or motion capture methods) should be practiced before using more analog methods. This includes accurate proprioception in the user's feedback loop to minimize sensory conflicts. Proper audio has been shown to reduce VRISE and increase the level of presence in immersive environments if properly spatially organized [97,98]. In addition to the recommended FOV, frame rate, and picture quality guidelines, there is a semblance of uniformity that is beginning to appear for VR immersion, which is a significant step forward in the field.

7. Conclusions

Symptoms from virtual reality immersion, known as VRISE, are reported at a higher than acceptable rate. The origin of these symptoms has been widely theorized Sensory Conflict Theory and Postural Stability Theory have received most of the attention in the literature. To increase acceptability and utilization of the versatility provided by VR, these sensory conflicts and accompanying symptoms need to be reduced or eliminated. Higher quality and realistic environments may not be the answer, as several studies have reported increased immersion realism to increase VRISE severity and onset. The individual characteristics that can predict VRISE susceptibility and decrease symptoms when adjusted have been researched, but not to the extent needed to optimize VR immersion individually. Often research has delivered mixed results on these characteristics as well, muddying the water—the previously suggested user characteristic predictors of sex and age yield inconsistency. Age may have the reverse effect of the initial suggestion that the elderly is less likely to experience VRISE or at least they are less likely to report symptoms. The sex-based differences in VRISE may have to do with interpupillary distance, or another area of concern in the field, subjective reporting. To date, most studies have used subjective measures based on participants self-diagnosis via questionnaires like the SSQ, commonly used before and after immersion and the FMS used during immersion. The SSQ was not intended to evaluate VRISE, and updates to this questionnaire have been attempted but not widely accepted. This allows for interpersonal differences in perception to interfere with the accurate reporting of VRISE. measures should be used to measure the severity of VRISE moving forward. Qualities such as R-R interval, EEG theta waves, and skin temperature have been validated to measure VRISE, but only recently. While these physiological qualities vary with immersion, it is impossible to know if this is the only variable affecting them. Potential alternative kinematic measures that could be utilized in the future to predict and monitor VRISE severity are postural control changes. Software and hardware qualities have been shown to cause different levels of VRISE and can assess for adequacy via the VIMSSQ, which is designed for such assessment. VRISE increases as a single session progresses with an initial spike, followed by a plateau in symptomology, which then spikes after long durations. While prolonged use of VR immersion can cause negative side effects in persistence of VRISE, r, repetitive exposure seems to lower the severity of symptoms and should be used to improve the VR experience. The persistence of VRISE has a wide variety of duration and is directly related to the onset of symptoms. This is important when considering the aftereffects of VRISE. Differences in cognition from before to after immersion correlate with VRISE intensity. They specifically increased motor components to choose RT post immersion. Subject symptoms must be fully subsided before leaving a laboratory, work, or rehabilitative environment to ensure safety. The benefits of using a virtual environment to access dangerous or unacceptable situations are too valuable to be limited by VRISE. Further research into the optimization of interpersonal VR experiences is needed to combat the barrier of VRISE acceptability amongst the populous.

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