The Persistent Issue of Simulator Sickness in Naval Aviation Training

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INTRODUCTION: Virtual simulations offer nearly unlimited training potential for naval aviation due to the wide array of scenarios that can be simulated in a safe, reliable, and cost-effective environment. This versatility has created substantial interest in using existing and emerging virtual technology to enhance training scenarios. However, the virtual simulations themselves may hinder training initiatives by inducing simulator sickness among the trainees, which is a series of symptoms similar to motion sickness that can arise from simulator use. Simulator sickness has been a problem for military aviation since the first simulators were introduced. The problem has also persisted despite the increasing fidelity and sense of immersion offered by new generations of simulators. As such, it is essential to understand the various problems so that trainers can ensure the best possible use of the simulators. This review will examine simulator sickness as it pertains to naval aviation training. Topics include: the prevailing theories on why symptoms develop, methods of measurement, contributing factors, effects on training, effects when used shipboard, aftereffects, countermeasures, and recommendations for future research involving virtual simulations in an aviation training environment.

KEYWORDS: simulator sickness, aviation training, virtual reality, augmented reality.

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After a protractedly false start in the mid-1980s, virtual environment (VE) technologies have finally begun to catch up with the early promises of creating virtual worlds that accurately replicate real-life environments. The pivot-and-swivel, cathode-ray tube (CRT) military flight simulators of the 1980s are being replaced by modern virtual reality (VR) and augmented reality (AR) systems with nearly unlimited potential for naval aviation training. The newest generation of head- and helmet-mounted displays (HMDs) are lightweight, portable, affordable, and capable of producing high fidelity displays previously available only through massive screen-and-projector setups. These technologies could allow trainees to simulate any number of scenarios they might encounter in complete safety, at minimal cost, and—most importantly—anywhere at any time. One potential drawback involves simulator sickness and its resultant symptoms, including dizziness, pallor, cold sweating, increased salivation, stomach awareness, headache, fatigue, apathy, nausea, and vomiting. There is also the question as to the time course of these symptoms and whether negative aftereffects persist beyond simulator usage. Given the immense potential and aeromedical risks, which are further complicated by operational requirements such as integrating virtual systems aboard an aircraft carrier, it is important to fully understand the advantages and disadvantages before the military decides to fully pursue these capabilities with significant financial investment.

This review will examine simulator sickness as it pertains to naval aviation training. Topics include: the prevailing theories on why symptoms develop, measurement and incidence, contributing factors, effects on training, effects when used shipboard, aftereffects, countermeasures, and recommendations for future research involving virtual simulations in an aviation training environment.

METHODS

A comprehensive search was conducted using PubMed, Google Scholar, and the Defense Technical Information Center.

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Military and flight simulator studies were emphasized, with priority given to studies using the Simulator Sickness Questionnaire (SSQ) to quantify sickness levels. As simulator sickness is a form of motion sickness, key findings from motion sickness literature were also reviewed. Subsets and alternate designations of simulator sickness were also searched in relation to military simulators, flight, and naval aviation. Searched terms included: virtual reality sickness, virtual environment sickness, augmented reality sickness, simulator sickness, motion sickness, visually induced motion sickness (VIMS), and cybersickness. Due to the significant commercial investment in VR and AR devices over the past decade, online magazines, trade journals, and technology blogs were reviewed for additional references as applicable to naval aviation. All articles were available in English and published between 1950 and 2017. Each bibliography was further reviewed for additionally relevant sources, including text books. Findings were organized by the following principle issues: history, terminology, causal theories, measurement methodologies, incidence, contributing factors, training effects, shipboard use, aftereffects, and countermeasures.

Definitions and Distinctions

Terminology. In simulator sickness research, terms are often used interchangeably. This review retains the term simulator sickness to reference all motion sickness-like symptoms generated by a VE. Motion sickness arises from a susceptible individual's exposure to provocative motion; simulator sickness is motion sickness without true motion. Several subsets of motion sickness and simulator sickness have been identified, though these terms tend to be technology-specific descriptors (e.g., video game motion sickness). When qualified, these subsets can categorically and symptomatically overlap with, yet remain distinct from, simulator sickness. For example, VIMS is motion sickness derived from visually provocative yet physically static environments.[15] Other motion sickness studies may focus more upon vection-induced issues or vestibular issues while investigating motion sickness or simulator sickness rather than VIMS. Video game motion sickness can be either synonymous to, or a subset of, both simulator sickness and VIMS. Reciprocally, simulator sickness can be considered a subset of VIMS, yet also occurs in simulated motion. Since the late 1990s, cybersickness, once a direct synonym for simulator sickness, has increasingly referenced sickness induced by HMDs and other computer-generated displays, although most commercial and media usage references only nausea and dizziness; more subtle symptoms and aftereffects are usually ignored. For a comprehensive differentiation between the two terms, see Stanney et al.'s review.[79] Importantly, for the purposes of this review, we will use the term simulation sickness to describe all motion sickness-like symptoms—including visual and vestibular symptoms—that arise from interaction with a VE.

Environments. A VE is any computer-generated environment with which a user can explore and interact. VR is an entirely artificial VE within which the user is fully immersed. Immersion, or presence, is the perception of being physically present in VR, which in turn is reliant on a simulation's fidelity, which for this review is defined as the simulator's perceptual ability to display an accurate and realistic visual experience.[94] The less physical reality that intrudes into VR, the greater the sense of immersion. Reciprocally, immersion is diminished by simulator sickness. AR, in contrast to VR, introduces synthetic elements to the visual display while allowing continuous visualization of the real environment, creating a "mixed" reality. High immersion in AR would constitute a seamless mix of virtual and real elements. HMD AR can be implemented as either an optical- or video-based display. Optical-based AR superimposes computer-generated objects on a user's real-world view. Video-based AR uses external cameras to relay and combine the real-world environment and computer-generated images into one display, and technologically is identical to VR.

Technologies. There are two primary simulator technologies applicable to military aviation training: HMDs and cave automatic virtual environments (hereafter referred to as CAVE). HMDs have existed since the mid-1960s, but are now at the forefront of VE technology. Although configurations vary, CAVEs are essentially rooms with projectors directed to display 3D images across most, if not all, surfaces and a motion capture system recording real-time position of the user. While much of the literature differentiated between CAVEs and military flight simulators, advances in VE are rendering the two essentially synonymous. Unless specified otherwise, simulators using screens and projectors for an out-the-window (OTW) display will be viewed (imperfectly) as CAVE constructs outfitted with high systems fidelity cockpits. Examples include CAE USA's six degree-of-freedom MH-60R and L-3 Link's F/A-18E/F tactical operational flight trainers.

Theories on Motion Sickness

Researchers have hypothesized multiple causal theories for motion and simulator sickness. The most widely accepted is Sensory Conflict Theory (SCT), first defined in 1975.[72] SCT proposes that when any motion detected by vestibular, visual, and proprioceptor systems conflicts with expected (or previously learned) motion, a centralized signal gradually builds until reaching an individually variant threshold. If this threshold is surpassed, motion sickness occurs.[71,72] Sensory conflicts can be intersensory, between visual and vestibular systems, or intrasensory, between angular (semicircular canals) and linear motion (otoliths) detection.[6] A modification of SCT hypothesizes that the only conflict necessary is between expected (learned) and sensed direction of gravity: the subjective vertical.[8,10] The SCT paradigm differentiates simulator sickness from motion sickness as caused by the inability to accurately replicate motion with which the individual is accustomed, rather than provocative motion in and of itself.[41,53,70] A prime example is when experienced pilots trend higher in simulator sickness incidence during flight simulator training than student pilots—the latter not yet having "learned" the real motion of aircraft.[41]

The leading alternative is the postural instability theory (PIT). Riccio and Stoffregen[74] noted that sensory information is conflicting even in everyday tasks and theorized motion sickness develops when an individual is placed in a novel environment for which the correct balance or posture has not yet been learned. Therefore, postural instability should always precede motion sickness. Per PIT, simulator sickness occurs when a simulator's imposed motion oscillations overlap with an individual's natural body oscillations, creating a wave interference effect that directly causes the postural instability.[84,85]

Neither theory can predict time course, incidence, or symptomology.[90] Other ideas have been proposed, but typically aim to explain the 'why' rather than the 'how'. Examples include Treisman's Evolution Theory,[87] which proposes the vestibular system serves as a toxin detector, inducing vomiting to expel any neurotoxins adversely affecting the vestibular system, and Bowin's[30] proposal that motion sickness originated as a negative reinforcement model to prevent the development of movements detrimental to survival. Though of academic interest, these 'why' theories do not provide a framework for developing solutions to motion sickness, hence the preference for SCT and PIT in applied research.

Measurement and Incidence

To date, no validated objective measurement of either motion sickness or simulator sickness has been identified. Physiological variables are routinely measured pre- and postexposure, but magnitude and direction of change remain inconsistent between studies, regardless of physiological indices used. Postural equilibrium tests provide a measure of ataxia and/or sway, yet none have been thoroughly validated, and more than one study has been unable to correlate sickness levels with postural instability.[19,56] Motion magnitude affects sickness levels, but in a decidedly nonlinear manner, with sickness incidence peaking at real or simulated motion frequencies approximating 0.2 Hz.[32]

This lack of objective measurement has led to a reliance on self-reported symptoms collected via questionnaires. The Pensacola Diagnostic Index[33] and Pensacola Motion Sickness Questionnaire (MSQ)[40,49] are predominate favorites, although each assesses motion sickness as a univariate symptom, existing along a single continuum with variance only in severity.[29] For example, the MSQ converts its 25 to 30 symptoms to a single scale, ranging from no symptoms to vomiting as the highest score. Yet motion sickness and its subsets are best understood as a multidimensional syndrome, due to the wide individual differences in both symptom types and severity.[29,45]

In 1993, Kennedy et al.[46] developed the multidimensional SSQ from a factorial analysis of more than 1100 pre- and postexposure MSQs from 10 different rotary- and fixed-wing Navy simulators. Symptoms lacking statistical significance were eliminated, including vomiting, which occurred in less than 2% of all cases.[39,46] The remaining 16 symptoms were divided into three subscales: oculomotor (i.e., eye strain, difficulty focusing, blurred vision, headache), nausea (i.e., stomach awareness, nausea, salivation, burping), and disorientation (i.e., dizziness, vertigo). Postural instability was not included on the MSQs, though subsequent research has found significant correlation with the disorientation subscale.[42] Symptoms are scored on a four-point scale (0–3) and each subscale is weighted and summed together for a maximum score of approximately 300. Kennedy et al. defined a simulator as problematic if central tendency scores reach 20 or higher.[46,47]

Despite the introduction of the SSQ, determining incidence is problematic. Motion sickness incidence is traditionally defined by the endpoint of vomiting, but there is no such agreed-upon endpoint in simulator sickness. Most studies quantify incidence as the percentage of subjects reporting at least one symptom, regardless of severity. Furthermore, single-study incidence rates are typically device- or technology-specific, and not applicable as a population estimate.

However, generalizations can be drawn by comparing aggregate SSQ scores across simulator technologies and types. Kennedy et al.'s 2001 review[44] found CAVE SSQ scores ranged between 8 and 20, with most under 10, with subscale scores highest for oculomotor and lowest for nausea. In contrast, HMDs ranged from 19 to 55, with subscale scores highest for disorientation and lowest for oculomotor. In 2005, Johnson's[39] comprehensive review of military flight simulators found sickness incidence among rotary-wing CAVEs significantly higher than fixed-wing simulators, with as many as 60% of users experiencing at least one SSQ symptom in individual simulators.[12,39,47] Drexler's[23] 2006 meta-analysis of 21 CAVE and 16 HMD studies also found HMDs scoring significantly higher in SSQ severity scores than CAVEs (**Table I**). By CAVE type, SSQ scores were highest for driving simulators, followed by rotary- and fixed-wing.

The differences between technologies are pronounced enough that in 2005, Ames et al.[2] proposed a cybersickness-specific alternative to the SSQ: the 13-item Virtual Reality Sickness Questionnaire, to be completed in under 1 min. This questionnaire has yet to see widespread usage, but it is not without its supporters, and its existence underlines the difficulty in measuring sickness across technologies.[13]

The incidence and duration of negative aftereffects is, despite being of prime importance for military pilots, mostly theoretical. Only two large studies were found following postexposure symptomology beyond an hour, both from 1989 and reliant on retrospective questionnaires. Baltzley et al.'s[4] post hoc survey of 742 motion history questionnaires found 334 (45%) military pilots reported after-effects: 114 (34%) lasting more than 1 h, 20 (6%) over 4 h, and 13 (4%) longer than 6 h. Ungs[88] surveyed 196 U.S. Coast Guard pilots training in three rotary- and one fixed-wing simulator. Nine (4.6%) reported symptoms lasting 24 h or longer, including: visual flashbacks, ataxia, and decreased hand-eye coordination. Three (1.3%) reported subsequent difficulties flying aircraft, though each noted that they would not hesitate to use the simulators again.

Factors Linked to Simulator Sickness

Three categories of factors contributing or correlated with simulator sickness in VR and AR were identified in the literature:

Table I. Aggregate SSQ Scores by Type and Technology.

	N	Mean SSQ	SD
CAVE Type			
Driving	262	23.34	22.57
Rotary-Wing	496	17.12	15.77
Fixed Wing	150	12.37	11.10
Technology Type			
CAVEs	908	18.13	17.79
HMD	1100	28.97	27.01

individual, technological, and usability.[2,53] Individual factors are not directly correlated to sickness levels, but susceptibility is and includes: higher female susceptibility to oculomotor and disorientation symptoms;[30,78] relative immunity among young children and older adults;[30,72] a potential genetic predisposition, especially for those of Chinese ancestry;[25,82] and prior history, which is the primary determinant of simulator sickness susceptibility.[12,78]

Four technological factors common to all VR and AR devices make up the bulk of research: visual field-of-view (FOV), accommodation-vergence conflict, latency, and frequencies of simulated motion and/or visual displays. For both CAVEs and HMDs, a wide FOV induces a greater sense of vection—the illusory sense of motion when there is none and a known prerequisite of simulator sickness, though there is no linear relation between sickness scores and FOV.[7,50,61]

Field of view. Whereas CAVEs have a single FOV, HMDs have two distinct FOVs: display FOV (DFOV) and geometric FOV (GFOV). DFOV is the FOV allowed by physical dimensions of the device, and GFOV is the simulated FOV. If DFOV is larger than GFOV, the image must be magnified to fill the physical dimensions, and vice versa. Most GFOVs range between 110° and 120° compared to real-world FOV of 180° or more. Several studies have examined sickness levels and the ratio of DFOV to GFOV, or image scale, but with conflicting results. Bos et al.[11] found that altering image scale factor in either direction from a 1:1 ratio decreased sickness incidence. By comparison, Moss and Muth[63] found no effect using 2.0 and 0.88 ratios, whereas Draper et al.[22] found sickness levels significantly greater using 2.0 and 0.5 image scale factors.

Accommodation-vergence conflict. Accommodation-vergence conflict is a major source of eye strain and fatigue. When viewing an object, the eyes have two primary actions: converging dually upon an object so that both are directed at the point of interest (vergence), and changing the shape of the eyes' lenses to sharpen the retinal image (accommodation, or focal distance). These two actions are coupled as dual parallel feedback control systems. In stereoscopic AR and VR, the display causes vergence distance to vary depending on image contents (i.e., artificial location of a 3D image), whereas the focal distance remains the same—the distance between the eyes and display screen.[54,75] This conflict is especially prolific in HMDs and a significant source of oculomotor disturbances.

Latency. Latency, or lag, is the time delay between a user's input and a VE's ability to update. The joystick-to-display latency in CAVEs has largely been resolved due to modern processing power, but HMD latency is between a user's head movements and the display's ability to update—a significantly faster action. A maximum latency of 60 ms is required to remain undetected by the user, though some researchers have argued for rates below 20 ms.[55] Two studies found increased latency correlated with higher sickness scores.[16,20] In contrast, three separate studies found latencies between 40 and 250 ms had no effect on sickness scores.[22,63,68] However, latency in each of these studies remained constant and more recent work has examined the relationship between latency and amplitude over time. One study found that sinusoidally varying latency amplitude by 20–100 ms at a 0.2 Hz frequency caused significantly higher sickness scores than chronic-rate latency.[77] A second study found varying latency amplitude with a frequency of 0.2 Hz had significantly higher sickness levels than 0.1 Hz.[51]

Frequencies. The most problematic motion frequencies (simulated or real) are between 0.1–0.3 Hz, with greatest incidence centered at 0.2 Hz.[31,32,56] This would explain the increased sickness levels with a latency amplitude at 0.2 Hz compared to the 0.1 Hz condition.[78] However, there is evidence that this frequency range is problematic not just as a direct motion frequency, but in differences between motion frequencies. Groen and Bos[34] looked at the frequency of the mismatch signal between simulator platform motion and actual vehicle motion. The simulator was a full-sized car on a six degree-of-freedom platform, with the OTW display generated by screen and projectors. They analyzed 58 SSQs from two different experiments, and found significantly higher sickness scores with the main frequency component of the mismatch signal at 0.08 Hz compared to 0.46 Hz.

Technological and Usability Factors

Usability factors correlated with increased sickness scores include: presence, vection, peripheral vision, time in the simulator, and the user's actions within the simulator.[81] It was previously believed that as a simulator's fidelity increased to the point of accurately replicating reality, sickness levels would drop.[94] More precisely, the greater the presence, the lower the potential for sickness. However, heightened visual detail has been proving more, rather than less, nauseogenic, especially in HMDs.[78] In an Oculus Rift experiment, seated subjects were shown two different roller coaster scenarios with either high or low fidelity, with all other factors identical. The high-fidelity track not only had significantly higher sickness scores, but more users were unable to finish compared to the low-fidelity track.[18,67]

Vection. Although vection is a prerequisite for simulator sickness, not all vection causes sickness.[26,35,83] Bonato et al.[9] found that subjects viewing an optic flow pattern were significantly more likely to develop simulator sickness when the direction of vection changed, as compared to a steady-state flow. Physiologically, vection—and by extrapolation simulator sickness—is

dependent on peripheral vision.[91] Moss et al.[63] found that after adjusting for latency and image scale factor, simulator sickness was highest when peripheral vision was wholly ensconced by VR.

Duration/time. Time in the simulator has been correlated with increased sickness in several studies.[39,53,80] Even so, time to the development of sickness is invariably linked with type of simulator, type of simulation, tasks being performed, etc., preventing identification of a uniform time course to sickness. Commercial HMD manufacturers (i.e., Oculus Rift) recommend breaks every 30 min. Johnson's[39] review suggested a maximum of 2 h in CAVEs. Reciprocally, Kennedy et al.'s[48] review of length and frequency of simulator exposures found that sickness levels tended to drop over multiple exposures, suggesting that multiple exposures of short duration may be an effective remedy.

Activity. Actions and tasks performed within a simulator are inextricably linked with other factors. Increased head movements have been linked to increased sickness scores in several HMD studies.[53,64] However, researchers noted that as sickness increases, users will minimize head movements, adopting a "move-and-wait" strategy;[13,22] it remains to be determined whether head movements are the nauseogenic source.[89] There is also evidence that sickness increases when users are passive observers compared to actively controlling movement. Jaeger and Mourant[37] had subjects traverse a VR hallway via HMD using either a mouse while sitting or via a treadmill-operated system, with sickness levels significantly lower in the treadmill condition.

Simulator Sickness and Training

Kennedy et al.'s[43] 1987 report recommended a simulator sickness program to ensure simulator-enhanced training is not compromised. Otherwise, users will avoid problematic simulators, or avoid actions or movements that would enhance symptoms, such as pilots avoiding looking at the OTW display and relying as much as possible on mock-up instruments.[42] There have been cases of users avoiding, or at least complaining of, specific simulators due to reputation, although there is no evidence of reputation negatively affecting training.[36] Johnson's 2005 review[39] noted there was virtually no evidence showing simulator sickness prevented adequate training among rotary-wing CAVEs. One study did find sickness negatively correlated with accuracy in an AR HMD target and shooting task, though training retention was not followed.[38]

There is evidence that not all simulator technologies are equal regarding the intersection between training and sickness. Draper et al.[21] had military personnel participate in a large-area, within-subjects search task using either HMD or CRT monitor. Subjects acquired as many targets as possible using either a joystick (CRT) or by line-of-sight (HMD). Sickness scores were significantly higher in the HMD condition, whereas situational awareness and accuracy were significantly higher in the CRT condition. Morphew et al.[62] conducted a similar within-subjects experiment, substituting the CRT display for a conventional computer monitor. Subjects performed an unmanned aerial vehicle sensor operator target search task by joystick or direct line-of-sight. Again, sickness scores were significantly higher in the HMD condition, whereas targeting accuracy was significantly higher in the computer monitor condition. Taylor and Barnett[86] examined HMD training effectiveness in two separate experiments. The first experiment assigned subjects to one of three conditions: desktop computer, HMD, or interactive videos. In the desktop computer and HMD conditions, a trainer explained and demonstrated each procedural task, and provided feedback to subject participation, whereas the interactive video group viewed three different training videos used by the U.S. Army. Training incorporated functions related to standard infantry tasks, including movement, observation, target engagement, and communication. Each condition lasted approximately 20 min. The second experiment assigned subjects to similar conditions: desktop computer, HMD, or live training. All subjects were then trained in the Army's hostage rescue missions. After training, subjects completed four live missions under the same conditions as the live training group, but without instructions or assistance from researchers. In both experiments, there was no significant difference in training retention or training transfer between conditions. However, the HMD conditions elicited significant levels of simulator sickness within 20 min.

Shipboard Simulator Training

The effects of simulator use shipboard are limited. Although no studies were found examining training acquisition using different simulator technologies shipboard, two studies did examine simulator usage and sickness levels aboard U.S. Navy Yard Patrol (YP) craft. Muth et al.[66] exposed subjects to three conditions over three separate days: piloting a fixed-base flight simulator ashore, riding aboard the YP craft without using the simulator; and piloting the simulator aboard the YP craft. SSQ scores in all three conditions were minimal, with no significant differences between conditions. In a follow-up study[69] using the same three conditions, the fixed-base simulator was replaced with an HMD. Nine subjects used stick-and-throttle controls to navigate a 1-h flight simulation, with flight instruments digitally overlaid on a virtual heads-up display in the HMD. In both HMD conditions, simulator sickness levels were five times higher postexposure, though there was no significant difference between conditions.

Aftereffects

Negative aftereffects were first described anecdotally. Miller and Goodson's[58,59] reports described the first significant adverse reaction postexposure: "One of these men had been so badly disoriented in the simulator that he was later forced to stop his car, get out, and walk around in order to regain his bearing enough to continue driving."[39] Despite the incident occurring prior to the advent of computers and having no recorded second occurrence, the anecdote has become proof by repeated assertion, and often referenced as the cumulative aftereffect in the literature.

Additional aftereffects repeatedly mentioned in the literature include: postexposure ataxia and disorientation,[43,53,74] disorienting flashbacks,[53,88] and adaptation to behaviors and stimuli that, when transferred to the aircraft, would be detrimental.[53,68] Increased ataxia does occur for some persons postexposure, but duration and severity have been difficult to determine—likely due to the difference in technologies and tasks being performed. Cobbs[16] and Cobbs and Nichols[17] had 40 subjects play an interactive VR game via HMD while standing immobile. Navigation and shooting tasks were controlled by a hand-held input device. Each exposure lasted a maximum of 20 min. A mild increase in ataxia was noted postexposure, though brief and not correlated to sickness scores. Murata[65] had eight subjects play a VR HMD game while immobile for 3 h, with posture stability measured hourly. While instability was higher postexposure, there was no correlation between increased postural instability and time in simulator. However, a study with more than 900 college students exposed to VR HMD from anywhere between 15 and 60 min found significant levels of postural instability postexposure that had not returned to pre-exposure levels by 60 min postexposure.[14]

Flashbacks are the least documented aftereffect, reliant primarily on self-report. Johnson[39] notes the only direct evidence comes from a single anecdote from Goodwin and Miller's aforementioned report. Baltzley's[4] post hoc review of 742 motion history questionnaires, which do not specifically query flashbacks, identified 4 (0.5%) reported instances of spontaneously occurring flashbacks. Other than a brief reference to 'visual flashbacks' written on one anonymous questionnaire in Ung's survey,[88] there is no further evidence of such drastic disorientation occurring.

Adaptation has the highest potential for adverse effects as it requires a modulation of sensory perception. The theoretical fear is that any behaviors, postures, and sensory interactions learned by the user to prevent or adapt to simulator sickness will cause adverse aftereffects once the user is placed in real aircraft or other real environments. Essentially, users' nervous system plasticity will allow them to incorporate the sensory-motor cues provided by a VE.[5,14] Stanney et al.[81] summarized the theoretical problem of adaptation: "…those individuals who exit VE interactions feeling less affected (less ill) may actually be the ones at greatest risk." Cobb[16] theorized that adaptation may affect postural instability, whereby users leaving the simulator would suddenly encounter simulator sickness symptoms due to a need for readaptation to the real environment. There is also the possibility that as eye accommodation is controlled by the autonomic nervous system, simulator sickness' autonomic nervous system driven symptomology and subsequent adaptation could resultantly affect accommodation in heretofore unknown ways.[27,60]

Countermeasures

Despite its potential for adverse effects, adaptation is the most effective countermeasure to simulator sickness. Johnson[39] noted that most users will adapt to any provocative simulator over repeated exposures, though 3–5% of individuals never adapt, for unknown reasons.[70] However, sensory changes acquired during simulator exposure likewise require countermeasures. Champney et al.[14] identified two routes for readaptation: natural decay and active recalibration of sensory systems. All military services ascribe to natural decay when mandating a specific duration of elapsed time between simulator exposure and flight. Champney et al.[14] found that certain tasks might assist in active recalibration. Over 900 college students were exposed to a series of VR HMD tasks while seated, including locomotion, object manipulation, and choice reaction time tasks. Time in the VR varied between 15 and 60 min. Postural stability, hand-eye coordination (via a pointing task), and an SSQ were measured pre- and postexposure, and every 15 min for a maximum of 1 h postexposure. Subjects were divided into three different postexposure re-adaptation groups: natural decay, where subjects would sit with eyes closed between measurements; vestibular re-adaptation, where subjects walked heel-to-toe along an 8-ft metal rail on the floor for 5 min between measurement sessions; and hand-eye re-adaptation, where subjects filled a pegboard with 25 pegs as quickly as possible, one at a time, then removed the pegs in the same manner, repeating the task for 5 min between measurement sessions. The hand-eye coordination re-adaptation condition showed a significant decrease in pointing errors compared to the other two groups, while natural decay and vestibular re-adaptation had no effect. However, neither postural instability nor hand-eye coordination skills had returned to baseline at 60 min postexposure in all three conditions.

Besides adaptation, several engineering remedies have attenuated sickness scores. For latency, predictive compensation has shown promising results. A computer algorithm predetermines the direction and speed of head movements and updates the display appropriately, without apparent lag.[13] Dynamic FOV—essentially the occlusion of peripheral vision—is another potential remedy. A recent study found that reducing FOV in HMDs during real or virtual head movements reduced sickness scores.[24] Researchers had stationary subjects view a VR HMD with joystick controls to rotate the display. During head or display movement, FOV would begin blacking out at the 120° mark and, depending on movement speed, up to the 50° mark. Dynamic FOV significantly reduced sickness scores, though the authors note more research is needed to increase efficiency, and that textures and shapes may also affect sickness levels.

Although pharmaceutical countermeasures for motion sickness exist, there is little research of their efficacy against simulator sickness. Only one study was found, examining the effect of cinnarizine, a medication that is not legally available in the United States. There was no difference in SSQ scores between cinnarizine and placebo.[57]

Recent forays into galvanic vestibular stimulation (GVS) and galvanic cutaneous stimulation (GCS) present a potential means of bypassing sensory conflict by creating a false sense of acceleration when one does not exist. When a small current is run through electrodes placed on each mastoid (GVS) or on the neck (GCS), the vestibular nerve is activated, creating a sense of

acceleration. Perceived direction can be controlled by direction of the applied current. In a recent study with a fixed-base driving simulator, subjects received either GVS, GCS, or no stimulus while driving around curves. Both stimuli conditions had significantly lower sickness scores than the no stimulus condition.[73] Glavez-Garcia's[28] study applied GCS to subjects in a fixed-base driving simulator known to induce simulator sickness. Subjects underwent three conditions: no stimulus, GCS delivered at 40 m from a curve until the curve end, or GCS applied intermittently at either curves or during straight patches. Subjects experiencing GCS only at curves had significantly lower sickness scores than the other two conditions. Nonetheless, at this time, neither GVS nor GC is sensitive or specific enough to warrant usage in military flight simulators. The ability to artificially create a sense of acceleration is limited to an immediate and simultaneous perception of strong roll and slight yaw that is lacking any proportionality to the stimulus being replicated.[93]

DISCUSSION

Our review found that the lack of succinct terminology or uniform measurement methodology for simulator sickness can lead to misleading claims by commercial producers of VE technology. Caution must be exerted when HMDs and other devices are marketed as free of "cybersickness." As VE technology progresses, symptoms and severity between different simulator technologies are increasingly disparate, to the point that researchers are differentiating HMD-induced sickness as cybersickness, with simulator sickness reserved for CAVEs. Commercially, cybersickness is almost exclusively used to reference nausea and vomiting. Conversely, simulator sickness encompasses an array of symptoms, including multiple disorientation and oculomotor disturbances—symptoms with significant risk to the safety and well-being of highly skilled military pilots flying multimillion dollar aircraft.

Though multiple factors are correlated with increased sickness scores, they should not all be given equal weight. Individual factors, for example, cannot be directly countered by design. Instead, an accurate methodology to predict susceptibility is needed, especially for pilot subpopulations. Whereas experienced pilots were once more susceptible to simulator sickness than student pilots, there is now an entire generation with lifelong exposure to video games, VR, and AR. Research is needed to determine if this new generation adapts to simulators in the same manner as previous generations, or if they move between simulation and real aircraft without detrimental changes in sensory perception.

Technologically, latency and motion frequency are of the most concern for naval aviation. A wide FOV, though a prerequisite for simulator sickness, is necessary for both vection and presence, and reducing a pilot's FOV below what would be experienced in real aircraft could have deleterious training effects. Conflicting study results concerning HMD image scale suggest other factors, such as fidelity, latency, etc. play a larger role in sickness production than image scale alone. The accommodation-vergence conflict does contribute to oculomotor symptoms, but most researchers view it as separate from simulator sickness with an achievable engineering solution.

Latency varying in amplitude may be the predominate causal factor for sickness in VR HMDs and may be even more problematic in AR HMDs.[3] Allison et al.[1] suggested AR latency is more nauseogenic due to users being more sensitive to relative than to absolute motion. Buker et al.[13] suggested that AR has two levels of sensory conflict due to latency: intersensory, between head movements and the AR, and intrasensory, between the AR and OTW displays. Theoretically, simulator sickness is a lesser concern with optical-based than video-based AR, as the latter requires higher resolution and processing powers in addition to challenges arising from improper placement of the external cameras.[52] However, we were unable to identify any research explicitly comparing sickness levels between AR and VR HMDs.

The most problematic motion frequencies are between 0.1 and 0.3 Hz. The proposed reason is that the otoliths' 'break' frequency between tilt and oscillation perception is approximately 0.2 Hz, causing vestibular indecision regarding movement—an intersensory conflict per the SCT.[76] This idea would explain the increased sickness levels with a latency amplitude at 0.2 Hz compared to the 0.1 Hz condition.[77] Kennedy et al.[44] recommended any simulated motion frequency occur below 0.01 Hz or above 0.8 Hz. However, with evidence that differences between real and perceived motion frequencies can also be nauseogenic when approaching 0.2 Hz, more research is needed.

Usability factors appear to be inextricably linked. High fidelity is linked with increased sickness, but the exact relation between fidelity, vection, and sickness is unknown. Increased head movements in HMDs is linked with increased sickness levels, but it remains unknown if sickness-inducing head movements exist in isolation. And if a high-fidelity HMD is coupled with a moving cockpit base, how would sickness scores be affected?

Though we found few references linking time in simulator to sickness scores and training retention, these are significant concerns for naval aviation. Military CAVE training sessions may last up to 4 h, without evidence of simulator sickness negating training retention. Yet our review suggests comparative sessions in an HMD would significantly increase both sickness incidence and scores. Most reviewed HMD studies had exposure sessions under an hour, yet produced significantly higher sickness scores. And unlike CAVEs, there is evidence that HMD-induced sickness does negatively affect training retention. And although existing research would suggest that HMD use shipboard lacks an additive effect on sickness scores, it is unknown what effect a longer exposure would have. Additional research is needed to identify whether lengthy training sessions can occur in HMDs without deleterious effects.

The time course of symptoms and aftereffects is almost entirely unknown beyond an hour postexposure. The duration and effect of disorientation and oculomotor aftereffects requires

further research, especially for pilot subpopulations. Also, any resultant sensory changes from adaptation to a simulator must be explored, as well as potential readaptation solutions. Concurrently, any proposed readaptation methods to counter adaptive sensory changes may create an additional set of maladaptive behaviors.

Excluding adaptation, there is no readily-identified countermeasure to simulator sickness directly applicable to naval aviation. The most promising engineering solution via manipulation of peripheral vision and FOV is an unacceptable trade-off for military pilots, who require full FOV at all times. It may be that allowing some aspect of peripheral vision to remain open to the external environment will reduce sickness levels, but it is unknown what effect this would have on a user's sense of vection and immersion, and is irrelevant for AR HMDs.

The efficacy of pharmacological countermeasures against simulator sickness is unknown. Pharmaceuticals aimed at relieving nausea-like symptomology (i.e., antihistamines) of motion sickness may not resolve oculomotor or disorientation symptoms. An in-depth study would be necessary to compare the efficacy of different pharmacological interventions in alleviating simulator sickness rather than motion sickness.

One potential avenue for future research involves new modeling and quantitative methods. In particular, an isoperformance approach may help address many of the individual difference factors that contribute to simulator sickness. Isoperformance begins with a desired performance outcome and works to identify methods to control for latent variables and achieve acceptable solutions within the design space.[92] This approach could lead to new procedures that would reduce simulator sickness because the design would create "slack" within the acceptable variables to account for performance differences. In this case, known instances of simulator sickness could be incorporated directly into the design rather than addressed solely after the fact. Other modeling and quantitative methods could help address the wide array of potential influences involved with predicting simulator sickness. Although it is well known that individual differences play a large role, the sheer diversity of potential contributing factors limits current predictive models. Perhaps better models and big data platforms could help address some of these complicated issues.

An operational consideration involves updating technical manuals and field guides for future research. Current materials are largely out of date and based upon simulator sickness or technology issues as they stood in the 1980s and 1990s. Rapid advancements in simulator technology have rendered many such guides obsolete, yet they have not been suitably replaced. Updated materials based upon newer technologies, including augmented reality, could help prepare people for simulator sickness issues. At the very least, existing materials need to be updated to current state-of-the-art technology.

Our review identified multiple fields requiring further investigation before replacing legacy CAVE-style simulators with HMDs. HMDs are significantly more prone to produce sickness, and at higher levels than CAVEs. Technologically, variable latency appears to be the primary contributor to simulator sickness in HMDs and requires additional research. The differences between real and simulated motion frequencies also require research to determine the extent that the 0.1 to 0.3 Hz range is nauseogenic and under what conditions. It is unknown whether users can sustain extended training sessions in HMDs without experiencing training-negating sickness. Aftereffects, whether caused directly by simulator exposure or by sensor changes via adaptation/readaptation, require significant research, especially those pertaining to disorientation and oculomotor disturbances. Pharmacological countermeasures require research to identify whether they can attenuate disorientation and oculomotor symptoms. A means of bypassing the need for countermeasures would be the development of a methodology for determining sickness susceptibility within a pilot subpopulation. Most importantly, this review identified that whereas VR systems have been extensively researched, there is almost no quality AR HMD systems research. This lack of AR HMD systems research as it applies to military simulator use is a significant knowledge gap requiring immediate closure.

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