

Simulator Sickness in Flight Simulators: A Case Study

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ABSTRACT

Simulator sickness is a recently publicized phenomenon in which pilots who use flight simulators experience symptoms characteristic of motion sickness. In this paper is presented a field study performed on a U.S. Navy helicopter simulator (Device 2F120) to identify and correct factors suspected of causing simulator sickness. A survey of 42 U.S. Marine aviators before and after training flights in the simulator revealed a significant incidence of simulator sickness (62 percent). Symptom clusters most often reported included eye strain, general discomfort, headache, nausea, and fullness of the head. Engineering and observational data point to the visual system as a likely culprit in this particular system. Changes in procedures and in the software of the visual system are recommended.

Training, the military's number one mission during peacetime, makes large and continuing demands on resources allocated to the U.S. Department of Defense. Training is also a major component of all military budgets. For example, it costs about \$3.6 billion per year for fuel and supplies needed to operate military aircraft in the United States. Many of these operations are conducted for training purposes. Ground-based flight simulators, however, can be operated at costs that vary from 5 to 20 percent of the cost to operate comparable aircraft; the median value is 12 percent in cost savings (1). In general, pilots trained in simulators are able to acquire necessary mission skills with fewer flight hours than are pilots who are not.

Ground-based flight simulators are cost-effective, safe, flexible systems that are becoming more important to military training. Advancing engineering technologies permit a range of capabilities to simulate the real world through compelling kinematics and computer-generated visual scenes. Simulators, by their very nature, provide a sensory environment that attempts to "fool" the human into "believing" certain conditions, which are contrary to the physical evidence, exist. This synthetic visual and vestibular environment can on occasion be so successful that conflict is established among the different forms of sensory input. This adheres most closely to the cue conflict theory of motion sickness that has been accepted as the working model for simulator sickness (2). In brief, the model postulates a referencing function in which motion information signaled by the retina, vestibular apparatus, or proprioception may be in conflict with "expected" values based on a neural store. In turn, neural store reflects past experience, or the neural system's circuitry. The resulting cue conflict taxes a pilot's perception beyond his ability to adapt, inducing in some cases simulator sickness (2).

Anecdotal, as well as some empirical field study, data have alluded to the incidence of symptoms in some pilots who have been exposed to ground-based flight simulators (3). This problem has been termed simulator sickness, simulator-induced syndrome, or at other times simulator aftereffects. Simulator

sickness refers to a cluster of symptoms that includes, but is not limited to, nauseogenic, visual, and vestibular dysfunctions. These can occur while a person is in a simulator, immediately after exposure to a simulator, or at some later time after exposure to a simulator. A review of the literature dating back to 1957 has documented occurrences of simulator-induced syndrome (4).

PURPOSE OF THE STUDY

This study was performed in response to a high frequency of anecdotal reports from simulator users about a variety of symptoms experienced during and after training in the 2F120 device. Engineers and psychologists collected behavioral, engineering, interview, and observational data to eliminate or confirm factors suspected of causing simulator sickness. The overall objectives were (a) to provide low-cost, short-term remediations that can be employed by on-site personnel for little or no cost to the government and (b) to derive human factors guidelines that could eliminate or reduce the problem in future simulator designs.

SIMULATOR

The 2F120 device, examined in this study, simulates a CH-53E "Super Stallion" Navy helicopter built by Sikorsky Aircraft Company and powered by three General Electric Turboshift engines. The CH-53E is used by the Marine Corps as a troop-carrying assault ship and by the Navy as a heavy-lift helicopter. It can carry 56 troops or 14,500 kg of cargo with a mission radius of 50 nautical miles. The maximum speed of the CH-53E is 170 knots with a ceiling of 18,500 ft. Other missions of the helicopter include medical evacuation and airborne mine countermeasures. The Super Stallion carries a crew of three (pilot, copilot, and crew chief).

The 2F120 device is a fully operational flight trainer (OFT) with a wide field-of-view computer-generated image (CGI) visual display with a 6-degree-of-motion base (Figure 1). The six visual display channels are adjusted with the design eye point for the pilot's seat (right seat). The visuals displayed on a CRT are reflected from a collimating mirror in order to give a focal length close to infinity. The

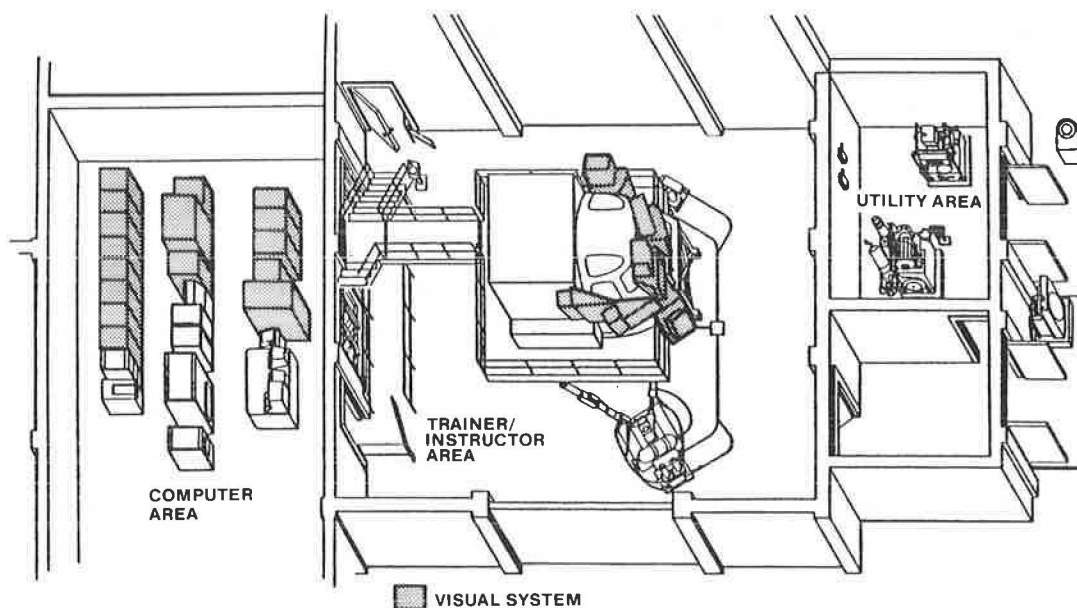


FIGURE 1 CH-53E operational flight trainer, Device 2F120.

simulator layout has the pilot (right seat) and co-pilot (left seat) in their normal flight stations with an instructor seat and console directly aft of the two seats.

The visual scenes simulated include airfields, confined area landings (CAL); mountain area landings (MAL); and three ships with helicopter landing pads (LHA, LPH, and LST). Simulator flight missions include formation flying; transporting external loads; normal, steep, tactical, and nonprecision approaches; and hover, no-hover, and running landings. Pilots also practice autorotations and various other responses to emergency situations. An instructor can set up a mission for pilots according to the Navy squadron training syllabus to present typical flight tasks as well as unusual problems. An instructor can freeze any flight to highlight student errors or replay a mission segment in order to provide a student with more detailed feedback.

The "universe" of the simulator is divided into five major components: engineering (visual and motion systems), environmental (ambient surroundings), flight hop (missions flown), individual (physiological makeup of the subject), and instructional (use of the simulator as a teaching medium) characteristics. Simulator sickness occurs as a function of some variable or more likely some set of variables within these five categories. The most likely candidates from each category were examined in this field investigation in order to recommend immediate remedies, future field work, and laboratory studies for questions unanswerable on site.

The present study attempted to answer the following questions: Is there evidence of significant incidence of simulator sickness resulting from flying the 2F120 device? If so, what is the clustering of symptoms reported? What candidate factors that cause simulator sickness can be eliminated, and what recommendations can be made to field personnel in order to reduce the incidence rate?

METHOD

Subjects

Forty-two, male, U.S. Marine Corps helicopter pilots, ranging in rank from Second Lieutenant to Major,

took part in the study. There were 20 Second Lieutenants, 13 First Lieutenants, 5 Captains, and 4 Majors. Pilots included designated aviators (pilots receiving final training), fleet pilots, and augmented pilots (squadron staff personnel). Flight experience ranged from 170 to 3,700 flight hours with a mean total flight time of 1,348 hr (standard deviation = 1,163 hr). Twenty-six of these pilots flew only one training flight during this study, 14 flew twice, one flew three flight hops, and one flew four training missions. There were a total of 61 training missions flown in this study.

Apparatus

Three calibrated accelerometers measured "g" forces and vibration output of the three axes of the motion base of the simulator. A brush strip recorder was used to record outputs of the three accelerometers (5). A hand-held theodolite measured the collimating points of the six windows of the CGI visual system. A CCD Sony videotape camera was used to record visual scenes from the pilot's front window for later analysis.

For the environmental readings taken in and around the simulator, a calibrated General Radio Model 1982 Type 1 sound level meter and octave band analyzer was used for sound level measurements. A calibrated MSA Model 5 CO analyzer monitored the presence of carbon monoxide, and an HNU Model PI-101 UV photometer was used to detect low concentrations of a variety of contaminants. A Miran Model 1A infrared spectrometer was also used to analyze a sample of air collected from inside the 2F120. Temperature and relative humidity readings were recorded on a 7-day Omega Model CT-424-7 strip chart recorder placed within the room housing the simulator.

Procedures

To test the motion system, control stick step commands were introduced and the resulting motion cues were recorded by the accelerometers at the pilot's station (right seat). This procedure measured total system hardware and software throughput delays and cue synchronization between the motion and the visual

onset. Aerodynamic lags were set to zero using software logic. A more thorough explanation of the method is provided elsewhere (6). Strip charts not only recorded throughput delay but also calculated the frequency of induced motion in the simulator.

The sound level meter instrument was placed at head level on the pilot's seat (right seat) for all measurements. Sound was emitted from a small speaker located approximately 0.5 m away from the meter on the rear bulkhead. Three tests were performed on sound levels produced by "normal aircraft engine noise" and for blade-out-of-track noises.

Typical flight mission segments were flown by Marine instructors. The simulator's computers stored the visual scenes for later replay. Missions were videotaped by placing an electronic camera at the design eye point when the segments were replayed with the motion system off. Several engineering experts viewed the videotape for anomalies in the CGI presentations.

The self-report survey used was the Motion Symptomatology Questionnaire (MSQ) (4). The MSQ is a pre- and posttest symptomatology checklist. The pretest portion of the questionnaire also collects general physical health and demographic information about the pilot. Subjects filled out the questionnaire just before entering the simulator and filled out the last portion of the questionnaire during their debriefing period immediately following completion of the simulator flight. All pilots flew their training missions with both the visual and the motion system on. Each simulator training flight lasted an average of 1.5 hr.

RESULTS

The results of the self-report simulator sickness questionnaire (see Appendix A) are presented in Figure 2. A pilot received a score from zero to seven depending on the number and intensity of his self-reported symptoms (see Appendix B). There is a definite shift from pre- to postflight reports in the symptomatology reported because of some casual factor or factors in the simulator. In the preflight questionnaire, 31 simulator flights induced no symptoms, but only 20 subjects were not affected by any training flight in the simulator. Likewise, noticeable symptoms (at least one minor and another symptom) are evident in only 11 subjects before fly-

ing in the simulator (sickness or discomfort because of different nonsimulator-related events); this number increases to 26 in the postflight condition.

Tables 1 and 2 give the frequency of simulator sickness scores for pre- and postflight conditions. The data in Table 1 indicate that some of the subjects are bringing some fatigue, drowsiness, and eye strain into the experimental situation. The data in Table 2 indicate the shift in symptom self-report. Eye strain is the most frequent complaint in the postflight condition followed by general discomfort, headache, nausea, fatigue, difficulty concentrating, and fullness of head.

Table 3 gives cue synchronization test results on the range of and average visual and motion throughput delays. The average visual delay is 167 msec, and

TABLE 1 2F120 Preflight Scores

	None	Slight	Moderate	Severe	No	Yes
General discomfort	54	7				
Fatigue	50	9	2			
Boredom	49	8	3	1		
Drowsiness	53	7	1			
Headache	56	5				
Eye strain	52	9				
Difficulty focusing	61					
Increased salivation	61					
Decreased salivation	60	1				
Sweating	61					
Nausea	60	1				
Difficulty concentrating	57	3		1		
Depression					59	2
Full head					57	4
Blurred vision					61	
Dizzy with eyes open					61	
Dizzy with eyes closed					61	
Vertigo					61	
Visual flashbacks					61	
Faintness					61	
Awareness of breathing					61	
Awareness of stomach					61	
Decreased appetite					61	
Increased appetite					61	
Desire for bowel movement					61	
Confusion					61	
Burping					61	
Vomiting					61	

TABLE 2 2F120 Postflight Scores

	None	Slight	Moderate	Severe	No	Yes
General discomfort	40	18	3			
Fatigue	44	16	1			
Boredom	53	8				
Drowsiness	54	7				
Headache	43	16	2			
Eye strain	38	20	3			
Difficulty focusing	52	9				
Increased salivation	58	3				
Decreased salivation	59	2				
Sweating	56	5				
Nausea	53	6	2			
Difficulty concentrating	53	7	1			
Depression					58	3
Full head					54	7
Blurred vision					58	3
Dizzy with eyes open					57	4
Dizzy with eyes closed					57	4
Vertigo					56	5
Visual flashbacks					60	1
Faintness					60	1
Awareness of breathing					61	
Awareness of stomach					57	4
Decreased appetite					60	1
Increased appetite					60	1
Desire for bowel movement					61	
Confusion					61	
Burping					61	
Vomiting					61	

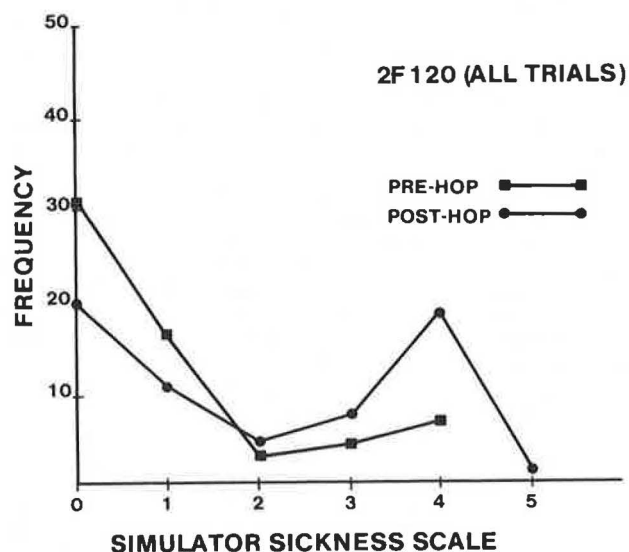


FIGURE 2 Pre- and posthop simulator sickness frequency scores.

TABLE 3 2F120 Cue Synchronization Test Results

	Minimum (msec)	Maximum (msec)	Average (msec)
Visual throughput delay	144	190	167
Motion throughput delay			
Heave	88	152	120
Roll acceleration	104	144	124
Pitch acceleration	72	108	90
Pitch rate	160	200	180

the motion system has an average throughput delay of between 90 and 180 msec depending on the axis measured. The motion onset consistently precedes the visual scene. The frequency spectrum analysis of the motion system shows that there were no induced frequencies between 0.1 and 0.5 Hz.

Environmental readings found between 0 and 1 part per million (ppm) of carbon monoxide. The photoionizer equipment detected no contaminants in the simulator area. A spectrum analysis of the air sample from the simulator showed that it was essentially identical to a clean air sample (i.e., no contaminants were detected). Temperature and humidity readings were found to be well within the normal thermal stress comfort zone.

The ambient cockpit noise with the noise generation equipment off was 62 dbA. Figure 3 shows that loudness settings of 25 percent or above required crew members to shout at one another. Settings at 75 percent or higher reached and surpassed the limits of maximum vocal effort. During this study, most

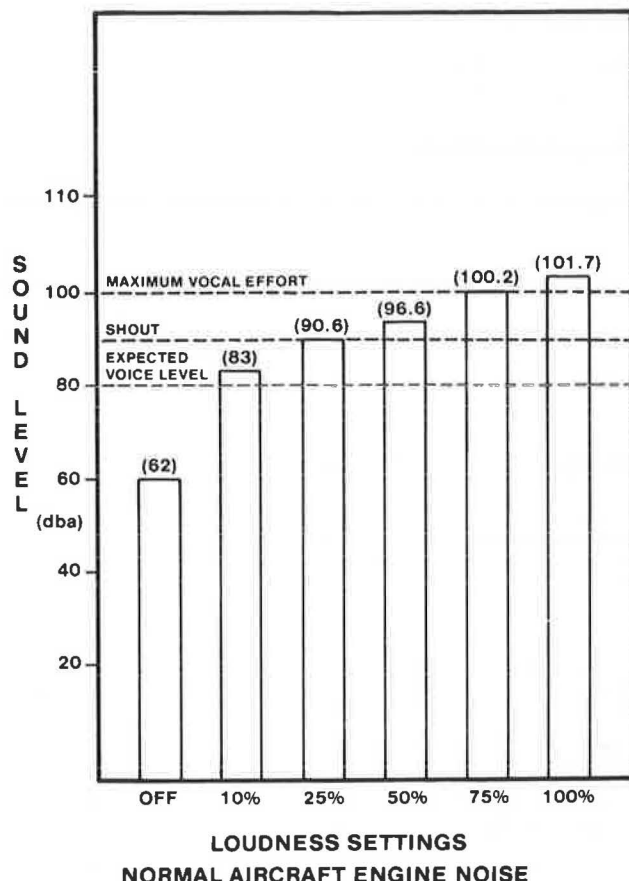


FIGURE 3 Sound level readings for selected simulated normal aircraft engine noise.

pilots set the loudness at the 2 percent level with a minority of subjects using a slightly higher setting. None of the subjects set the level above 10 percent.

Theodolite readings showed that all six windows were collimating at infinity. Videotape recordings of flights revealed visual discontinuities within and between several visual channels. Transitions from altitude to landing pattern at times displayed a visual scene that moved in fits and jerks for a brief period. Video records plus postflight interviews indicated that roll and pitch rates may be much faster than experienced in actual aircraft. Pilots were also bothered by the occasional "flickering" and "shimmering" of the right window screen. The right screen is the only window with a vertical raster; all other windows have a horizontal raster.

DISCUSSION

Simulator sickness is real in this simulator. It appears that the environment of the simulator (air, temperature, humidity, and contaminants) has no thermal stressors or toxicological hazards that might contribute to or cause the symptoms exhibited by pilots. The sound level capable of being produced by the simulator could induce temporary or permanent hearing loss and even pain to the ears. The noise, however, is self-limiting as evidenced by the settings used by the pilots.

The accelerations and vibrations experienced by the subjects do not appear to contribute to the simulator sickness problem. Whole body vibrations at between 0.1 and 0.5 Hz are the bandwidth that is most likely to induce motion sickness on boats, trains, and other vehicles (7). There is no evidence that pilots receive any energy in this sensitive spectrum area. The throughput lags in the onset of the motion and the visual scene are most likely detectable by pilots and cause some decrement to pilot performance. However, the throughput has a short range over which it varies and the pilot probably is able to adapt to it. The motion system precedes the change in the visuals at a rather constant rate giving a "good feel" to pilots. Laboratory studies at the NAVTRASYSCEN Visual Technology Research Simulator (VTRS) are under way to vary the cue synchronization between stick input and visual scene response to determine if there is a critical bandwidth of throughput lag that induces simulator sickness.

An attempt to fly with the subjects to record the time history of the flight maneuvers proved unworkable. A maneuvers checklist to be administered during debriefing is under development. Data from this checklist may reveal that specific maneuvers and scenarios are more conducive to simulator sickness than others. Instructor interviews disclosed that instructors in the station behind the pilots could also be susceptible to simulator sickness. It is hypothesized that viewing the visual scene outside of the design eye point gives instructors a distorted view that can be nauseogenic. The instructors are quite interested in reducing simulator sickness not only for themselves but for their students. They have already begun a number of new procedures to aid in this process. For instance, the simulator has the capability to slew the visual scene from one geographic location to another at "warp speed." This unnatural streaming of the picture causes discomfort in a majority of subjects. The instructors have devised a no-cost solution to this problem. They direct the pilot to fly into the clouds at an altitude where the visuals are all grey (simulating clouds). The instructors can then slew the scene without the accompanying side effects.

The subjects themselves do not show any strong pattern that could be used to predict which pilots are most likely to get sick and which are not. These pilots have been through an extremely rigorous selection process. If there were any who were susceptible to motion sickness (of which simulator sickness has been considered a subset), it would have already shown up in basic flight training. Students who cannot adapt to the unique physiological conditions of flight are dropped from the Navy's flight program as not being aeronautically adapted to flight. They would not have been retained long enough in the program to reach this training site.

The pilots in this inquiry did not always fly the simulator with an instructor. It was found that some pilots flew the simulator with the crash override in the active mode. That is, if the pilot flew beyond the limits of the helicopter or struck an object, the simulation would continue. This resulted in unusual flying attitudes, unnatural bumps and jerks in the visual system, and some unique flying conditions such as flying underground and flying through a hangar without the doors being open. This points out that a simulator can be used in ways that were never intended. The correlation between using crash override and the symptoms of simulator sickness is still under investigation.

The visual system hardware and software configuration appears to have some anomalies and distortions that may induce the symptoms reported by the pilots. Adapting to unusual visual and vestibular conditions for relatively short periods and readapting to normal conditions may be a factor. There is a large body of literature that describes the effects of wearing goggles that distort vision (8). Subjects are able to adapt to changes in their view of the world. Some of them, however, have reported discomfort and illness analogous to that experienced in the 2F120. Early studies also found that when a person takes off the visually distorting glasses or goggles, he must adapt to the real world and again may get sick.

CONCLUSIONS AND RECOMMENDATIONS

In this field study it was found that the environmental and instructional components of the simulator do not appear to contribute to simulator sickness. Experimenters were unable to determine adequately which flight maneuvers were most likely to induce sickness. From an engineering standpoint, the synchronization of the motion and visual systems is not unusual and does not transmit energy at the bandwidth where most subjects are sensitive to motion sickness.

The simulator can produce some unusual attitudes and visual scenes when used with crash override in the active mode. It has been recommended that students not be given this option when flying without an instructor. Strict adherence to the training purpose of the simulator should be demanded to obtain maximum training during the flight.

Although the evidence is not conclusive, the visual system of the simulator appears to be a major contributor to simulator sickness. The cluster of symptoms such as eye strain, headache, and fullness of head could be visually induced and the rest of the symptoms may be induced by these major symptoms. Recommendations have been made to change the software of the 2F120 to reduce the geometric discontinuities, color imbalances, jerky motions in certain situations, and possible excessive roll and pitch rates of the system. A field engineering team will be making those changes that can be most cost-effectively and easily made on site. A follow-up field investigation will sample the occurrence of simulator sickness after these engineering changes are made.

Should the incidence rate drop dramatically, this will provide strong evidence that the visual system is the main causal factor (in this particular simulator) of simulator sickness.

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APPENDIX A--Post-Hop Symptom Checklist

Instructions: Please fill this out AFTER you go into the simulator. Circle below if any symptoms apply to you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Boredom	None	Slight	Moderate	Severe
4. Drowsiness	None	Slight	Moderate	Severe
5. Headache	None	Slight	Moderate	Severe
6. Eye strain	None	Slight	Moderate	Severe
7. Difficulty focusing	None	Slight	Moderate	Severe
8. a. Salivation increased	None	Slight	Moderate	Severe
b. Salivation decreased	None	Slight	Moderate	Severe
9. Sweating	None	Slight	Moderate	Severe
10. Nausea	None	Slight	Moderate	Severe
11. Difficulty concentrating	None	Slight	Moderate	Severe
12. Mental depression	No	Yes		
13. "Fullness of the head"	No	Yes		
14. Blurred vision	No	Yes		
15. a. Dizziness with eyes open	No	Yes		

b. Dizziness with eyes closed	No	Yes	
16. Vertigo	No	Yes	
17. Visual flashbacks ^a	No	Yes	
18. Faintness	No	Yes	
19. Aware of breathing	No	Yes	
20. Stomach awareness ^b	No	Yes	
21. Loss of appetite	No	Yes	
22. Increased appetite	No	Yes	
23. Desire to move bowels	No	Yes	
24. Confusion	No	Yes	
25. Burping	No	Yes	No. of times
26. Vomiting	No	Yes	No. of times
27. Other			

^avisual illusion of movement or false sensations similar to aircraft dynamics when not in the simulator or the aircraft.

^bStomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea.

APPENDIX B--Diagnostic Criteria for Levels of Severity of Motion Sickness

TABLE B1 Symptoms

Symptom	Degree
Vomit (pathognomic)	
Major	
Increased salivation	Moderate and severe
Nausea	Moderate and severe
Sweating	Severe
Drowsiness	Severe
Minor	
Increased salivation	Slight
Nausea	Slight
Sweating	Moderate and slight
Drowsiness	Moderate and slight
Other	
Stomach awareness	
Burping	
Desire for bowel movement	
Headache	
Dizziness	
Vertigo	
General fatigue	

TABLE B2 Diagnostic Categories

Diagnostic Category	Criteria
0	No symptoms reported
1	Any symptom related to motion sickness is reported
2	More than two other symptoms are reported
3	One minor plus other symptoms are reported
4	One major symptom alone or Two minor symptoms or One major and one minor symptom or One minor plus four other symptoms
5	One major and two minor symptoms
6	Subject's report of emesis
7	Experimenter's report of emesis

The opinions expressed in this paper are those of the authors and do not necessarily represent those of the Naval Training Systems Center, the Department of the Navy, or the U.S. Department of Defense.

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