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DEVCOM Data & Analysis Center

Motion Sickness Literature Review

by Patricia Burcham

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* The work outlined in this report was performed while the Dismounted Soldier and Team Performance Branch was a branch of the Human Research and Engineering Directorate (HRED) within the US Army Research Laboratory. As of the date of report publication, the Dismounted Soldier and Team Performance Branch is now part of the Data & Analysis Center, reporting directly to the US Army Combat Capabilities Development Command.

14. ABSTRACT

There continues to be a need to identify causal effects of motion sickness, susceptibility factors, and potential preventative measures as the Army moves forward in the development of the Future Combat Vehicle and numerous other modernization efforts. The objective of this report is to review more recent literature in an effort to identify new findings and proposed countermeasures for various types of motion sickness. Twenty-one hits were found and summarized.

15. SUBJECT TERMS

motion sickness, seasickness, cybersickness, sopite syndrome, simulator sickness

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1. Introduction

The Army recently opened the Army Futures Command to provide future Warfighters the concepts, capabilities, and organizational structures to dominate the future battlefield. In the continuous efforts to modernize the Army and deter future adversaries and prepare to defeat them, there will be a continued need to be vigilant about the technologies, vehicles, and equipment being developed that does not suffer from detrimental human performance decrements. More specifically, scientists and engineers alike must be vigilant during their design processes not to overlook the debilitating effects of motion sickness. Motion sickness continues to be a concern for teleoperation and many tasks performed within moving ground or air vehicles. It remains the Army Human Systems Integration practice to ensure that capabilities and limitations are incorporated into all steps of the system acquisition process. A motion sickness literature review was conducted and published in May 2002 (Burcham 2002) to address performance decrements as a result of indirect vision driving. There continues to be a need to identify causal effects of motion sickness, susceptibility factors, and potential preventative measures as the Army moves forward in the development of the Future Combat Vehicle and numerous other modernization efforts. The objective of this report is to review more recent literature in an effort to identify new findings and proposed countermeasures for various types of motion sickness.

A literature review was performed to identify any new findings since 2004 in relation to motion sickness prediction and mitigation. The US Army Research Laboratory (ARL)[*] Technical Library was tasked to search for a combination of sources that included Department of Defense literature (i.e., Defense Technical Information Center and peer-reviewed literature with key words motion sickness prediction, motion sickness mitigation, and motion sickness history questionnaire). Twenty-one hits were found and summarized.

[*] During the time this work was performed, the US Army Research Laboratory (ARL) was part of the US Army Research, Development, and Engineering Command (RDECOM). As of 31 January 2019, the organization is now part of the US Army Combat Capabilities Development Command (formerly RDECOM) and is now called CCDC Army Research Laboratory.

2. General

2.1 Theory

Some of the most widely accepted motion sickness theories are the neural mismatch theory (Benson 1999), conflict mismatch theory, and sensory rearrangement theory (Reason and Brand 1975). These theories are all variations of the same theme (Figs. 1 and 2).

Type of Conflict	Category of Conflict	
	Intersensory (Visual – Vestibular)	Intrasensory (Canal – Otolith)
Type I	Visual and vestibular systems simultaneously signal different (i.e. contradictory or uncorrelated) information	Canals and otoliths simultaneously signal different (i.e. contradictory or uncorrelated) information
Type II	Visual system signals in the absence of an expected vestibular signal	Canals signal in the absence of an expected otolith signal
Type III	Vestibular system signals in the absence of an expected visual signal	Otoliths signal in the absence of an expected canal signal

Fig. 1 Types and categories of sensory conflict (Griffin 1991)

Type of Conflict	Category of Motion Cue Mismatch	
	Intersensory (Visual [A] – Vestibular [B])	Intrasensory (Canal [A] – Otolith [B])
Type I A and B simultaneously signal different (i.e. contradictory or uncorrelated) information	Watching waves from a ship Use of binoculars in a moving vehicle Making head movements when vision is distorted by optical device "Pseudo Coriolis" stimulation	Making head movements whilst rotating (Coriolis or cross-coupled stimulation) Making head movements in an abnormal acceleration environment which may be constant (hyper – or hypo-gravity) or fluctuating (linear oscillation) Space sickness Vestibular disorderd
Type II A signals in the absence of an expected B signal	Cinerama sickness Simulator sickness Circular vection	Positional alcohol nystagmus Caloric stimulation of semi-circular canals Vestibular disorders
Type III B signals in the absence of an expected A signals	Looking inside moving vehicle without external reference; below deck in a boat Reading in a moving vehicle	Low-frequency (<0.5 Hz) translational oscillation Rotating linear acceleration vector ("barbeque spit" rotation, rotation about an off-vertical axis)

Fig. 2 Types of motion cue mismatch produced by various stimuli (Griffin 1991)

According to Griffin, there is wide variation in the susceptibility of an individual to motion sickness (Griffin 1991). The variation is a function of psychological variables such as personality, past motion exposure, and adaptability.

There are also observed predisposing factors that can affect an individual's susceptibility such as sex (Benson 1999), age (Benson 1999), sleep history (Dowd 1974), and personality (Guedry 1991). Adaptation does not take place in approximately 5% of the population (Hemingway 1945; Tyler and Bard 1949). According to Reason and Brand (1975), the body expects its sensory systems to send signals in recognizable combinations at every instant in time. When the contrary occurs, the body is subject to motion sickness. However, over time the brain learns new combinations resulting from the sensory environment, thus enabling adaptation. The susceptibility of an individual is a function of the rate at which the brain recognizes updated combinations. According to Reason and Brand (1975), there are three characteristics that affect the rate of recognition: receptivity, adaptability, and retentiveness.

Receptivity refers to the motion stimulus signal amplification within the individual. Adaptability refers to the rate at which the internal model updates to the revised signal combinations. Retentiveness refers to an individual's ability to retain the internal model of signal combinations and adjust to motion in succeeding motion exposures (Reason and Brand 1975).

Unlike the recognizable physiological symptoms normally associated with motion sickness, there exists a subtle subcategory of fatigue-related symptoms. According to Graybiel and Knepton (1976), these more subtle effects are merely part of a symptom-complex termed Sopite syndrome. Symptoms of Sopite syndrome regularly remain unnoticed and are not drastically felt such as yawning, drowsiness, headaches, and feelings of indifference to one's fate (Griffin 1991).

2.2 Cheung B, Nakashima A, Hofer K, Coyle B. Field Survey on the Incidence and Severity of Motion Sickness in the Canadian Forces Enclosed Light Armoured Vehicle. 2007 Apr.

A need was defined to identify the requirements of the active suspension system as it related to vibration and absorbed power. The system suspension response was investigated to determine if there was a human performance degradation, specifically, the incidence and severity of motion sickness. A study was completed to define the motion disturbance of the Light Armoured Vehicle (LAV) III. During a 2-week Platoon commander course, a questionnaire was administered daily to all of the participants to identify motion sickness symptoms and mood and alertness. Participants did not always complete the questionnaire as instructed due to the operational and physical demands of the course. Other factors such as noise, vibration, adverse weather, stress, and fatigue likely affected the scores. The most frequently reported symptoms were drowsiness, feeling warm, and headaches. The most frequently reported motion sickness symptoms were weariness, sleepiness, and physical discomfort. Anecdotal reports suggested that the course participants, experienced infantry, had habituated to the LAV III motion, and were less susceptible to motion disturbance than the less-experienced members.

2.3 Oving AB, Van Erp JB, Schaap E. Motion Sickness When Driving with a Head-Slaved Camera System. 2003 Feb.

Motion Sickness Incidence (MSI) when driving with a head-slaved camera system was examined. More specifically, the contribution to motion sickness of visual feedback on head roll and of stereoscopic view with the head-slaved camera system was examined. The system was capable of motion in all three rotational degrees-of-freedom (DOF). Twelve subjects drove a car around a closed circuit in four different viewing conditions. In two conditions, no feedback on head roll was present by disabling the roll DOF of the camera platform (i.e., resulting in a 2-DOF system), and either mono view or stereo view was used. In the other two conditions, visual feedback on bead roll was present (i.e., a 3-DOF system), and again either mono view or stereo view was used. As a baseline, subjects also drove with direct view, either with an unrestricted field of view (FOV) or with FOV-restricting goggles. The 2-DOF conditions were tested on a separate day from the 3-DOF conditions, and a direct view condition always preceded a condition with the head-slaved camera system. The subjects filled in the motion sickness questionnaire (MSQ) after completing the driving task in each condition. Simulator sickness questionnaire (SSQ) total scores were derived from the MSQ. Results revealed a significant difference between the 2-DOF and 3-DOF conditions (average SSQ total scores of 17.7 and 8.4, respectively). There were no significant differences between mono and stereo conditions observed. The results indicated that by adding a roll component to the system, MSI with a head-slaved camera system can be reduced considerably.

2.4 Matsangas P. A Linear Physiological Visual-Vestibular Interaction Model for the Prediction of Motion Sickness Incidence. 2004 Sep.

This paper proposes a linear model based on human physiology for the explanation of the MSI found in experiments reported by McCauley et al. (1976). The main human sensory systems discussed are the interaction of the vestibular and visual system. The model is validated against the previous descriptive model and the corresponding experimental data. The proposed model predicts MSI with adequate precision (less than 5%) in the frequency range between 0.07 and 0.25 Hz. The difference between the proposed model and the previous descriptive model is increased at the outer frequency regions of the data. The model is limited to vertical motions based on the assumption that motion sickness on ships is vertical motion. The final product gives an acceptable approximation for the critical region of frequencies. The model cannot be used to predict seasickness of a specific individual as a connection between a specific parameter and susceptibility to motion has yet to be discovered.

Further research needs to be done to gain a better understanding of the connection between physiology and motion characteristics and the influence of proprioception to the overall sensory error estimation. The role of the human body stabilization and locomotion may play a key role in MSI.

3. Cybersickness

3.1 Chen R, Ho A, Lor F, So RH. Enhancing the Predictive Power of Cybersickness Dose Value (CSDV) to Include Effects of Field-of-view and Binocular Views. 2004 June 1.

Two experiments were conducted to investigate the effects of display's FOV and binocular views on motion sickness symptoms experienced following exposure to a virtual reality (VR) simulation. The results were used to enhance the scope of prediction of a previously reported cybersickness dose value (CSDV). Results revealed that simulation with a larger FOV produced significantly higher nausea ratings ($n = 24$, $p<0.05$, analysis of variance [ANOVA]). The two FOVs studied were 48° by 36° and 24° by 18°. Participants' sickness symptoms of a VR simulation were not significantly affected by the choice of binocular or biocular presentation ($n = 20$, $p>0.2$, ANOVA). A possible explanation was that the virtual environment was an outdoor scene and most of the objects were at least 3 m away from the viewer. The data were added to the CSDV regression model.

3.2 Patterson FR, Muth ER. Cybersickness Onset with Reflexive Head Movements during Land and Shipboard Head-mounted Display Flight Simulation. 2010 Sep 9.

The objective of this study was to determine whether shipboard deployment of head-mounted display virtual reality (HMD/VR) flight simulators increase risk of simulator sickness (SS) and negatively impact aircrew performance. At sea, uncontrolled variables—wind and wave action—generate ship motion incongruent with aircraft movements displayed on an embarked flight simulator increasing risk of SS. Symptoms are caused from sensory discord between vestibular, proprioceptor, and visual systems. Previous research demonstrated that usage of a fixed monitor flight simulator, during low sea state, has a negligible report of SS; however, significant decrements in dynamic visual acuity were measured in 60 min of flight simulation exposure with mild ship motion.

Nine subjects flew an HMD/VR flight simulation during land-based and shipboard conditions. The simulated flight task required subjects to use stick and throttle controls for navigation through digitized satellite imagery (10-m resolution) of the Navy's primary flight training area. A yellow "follow-me" line was digitally embedded onto the VR imagery to aid with navigation around turns (20 right and 14 left) that made up the assigned route. Display of flight instruments was accomplished by digitally overlaying a virtual (visible when looking forward) heads-up display onto the HMD. While navigating the course, subjects were instructed to maintain their simulated aircraft at an altitude of 5000 ft above mean sea level, with 500 knots of indicated airspeed.

Disparity between VR visual flight conditions and ship-induced vestibular accelerations may generate changes in reflexive head movement, and thereby influence risk of SS. Reflexive head positioning and SSQs were used to evaluate differences between the two conditions. Results indicated that both land and shipboard HMD/VR flight simulations produced optokinetic cervical reflex (OKCR) responses ($p < 0.001$) in both coronal and sagittal planes; however, between land and sea conditions, these OKCR variations were not statistically significant. In contrast, land and sea OKCR head yaw did show a significant increase during shipboard trials. SSQ scores were significantly elevated after exposure to both land and sea HMD/VR conditions; however, SSQ differences (between land and sea conditions) did not reach a significant level. In summary, non-motion (land) HMD/VR flight simulations provoke significant coronal and sagittal OKCR responses that do not change when low sea-state shipboard motion is introduced; however, low sea-state shipboard motion did appear to trigger significant increases in OKCR head yaw.

4. Simulator Sickness

4.1 Mollenhauer MA, Romano RA, Brumm B. The Evaluation of a Motion Base Driving Simulator in a Cave at TACOM. 2004 Dec.

The purpose of this conference presentation was to highlight research programs designed to investigate the feasibility of creating a motion base driving simulator in a Cave Automatic Virtual Environment (CAVE). The goal was to create the most effective simulator possible using a compact, portable motion system. These simulators could be used to support rapid development and delivery of timely driver training programs to support operational and safety training needs of deployed personnel. There were state-of-the-art simulation technology reviews along with two human factors studies to determine the impacts of design trade-offs on simulator off-road driving performance. In the first study, field (FOV), display system, and motion cueing algorithm were evaluated. In the second study, the optimum configuration from the first study was compared to US Army Tank-automotive and Armaments Command’s (TACOM's) Ride Motion Simulator (RMS) off-road driving performance. In addition, several SS mitigation techniques were also tested. The important findings from each of these evaluations were discussed. Visual presentation of the driving terrain and the motion cue and control loading responses are important factors of off-road simulation design. Several methods of mitigating SS and nausea have been proposed and were studied. The methods include the independent visual background (IVB) and the Relief-Band, a medical device. The IVB is a grid superimposed over the window visual display. Regardless of how the displayed image moves, the grid stays fixed to the earth reference coordinate system. The hypothesis is that the grid provides stable earth-stationary references that help the brain maintain a solid frame of orientation reference. The Relief-Band provides electrical stimulators to a nerve located in the wrist that helps the stomach maintain normal rhythm of contraction. Generally, SS measures were the same between the RMS and CAVE simulators. The Relief-Band limited the increase in SS symptoms between the first and second drives. Subjects did not express a clear preference of visual conditions in the SS mitigation questionnaire. Therefore, no conclusive results were revealed with the use of the IVB.

4.2 Havir TJ, Durbin DB, Frederick LJ. Human Factors Assessment of the UH-60M Common Avionics Architecture System (CAAS) Crew Station during the Limited User Evaluation (LEUE). 2005 Dec.

The utility helicopter (UH)-60M Product Office requested ARL's Human Research and Engineering Directorate (HRED) to participate in the Limited Early User Evaluation (LEUE) of the Common Avionics Architecture System (CAAS) cockpit. ARL conducted a human factors evaluation during the LEUE, which assessed workload, situation awareness (SA), SS, pilot-vehicle interface (PVI), and eye tracker data. The data were used to identify CAAS cockpit characteristics that enhance or degrade pilot performance. Characteristics that degrade pilot performance should be considered for design changes at the earliest opportunity. Three UH-60 crews (six pilots) each conducted three mission scenarios for a total of nine flights. The three missions consisted of flights in visual meteorological conditions (VMCs), instrumented meteorological conditions (IMCs), and tactical conditions. The pilots completed the SSQ before and after each flight. They completed the Bedford Workload Rating Scale, SA Rating Technique, and the PVI questionnaire after each mission. In addition to pilot data, a tactical steering committee (TSC) was used to perform an independent assessment of workload, SA, and mission success. The TSC completed a survey after each mission. The data were analyzed using the Wilcoxon Signed Ranks Test to compare pilot ratings between seat position and results between instrument flight rule and visual flight rule flights. The mean workload rating for all tasks was 3.10, indicating that the pilots typically had enough workload capacity for all desirable additional tasks. The mean SA rating provided by the pilots was 25.84. This SA rating indicates that the pilots felt they had moderate levels of SA during the missions. The questionnaire results showed that these simulators induced low to moderate SS symptoms.

4.3 Havir TJ, Durbin DB, Frederick LJ, Hicks JS. Human Factors Assessment of the UH-60M Crew Station during the Limited User Test (LUT). 2006 Feb.

The UH-60M Product Manager requested ARL's HRED to participate in the Limited User Test (LUT) for the UH-60M Black Hawk. ARL conducted a human factors evaluation during the LUT, which assessed workload, SA, SS, pilot-vehicle interface, and eye tracker data. The data were used to identify characteristics of the UH-60M that enhance or degrade pilot performance. Characteristics that degrade pilot performance were included in the Manpower and Personnel Integration (MANPRINT) assessment for the system's milestone decision and should be considered for future design changes at the earliest opportunity. Three UH-60 crews (six pilots) each conducted six mission scenarios for a total of 18 flights. The conditions of each mission were systematically varied and designed to become progressively more difficult as the pilots became more proficient at flying the aircraft. The pilots completed the SSQ before and after each flight. They completed the Bedford Workload Rating Scale, SA Rating Technique, and the Pilot-Vehicle Interface Questionnaire after each mission. In addition to pilot data, a TSC performed an independent assessment of workload, SA, and mission success. The TSC completed a survey after each mission. The data were analyzed with the use of the Wilcoxon Signed Ranks Test to compare pilot ratings between seat position and results between UH-60M and UH-60A/L model aircraft. The mean workload rating for all tasks for the UH-60M was 2.71, indicating that the pilots typically had enough workload capacity for all desirable additional tasks. The mean SA rating provided by the pilots was 28.25. This SA rating indicates that the pilots felt they had high levels of SA during the missions. Subjects reported mild SS symptoms after the Battlefield Highly Immersive Virtual Environment (BHIVE) flying missions. However, pilots reported higher severity scores after VMC flight. The severity scores were 6.23 for IMC missions and 12.15 for VMC missions. Pilot performance was not adversely affected by the SS symptoms.

4.4 Ruffner JW, McDowell K, Paul VJ, Zywiol HJ, Mortsfield TT, Gombash J. Assessing the Validity of the Ride Motion Simulator for a Remote Vehicle Control Task. 2005 Sep 26.

Within 5–10 years, Soldiers riding as passengers in moving vehicles will be required to perform operations previously conducted in stationary-only environments. Performance degradation can result from operating under motion conditions that are associated with physical perturbations and sensory input conflicts resulting in motion sickness. Full-motion simulators allow modeling and testing of multiple vehicles' profiles and various crew station designs while providing improved experimental control. A major concern lies with whether or not a simulator can actually evoke the behavioral responses observed in real life. Result comparisons were made between two complementary experiments whereby task performance was examined while operators were either in simulated or actual vehicle motion. Differences of driving performance were indicated in several measures between experiments. MSQ subscales revealed similar result patterns across both experiments. Both experiments were marked by similarly high drop-out rates due to feeling ill. Support for both absolute and relative validity was found for using the simulator to examine motion sickness issues but not performance measures. Absolute validity is when the simulator has human-vehicle system performance that is the same as real life. Relative validity is when the same trend is seen without the simulator and real life. Results support that simulators can be valuable for inducing some real-life behaviors inherent to proposed designs for future forces.

Operations under motion conditions can lead to performance degradations due to physical agitation and conflicting sensory inputs, causing motion sickness. Full-motion simulators offer the flexibility to model and rapidly test multiple vehicle profiles and crew station design configurations while providing increased experimental control. A major concern is whether or not a simulator can evoke the behavioral responses observed in real life. This study compares the results of two experiments that examined task performance while operators underwent either simulated or actual vehicle motion. Driving performance indicated differences between the experiments for several measures, while MSQ subscales indicated similar patterns of results across both experiments. Overall, support was found for both absolute and relative validity of using the simulator to examine issues related to motion sickness, but not for performance measures. The results support the premise that simulators can be valuable for inducing specific types of real-life behaviors that will be inherent to designs proposed for future forces.

4.5 Johnson DM. Simulator Sickness during Emergency Procedures Training in a Helicopter Simulator: Age, Flight Experience, and Amount Learned. 2007 Sep.

This research measured SS both before and after exposure to a helicopter simulator that was being used for emergency procedures training. Research issues were the incidence and magnitude of SS, after effects, susceptibility, and the effect of SS on training effectiveness. A total of 474 AH-64A (Apache) Army aviators participated in this research. Participants were administered the SSQ prior to simulator exposure, immediately after simulator exposure, and 12 h later. In addition, participants' demographic data were collected that included their age, total flight hours, prior motion sickness history, and prior SS history. A no-notice, behavioral test that sampled prior instruction was given during the training session. The incidence rate following simulator exposure was 68%. The SSQ Total Severity score was significantly larger immediately after exposure than it was prior to simulator exposure or 12 h later. Age was significantly and positively correlated with SSQ score, after the effect of total flight hours was held constant. Flight hours did not correlate with SSQ score, after the effect of age was held constant. These results were consistent with postural instability theory. Both prior history of motion sickness and prior history of SS were significantly and positively correlated with SSQ score that agreed with earlier research that found a near universal relationship between history and reported discomfort during simulator training. The strongest susceptibility factor noted in this research was prior history of SS. SSQ score was not correlated with training effectiveness, as measured by a short behavioral test.

4.6 Bass JM, Webb CM, Johnson DM, Kelley AM, Martin CR, Wildzunas RM. Simulator Sickness in the Flight School XXI TH-67 Flight Motion Simulators. 2009 Feb 1.

In 2005, the US Army debuted the TH-67 Creek flight motion simulator (FMS). Comments from the first class to use the devices indicated an unusually high number of instructor pilots (IPs) and student pilots (SPs) experienced severe SS. To investigate the potential problem, a pre-study was conducted using the SSQ to collect data from three 5-day class cycles from 73 IPs and 129 SPs. Based on an analysis of these data, along with operator comments, recommendations to reduce SS were provided. The post study was conducted 1 year later to test the effectiveness of the recommendations at reducing the SS symptoms. SSQ data were collected on 25 IPs and 50 SPs, over one 3-day class cycle. After the recommendations were implemented, there was a significant reduction in SSQ scores in both IPs and SPs for three of the four SSQ subscales. Overall, IPs reported significantly greater SS than SPs across all four SSQ subscales. The implementation of the recommendations, which were based on previous findings, reduced SS in the TH-67 FMSs.

SS is a form of motion sickness caused by physical and/or visual motion in a simulator. Compared to motion sickness, the symptoms of SS tend to include more visual disturbances than gastrointestinal manifestations. Symptoms include dizziness, nausea, eyestrain, feelings of warmth, headache, disorientation, and fatigue. In addition, SS is known to produce aftereffects, like loss of balance and nausea, up to 6 h after the simulator session (Johnson 2005).

SS has a negative impact on military aviation training, including reduced simulator use, ineffective simulator training, and compromised ground and air safety. For example, if a simulator induces SS symptoms, aviators may develop "bad habits" (e.g., limiting head movements, closing their eyes during certain maneuvers) which may carry over to actual flight and result in devastating consequences (Crowley 1987). In accordance with Army Regulation 40-8 (HQDA 2007), aircrew exhibiting symptoms of SS are restricted from actual flight for 12 h after all symptoms completely resolve. Interestingly, aviators with high amounts of actual aircraft experience are more susceptible to SS than students with little flight time in the actual aircraft (Johnson 2005).

The SSQ is a well validated pen-and-paper questionnaire designed to detect the prevalence and severity of 16 possible symptoms generally associated with SS including, but not limited to, fatigue, headache, eye strain, sweating, nausea, difficulty concentrating, blurred vision, vertigo, and stomach awareness (Kennedy et al. 1993). Participants rate the severity of symptoms on a scale ranging from 0 (none) to 3 (severe). In addition to a total severity score, the SSQ yields a nausea, oculomotor, and disorientation subscale score, which provide diagnostic information about particular symptom categories. Stanney et al. (1997) describes a method to categorize simulators based on mean/median values of the total SSQ score. Total severity scores greater than 20 indicate participants are experiencing sufficient discomfort (i.e., a "problem simulator"), whereas scores less than 5 indicate symptoms are negligible (See Stanney et al. [1997] for additional information).

After analyzing the data from the pre-study, a number of recommendations to reduce SS were provided to the directors of Flight School XXI (Fig. 3). The recommendations that were implemented and incorporated into the simulator training program were as follows: simulator flights were reduced from 4 to 3 h (1.5 h per student); pilots were instructed to close their eyes before freeze/reset; and unusual or unnatural maneuvers were limited. The course was reduced from 5 to 3 days since most of the hover training and ground work were removed from the program of instruction entirely. There was an effort to avoid improperly calibrated simulators (e.g., misalignment, out of focus, luminance mismatch, distortions) until repaired. And finally, emphasis was placed on stressing the importance of proper rest/health discipline, and giving instructors enough time to adapt and maintain adaptation.

Conditions that increase the likelihood of SS and recommendations made to counteract those conditions.

Conditions contributing to SS	Recommendation to counteract SS
Session duration	2 hr daily maximum
Use of the freeze/reset command	Close eyes before freeze/reset
Unusual or unnatural maneuvers	No flying into buildings, radio towers, or air traffic
Maneuver intensity	IPs not allow students to get too far out of control
Height above terrain	If discomfort arises, limit hover/autorotation training
Degree of aircraft control	If discomfort arises, remove SP from back seat
Head movements	Limit head movements
Wide field of view visual displays	If discomfort arises, turn off side screens
Off-axis viewing; out of design eye point or viewing region	If discomfort arises, get student out of back seat
Optical distortion caused by misaligned or poorly calibrated optics	If visual display not "right" do not use simulator until fixed
Fatigue and sleep loss	Maintain health/rest at individual level

Fig. 3 Conditions that increase the likelihood of SS and recommendations made to counteract those conditions

4.7 Webb C. Simulator Sickness in the MH-47G Simulator. 2010 Jan 1.

An investigation was conducted into SS stemming from the MH-47G Chinook simulator following significant reports of SS. The objective was to quantify symptoms of SS induced by the MH-47G simulator and to recommend how to alleviate SS if unacceptable levels were discovered.

The SSQ was used to define the extent and the severity of the symptoms. SS is a form of motion sickness caused by physical or visual motion or a combination of both. SS tends to involve more visual than gastrointestinal disturbances.

The study focused on the assessment of the MH-47G simulator. The simulator consists of 6° freedom of motion platform and 3° vibration platform. It features a collimated display system with a 210° by 65° FOV.

Participants were rated H-47 pilots located in Fort Campbell, Kentucky. Everyone who utilized the MH-47G simulator was required to complete the SSQ immediately after their session ended. Each session lasted 2 h. A total of 232 SSQs were analyzed. When the simulator was on-motion, oculomotor scores were highest. When the simulator was off-motion, nausea scores were higher.

The SSQ data results suggest that the MH-47G simulator yielded negligible SS symptoms both on- and off-motion. Individual differences were illustrated in SS susceptibility in response to simulator motion. Collimated display advancements seemed to have improved image quality associated with simulators' wide FOVs.

4.8 Hicks JS, Durbin DB. A Summary of Simulator Sickness Ratings for US Army Aviation Engineering Simulators. 2011 June.

ARL's HRED uses US Army Aviation engineering helicopter simulators to assess crewstation design for new or modified aircraft. SSQ ratings for seven engineering simulators were summarized. Pilot ratings, obtained through the assessments, were used to identify if the simulators induced SS symptoms and if the symptoms caused significant discomfort that distracted the pilots during missions and contributed to an increase in perceived workload. The mean SSQ scores for the evaluated simulators were compared to the mean SSQ scores for several other helicopter simulators to assess whether the SSQ ratings were similar or different to ratings obtained in other helicopter simulators.

The AH-64D and UH-60M engineering simulators induced minimal SS symptoms. The RAH-66, ARH, and CH-47F simulators induced greater SS symptoms. RAH-66 pilots reported higher SS ratings that may have been caused by wearing an HMD during missions. The ARH pilots reported higher SS ratings that were likely caused by a visual lag in the out-the-window scene. It is uncertain what caused the higher SS ratings reported by the CH-47F pilots. It is interesting to note that the pre-mission SS scores were fairly high for CH-47F pilots. This indicates that they were experiencing physical discomfort prior to performing missions in the simulator. Based on mission observations and recordings and extensive postmission pilot interviews, the SS symptoms induced by the RAH-66, ARH, and CH-47F simulators did not appear to cause significant discomfort for pilots, distract them during missions, or contribute to an increase in perceived workload. The successfully completed missions of RAH-66, ARH, and CH-47F pilots reported low to moderate workload ratings for the flight and mission tasks they performed. Therefore, it appears that the AH-64D and UH-60M, RAH-66, ARH and CH-47F engineering simulators do not induce debilitating SS and are suitable for continued assessment of the design of US Army Aviation crewstations. There will be continued SS assessments during future simulations to identify whether SS symptoms negatively affect pilot performance.

5. Seasickness

5.1 Calvert JJ Jr. Motion Sickness, Crew Performance, and Reduced Manning in High-speed Vessel Operations. 2005 Dec.

The effects of ship motion on motion sickness, adaptation, susceptibility, and performance was investigated. Data collection periods found a relationship between the motion sickness history questionnaire and MSI. Data were collected from May 2004 to April 2005 during four periods on a HSV-2 SWIFT, a high-speed vessel with a catamaran hull type and a small crew. Data were collected using handheld personal digital assistants with a performance task along with questionnaires. Observations revealed adaptation to the ship's motion occurred between day 2 and 3. Lack of rough seas during the three periods made it difficult to determine if there were more significant relationships during the analysis. It was recommended to conduct future data collection during rough seas that have more variation in sea state, and efforts should address how motion sickness affects crew performance and if crew performance is degraded to a level that will affect the ship's missions, specifically the Littoral Combat Ship's (LCS's) missions of surface warfare, anti-submarine warfare, mine warfare, and high-speed operations. There is a possibility that crewmember cognitive performance, as measured by Lapses on the Psychomotor Vigilance Task (PVT), may be related to motion sickness. If future research confirms the relationship, then PVT can be used to assess the effects of motion on PVT performance. Results showed that it is possible to predict MSI with the motion sickness history questionnaire with three of four data collection periods showing significant relationships between MSI and MSQ.

5.2 Riola JM, Esteban S, Giron-Sierra JM, Aranda J. Motion and Seasickness of Fast Warships. 2004 Oct 4–7.

Seasickness, a form of motion sickness, is a result of erratic brain stimulation from sensory receptors and is prompted by constantly changing movements ending in symptoms of lethargy, nausea, cold sweat, stomach cramps, and vomiting. The sense of spatial orientation sends information to the brain about the space situation and this sense is regulated by body systems interaction to detect motions: the inner ear, skin pressure receptors, muscles, and joint sensory neural receptors. There are several competing causal theories of motion sickness and seasickness and this paper presents just one theory.

This paper looks at three models: excitation due to waves, ship motion response, and seasickness effects. More wave amplitude causes more ship motions amplitude and implies increased motion sickness index. Mathematical models identify three possible applications to the knowledge to alleviate seasickness.

The coupling between the sea, the ship, and humans is studied. In previous research, mathematical models of fast ships' motions have been determined. In literature, there are human sickness models and models of the sea. This knowledge about seasickness, waves, and ship motion was gathered. Using this information, it is possible to extract some criteria for the captain (maneuvering), ship designers, and actuators engineering. Taking advantage of the models obtained, a study of seasickness prediction was done. Using the algorithm presented in the paper, total sickness index for each place of the ship, coastal or open waters, for several speeds and headings, may be computed. It is possible to design the ship to work well under specific conditions. For example, it is important to optimize the characteristics and locations of the actuators to obtain maximum motion reduction.

6. Sopite Syndrome

6.1 Johnston JM. An Activity-Based Non-linear Regression Model of Sopite Syndrome and Its Effects on Crew Performance in High-Speed Vessel Operations. 2009 Mar.

Questions arose regarding crew performance resulting from ship motion of the Navy's future use of shallow-draft high-speed vessels. Sopite syndrome, discovered in 1976, is a subset of motion sickness commonly overlooked; its symptoms include lethargy, fatigue, drowsiness, difficulty concentrating, and many other performance-diminishing symptoms in shipboard crewmembers who appear to be vessel motion-adapted (Graybiel and Knepton 1976). No physically measurable parameter to quantify the syndrome and its effect on performance has been established. The manning modifications make it more important than ever to ensure that personnel readiness and performance degradation are accounted for in manning model calculations. Sopite syndrome is quantified in this study using non-linear regression to model activity as a function of time underway and linear regression to model performance. Performance is modeled using daily activity levels concurrently with ship's motion data, individual demographics, and MSQs as input parameters. Findings over an 8-day underway period revealed that performance on a 3-min manual dexterity task degraded by 2% to 3% due to Sopite syndrome.

LCS planners are focusing on trimaran and semi-planning monohull forms as candidates for the LCS hull. Either hull form produces a different motion stimulus distribution than that of a catamaran hull. However, appropriate variable and parameter selection allows this model to be extended to any hull form.

7. Countermeasures

7.1 Webb CM, Estrada A, Athy JR, King MR. Motion Sickness Prevention by 8 Hz Stroboscopic Environment during Actual Air Transport. 2011 Sep 27.

Previous research has shown that retinal slip can be a significant factor in causing motion sickness. Stroboscopic illumination is believed to prevent retinal slip by providing snapshots of the visual environment that are brief enough so each image is stationary on the retina.

The focus of this study was to assess the use of 8-Hz stroboscopic environments as a remedy for retinal slip, a significant causal factor in eliciting motion sickness. Retinal image slip was considered to contribute to space and terrestrial motion sickness. Retinal slip occurs when the eyes fail to hold an image stationary on the retina. Stroboscopic illumination may prevent retinal slip by providing snapshots of the visual environment so that the image is stable on the retina, thereby reducing motion sickness symptoms.

The study population was composed of 20 motion-sickness-susceptible participants. An MSQ was used as a measure of motion sickness symptoms (Kellogg et al. 1965). The MSQ was administered immediately after test flights. Participants completed a motion sickness symptom questionnaire, cognitive tasks, reaction time tests, and weapon utilization tasks after nauseogenic flight with and without 8-Hz stroboscopic illumination in the cabin.

Results indicated that self-reported nausea scores were significantly reduced in the stroboscopic condition. A significant performance decline of the reaction time task in the non-stroboscopic condition was recorded. The results support stroboscopic illumination usage as a non-pharmacologic countermeasure for motion sickness related to retinal slip.

7.2 RSK Assessments Inc. Preventing Simulator Sickness of Onboard Flight Simulators. Orlando (FL): RSK Assessments Inc.; 2009 Jan 14.

SS falls under two main categories: symptoms that occur during or immediately after exposure and those that occur after some delay. When these symptoms occur, naval flight personnel are required to stop the simulation and avoid encounters with motion by resting for 24 h. However, future simulation design plans call for containerized deployed simulators for mission rehearsals. Therefore, a rest period as a cure for SS will not be an option. The objective is to identify the causes of these delayed aftereffects so that they may be avoided or mitigated.

Potential SS aftereffects countermeasures were evaluated for use in Phase II experimental studies. A meta-analysis of the types of delayed simulator aftereffects that are believed to intrude on subsequent flight personnel performance has begun. There have been more than 400 studies reviewed. There are 100 separate descriptive experiences of long-term aftereffects available. These experiences, along with similar expressions of delayed aftereffects from VR devices, will be combined and used to form a controlled interview that will be administered to simulator users. This questionnaire was administered in Phase II to Embry-Riddle Aeronautical University (ERAU) student pilots that train in ERAU flight simulators. Preliminary analysis has begun of various handheld (or worn) devices that can be employed to record data from users after they have left the simulator facility in order to obtain information on long-term aftereffects. These devices will need to be capable of data storage and wireless transmission in several different environments. An experiment in Phase II will examine the feasibility of countermeasures proposed such as the Reschke plan and the Prothero plan as well as other techniques (timeouts, restricted field of view, etc.). It will include software and some hardware development to reconfigure simulators as well as other technical work for human use (i.e., Institutional Review Board) approval. Some of this has begun but is not yet complete. Analysis of the existing SSQ data (>10,000 observations) is underway and these data are being compiled and formatted in anticipation of a new factor analysis that will confirm or expand the existing three-factor profile for SS.

The research results will yield several viable products including software applications that will provide design information regarding major determinants of motion/simulator/cyber sickness. The program will be set in an "interview" format where the user will input design considerations for a new or existing simulation or virtual reality/virtual environment (VR/VE) system. The software will allow the designer to evaluate the best combination of traits for minimal inducement of sickness, and will be capable of diagnosing the determinants of sickness from an existing system.

7.3 Galea A. Preventing Simulator Sickness. 2013 Sep 30.

This report for Small Business Technology Transfer (STTR) Phase II Contract N68335-10-C-0119, Oculo-Vestibular Recoupling for the Mitigation of Simulator Sickness, summarizes all progress through August 18, 2013. In the Phase I program, it was demonstrated that by introducing vestibular stimulation in sync with visual stimulation in a simulator, the incidence and severity of nausea symptoms are reduced. In the Phase II program, further development of the vestibular stimulation device and creation of an integrated simulator in which to demonstrate the capabilities of a vestibular stimulation capable flight simulator was accomplished. In the Option Period, a compact device that can reduce sickness was created, based on the Base Period device and results. The key items to address were 1) dermal sensations with stimulations and 2) creating a device that is easy to use with a wide range of simulations. Tests showed that with the use of a simple, nre-set (system power reset or debug mode) on/off system, symptoms of sickness in subjects who report no history of motion sickness can be reduced. These symptoms are known to be associated with a decrease in cognitive function. Such a system, therefore, stands to maintain the ability of our troops to perform at peak functionality even in or immediately after adverse motion conditions.

Twenty-nine subjects participated; 15 subjects had galvanic vestibular stimulation (GVS) applied during flight simulation, while the remaining 14 subjects were in the Sham group where vibrostatic sensors were applied behind the ear on the mastoids instead of any electrical current. Electrogastogram recordings were monitored throughout the session. A visual analog scale was presented to subjects who were asked to mark the severity of sickness-related symptoms. In conclusion, GVS can induce sensations of motion in multiple axes selectively. GVS applied in synchronicity with a flight simulator enhances the realism of the simulation and decreases the incidence and severity of sickness symptoms. GVS applied from a simple on/off electronics unit decreases sickness symptoms that are associated with decreased cognitive ability in subjects who do not have a history of motion sickness

7.4 Estrada A. Preliminary Assessment of Stroboscopic Shutter Glasses on Motion Sickness in Helicopter Passengers. 2007 May.

This report presents preliminary test results conducted by the US Army Aeromedical Research Laboratory (USAARL) of two sets of stroboscopic shutter glasses (at 4 and 8 Hz) proposed as a countermeasure for motion sickness. The purpose was to examine the mission applicability and product potential of the glasses and to gain support for their inclusion in future USAARL motion sickness studies. Six participants experienced two flights in the cabin of a Black Hawk helicopter: the first flight with shutter glasses and the second without them. Following each flight, each participant filled out an MSQ and provided subjective feedback. This preliminary testing of the shutter glasses was conducted to determine their worthiness of further study. The testing was deliberately limited with no intentions of drawing firm conclusions as to the shutter glasses' efficacy.

Although the effectiveness of the shutter glasses as a countermeasure for motion sickness is not implied by this test, the results indicated that shutter glasses, particularly the 8 Hz device, demonstrated promise and should be explored as a non-pharmacological motion sickness prevention strategy.

7.5 Simmons RG, Phillips JB, Lawson BD, Lojewski RA. The Efficacy of Dextroamphetamine as a Motion Sickness Countermeasure for the Use in Military Operational Environments. 2008 July 9.

Prior research revealed that d-amphetamine provides significant protection against provocative motion. The military currently prescribes d-amphetamine during dynamic environment work where there are periods of high operational tempo and/or extended flight operations. If d-amphetamine can be confirmed, the military could have a single medication for motion sickness and fatigue. The purpose of the study was to validate the anti-motion sickness properties of d-amphetamine. The hypothesis was that subjects who took the oral 10-mg d-amphetamine would tolerate more head movements than subjects in the placebo condition without exhibiting performance degradation or significant side effects. Thirty-six aviator candidates, 31 male and 5 female, participated and were randomized into the two treatment groups (10-mg d-amphetamine or placebo) and then exposed to Coriolis cross-coupling. Medication efficacy was defined by number of head movements tolerated between groups. Cognitive and medication side-effect profiles were derived from performance on a cognitive battery, measurement of near-focus visual accommodation, scores on sleepiness scales, and motion sickness questionnaires. Results showed that d-amphetamine did not provide significant motion sickness protection as compared to the placebo and no significant impacts on performance or medication-induced side effects were observed.

8. Recommendations and Conclusions

This literature review reveals some potential motion sickness countermeasures. It is encouraged that these prevention methods be researched to determine their direct benefit to specific applications.

Research revealed that retinal slip can be a significant causal factor in motion sickness. Stroboscopic illumination may prevent retinal slip by providing snapshots of the visual environment that are brief enough so each image is stationary on the retina (Webb et al. 2011).

SS symptoms occur during or immediately after exposure and also occur after some delay. Research will yield several viable products, including software applications that will provide design information regarding major determinants of motion/simulator/cyber sickness. The program will be in an interview format where the user will input design considerations for a new or existing simulation. The software will allow the designer to evaluate the best combination of traits for minimal inducement of sickness and will be capable of diagnosing the determinants of sickness from an existing system (RSK 2009).

It was demonstrated that by introducing vestibular stimulation in sync with visual stimulation in a simulator, the incidence and severity of nausea symptoms are reduced. GVS applied in synchronicity with a flight simulator decreases the incidence and severity of sickness symptoms. GVS applied from a simple on/off electronics unit decreases sickness symptoms that are associated with decreased cognitive ability in subjects who do not have a history of motion sickness (Galea 2013).

A linear model based on human physiology predicts MSI with adequate precision (less than 5%) in the frequency range between 0.07 and 0.25 Hz. The cause is the interaction of the main human sensory vestibular and visual systems. The final product gives an acceptable approximation for the critical region of frequencies (Matsangas 2004).

The results of the shutter glasses, particularly the 8 Hz device, demonstrated promise and should be explored as a non-pharmacological motion sickness prevention strategy (Estrada 2007).

Prior research revealed that d-amphetamine provides significant protection against provocative motion. However, results in this research showed that d-amphetamine did not provide significant motion sickness protection as compared to the placebo, and no significant impacts on performance or medication-induced side effects were observed (Simmons et al. 2008).

For research earlier than 2004, please refer to Burcham (2002).

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List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance
ARL	US Army Research Laboratory
BHIVE	Battlefield Highly Immersive Virtual Environment
CAAS	Common Avionics Architecture System
CAVE	Cave Automatic Virtual Environment
CSDV	cybersickness dose value
DOF	degrees-of-freedom
ERAU	Embry-Riddle Aeronautical University
FMS	flight motion simulator
FOV	field of view
GVS	galvanic vestibular stimulation
HMD/VR	head-mounted display virtual reality
HRED	Human Research and Engineering Directorate
IMC	instrumented meteorological condition
IP	instructor pilot
IVB	independent visual background
LAV	Light Armoured Vehicle
LCS	Littoral Combat Ship
LEUE	Limited Early User Evaluation
LUT	Limited User Test
MANPRINT	Manpower and Personnel Integration
MSI	Motion Sickness Incidence
MSQ	motion sickness questionnaire
OKCR	optokinetic cervical reflex
PVI	pilot-vehicle interface
PVT	Psychomotor Vigilance Task

RMS	Ride Motion Simulator
SA	situation awareness
SP	student pilot
SS	simulator sickness
SSQ	Simulator sickness questionnaire
STTR	Small Business Technology Transfer
TACOM	US Army Tank-automotive and Armaments Command
TSC	tactical steering committee
UH	utility helicopter
USAARL	US Army Aeromedical Research Laboratory
VMC	visual meteorological condition
VR	virtual reality
VR/VE	virtual reality/virtual environment

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