

Motion Sickness Symptoms and Postural Changes Following Flights in Motion-Based Flight Trainers

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Abstract

Navy pilots flew over 193 standard training mission scenarios while acceleration recordings in three linear dimensions (g_x , g_y , and g_z) were made for two moving-base flight trainers. The pilots, who were of comparable age and experience in both groups, were interviewed for motion sickness symptomatology and were tested for ataxia after leaving the simulators. The aircraft simulated included a P-3C turboprop fixed-wing patrol aircraft (2F87F), and an SH-3 antisubmarine warfare helicopter (2F64C). Motion sickness incidence was high in the SH-3 simulator and nonexistent in the P-3C. Ataxia scores indicated departures, though not significant, from expected learning curve improvements after exposure in both simulators. Spectral analyses of the motion recordings revealed significant amounts of energy in the nauseogenic region of 0.2 Hz in the SH-3 simulator in the g_z and g_y , but not in the g_x . The levels exceeded those recommended for ship motion exposures by Military Standard 1472C. The P-3C simulator had low levels of energy in these regions, and well below recommended levels. The data are discussed from the standpoint that simulator sickness in moving-base simulation may be, at least in part, a function of exposure to frequencies that make people seasick.

INTRODUCTION

Simulator sickness is being reported with increasing frequency. A survey of Navy flight simulators determined that incidence ranges from 12% to 60% (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1987). Simulator sickness symptoms parallel those of motion sickness (Kennedy & Frank, 1986; Kennedy, Lilienthal, & Berbaum, 1986; Miller & Goodson, 1960), and can produce serious residual after-effects in pilots (Kellogg, Castore, & Coward, 1980; McGuinness, Bouwman, & Forbes, 1981). These after effects can limit Fleet Operational Readiness and reduce training effectiveness. The purpose of the present study was to relate pilot complaints of simulator sickness to attributes of the force environment by employing a pilot-in-the-loop methodology; characteristics of the inertial environment in two simulators were measured with pilots at the controls during actual simulator hops.

An early series of studies conducted by Professor G.R. Wendt and his associates during the 1940s (Alexander, Cotzin, Hill, Ricciuti, & Wendt, 1945a, 1945b, 1945c, 1945d; Alexander, Cotzin, Klee, & Wendt, 1947), related exposure to Very Low Frequency (VLF) vibration to motion sickness. The Wendt studies were designed to investigate variables which the authors termed rate of work, energy per wave, time per wave, and acceleration level. Waves at a frequency of 32 cycles per minute (cpm) (or 0.53 Hz), were found to induce less motion sickness than waves in the 13 to 22 cpm range (or 0.22 to 0.37 Hz), i.e., motion sickness declined with increasing wave frequencies between 13 to 32 cpm. Acceleration was also found to be a significant factor, although its role was not clarified because it was confounded with frequency due to equipment limitations.

Some corroboration of the curvilinear relationship between wave duration and motion sickness was provided by Kennedy, Moroney, Bale, Gregoire, & Smith, 1970 in a study on aircraft hurricane penetrations. Motion sickness was greatest in the C-121,

followed by the C-130 and the P-3C aircraft. Subsequent analysis of accelerometer data showed the average frequency of vertical linear oscillation to be 25 cpm (0.42 Hz), 50 cpm (0.83 Hz), and 59 cpm (0.98 Hz) in the C-121, C-130, and P-3C aircraft, respectively. These findings are in good agreement with Wendt's finding that increased incidence of motion sickness is associated with frequencies below 32 cpm (0.53 Hz).

Research leading to the prediction of motion sickness incidence was initiated in 1972 at Human Factors Research, Inc., Goleta, California, under the sponsorship of the Office of Naval Research and the Naval Bureau of Medicine and Surgery. A device, now at the Naval Biodynamics Laboratory, New Orleans, Louisiana, is capable of vertical displacements of 20 feet, as well as concurrent angular motion in the pitch and roll axes. The resulting data allowed a more precise formulation of the effects of VLF. O'Hanlon and McCauley (1973) used a sinusoidal waveform and varied frequency and acceleration independently. Subjects were exposed to frequencies ranging from 5 to 30 cpm (0.083 to 0.50 Hz) and were exposed to the motion for two hours. Independent groups of at least 20 (and up to 63) male college students participated in each motion condition, defined by frequency and acceleration. The dependent variable (Motion Sickness Incidence (MSI)) was percentage of individuals in each group who vomited. A mathematical model was derived from data based on 306 subjects (O'Hanlon and McCauley, 1973).

Subsequent experiments led to slight revisions of the model for predicting MSI at an exposure duration of two hours, and expansion of the model to predict MSI as a function of exposure time (McCauley, Royal, Wylie, O'Hanlon, & Mackie, 1976). The original model (O'Hanlon and McCauley, 1973) describes MSI as a log normal function of acceleration where the mean of the underlying normal distribution is a function of the wave frequency, and standard deviation is a constant. The mean value, g_{rms} , specifies the acceleration necessary at a given frequency to induce a vomiting incidence of 50%. The subsequent incorporation of the time function was based on an examination of MSI versus time, frequency, and acceleration. Thus, the model was postulated to predict motion sickness incidence from vertical sinusoidal motion as a function of wave frequency, acceleration, and time (exposure duration).

Because of the similarity between simulator sickness and motion sickness, one issue is whether motion-base simulators have inertial patterns comparable to those which have been shown to be nauseogenic in other platforms like ships at sea, aircraft, and spacecraft. However, we know of only one study (Hartman & Hatsell, 1976) which examined the motion profiles of simulators with pilot-in-the-loop. This study demonstrated the presence of VLF dynamics, but not the similarity between the vibrations in simulators and the acceleration profile of ships at sea, nor were the simulator data related to the recommended exposure limits for such vibrations (McCauley & Kennedy, 1976; Department of Defense, 1981).

We, therefore, set out to accomplish two purposes:

1. To determine whether VLF vibration occurs in moving-base flight simulators and, if so
2. Use man-in-the-loop to determine whether motion profiles were related to incidence of simulator sickness and ataxia.

METHOD

Field Setting

The Naval Air Station in Jacksonville, Florida (NAS JAX), was chosen as the study site because both the SH-3 Sea King (2F64C) and P3-C Orion (2F87F) simulators are located there. These two motion-base simulators were selected for study because: they possess several characteristics believed to be implicated in simulator sickness (viz., wide fields of view, moving base, computer-generated imagery versus dome displays), and are representative of the many simulators operational within the Navy. In addition, they were believed to be associated with a range of sickness incidences; previous experience (Kennedy et al., 1987) indicated that reports of sickness were more frequently associated with the 2F64C simulator than with the 2F87F simulator.

During data collection, the simulators were in constant use (15 to 16 hours/day) for military aviation training. The simulators are primary training devices for fleet replacement pilots; however, operational squadron pilots and midshipmen also frequent the trainer. Operational demands associated with the field setting environment

necessitated that data collection procedures, subject selection, and other research issues conform with the simulator training mission. This meant that there were no experimental controls over hop scenarios, hop length, number of times an individual pilot was observed, and the previous flight or simulator experience of the pilot. The presence of repeated observations in the data set is likely to minimize the reported incidences of simulator sickness because adaptation can be expected to occur (Uliano, Kennedy, & Lambert, 1986). In addition, the pilots, in general, had accrued a significant amount of simulator experience which will also minimize the effects of simulator exposure because of adaptation. Thus, any report based on these data is likely to be an underestimate of the possible effects of simulator exposure.

Subjects

To the extent possible, all individuals reporting for simulator training were surveyed for voluntary participation in the study. During the course of the field study only one individual declined to participate. The resultant pool of 191 pilots included a highly diverse group of designated naval aviators and nonaviator midshipmen. Pilots sampled from the 2F64C (N=148) and 2F87F (N=43) simulators were of comparable age and previous flight experience. All subjects were judged to be in good physical and mental health at the time of the study.

Simulators

The visual displays of the 2F64C training device were generated by a "Vital IV" calligraphic dusk/night CIG. Visual display was a 7-window, 5-channel, folded on axis virtual image CRT with a 130 deg. x 30 deg. (H x V) field of view. Motion was generated with a six-degree-of-freedom motion-base system. In general, the simulator operated on a 16 hours/day, 5 days/week schedule. Occasionally, the simulator would be "downed" for maintenance or repair purposes. One and one-half days of continuous downtime were encountered during the study due to a major update of the simulator site air conditioning system.

The visual displays of the 2F87F training device were generated with a TV camera/model board. Visual display was a 5-window, 3-channel CRT (off-axis reflective) with a 48 deg. x 36 deg. (H x V) field of view. Motion was generated with a six-degree-of-freedom motion based system. This simulator operated 15 hours/day, 5 days/week.

Measures

Measures of symptoms of simulator sickness and equilibrium were collected before (pre-), during a midsession break (mid-) when possible, and after (post-) each simulator training exercise.

Motion Sickness Questionnaire.

The Motion Sickness Questionnaire (MSQ) (Wiker, Kennedy, McCauley, and Pepper, 1979) identifies pathognomonic, major, minor, mental, visual, and other symptoms associated with motion sickness. Each symptom is marked by the subject as either present or absent, or rated by the subject for severity on a 1-to-4 Likert-type scale (Likert, 1932). Two signs (i.e., characteristic facies and pallor) were scored for severity by the experimenter and added when appropriate. Motion sickness symptoms were summarized by application of a 7-point ordinal scaling method. Average interrater correlation (a Pearson r) for scoring the pilot subjects' self-reports of symptoms is 0.956 (Wiker et al., 1979). Validity testing employing point-biserial correlations of MSQ scores with instances of emesis versus no emesis resulted in an average correlation of $r = 0.63$ (Wiker et al., 1979). An appropriate form of the MSQ was applied prior to each simulator flight (pre-MSQ), during a rest break if one occurred during the flight (mid-MSQ), and following each simulator flight (post-MSQ). Additional questions were included with the MSQ identifying the hop to be flown and the function, flight experience, simulator experience, and state of health of the subject. Additional post-MSQ questions were included to examine the nature of operational state of simulation channels during the hop (ex., visuals, motion, etc.), and the variables unique to each training experience (ex., number of landings, total time in the simulator).

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Equilibrium Tests.

Two Postural Equilibrium Tests (PET) were administered. Time permitting, the two tests were administered prior to each simulator flight (pre-), during the rest break if one occurred (mid-), and following the completion of the simulator flight (post-). Previous research had demonstrated that these tests are both stable and sensitive (Thomley, Kennedy, & Bittner, 1986) although means increase continuously over sessions. The Standing-on-Non-Preferred-Leg-Eyes-Closed test (SONLEC) (Thomley et al., 1986) required a pilot to stand on his "non-preferred leg," with eyes closed and arms folded, as long as balance could be maintained or until a maximum of 30 seconds had elapsed. The pilot then repeated the exercise for three to five trials. Individuals performing three perfect 30-second trials were not required to complete the full five replications. The experimenter used a stopwatch to record the pilot's performance. If at any time during the test the pilot moved the foot he was standing on, moved his nonstanding foot away from his body, or totally lost his balance and touched the floor with his nonstanding leg, the trial was terminated and the time score was recorded. The Walking-Toe-to-Heel Eyes Closed (WOFEC) test required the pilot to walk a maximum of 12 toe-to-heel steps with arms folded and eyes closed. If the pilot gave indications of inadequate balance (e.g., was unable to place following foot in the heel-to-toe position), the trial was terminated and the pilot's performance was noted. Performance was recorded as the number of steps taken prior to failing criterion or as 12 perfect steps. The WOFEC test was replicated five times, or until the pilot achieved three (3) perfect scores.

Procedure.

Data collection procedures were similar for the two simulators. Pilots were greeted by the experimenter upon arrival at the simulator training complex and the purpose and procedures of the study were described. Pilots were reassured that their questionnaire responses and performance test scores would in no way influence their training program and that all data would be held in confidence. Immediately preceding the simulator flight, the pre-MSQ was completed and the two Postural Equilibrium Tests were performed, the WOFEC tests always preceding the SONLEC test. If a break occurred during the simulator training and time permitted, pilots were retested with a mid-MSQ and the PET tasks immediately upon exiting the simulator. The first pilot always performed the PET tests then the MSQ, while the co-pilot first responded to the MSQ, then performed the PET tests. In general, the second half of the hop was flown with the two pilots exchanging seats and first pilot/co-pilot flight status. After completing the training session, subjects completed the post-MSQ and post-PET tests immediately upon exiting the simulator in the order described for mid-hop testing.

Vibration Measurement.

The measurement and acquisition of vibration data and control system command signals was undertaken by engineers from Oak Ridge National Laboratory (operated by Martin Marietta Energy System, Inc., or the U.S. Department of Energy). Three orthogonal linear transducers were mounted as near as possible to the pilot or co-pilot seat.

RESULTS

Experimental Measures

Vibration Exposures.

Figure 1 shows a comparison of the nominal mean run of the 2F87F (p-3C) simulator with the nominal mean run for the 2F64C (SH-3) simulator, overlaid on Military Standard 1472C (MIL-STD-1472C) for exposure to VLF vibration. It is obvious that the force environment of the two devices is markedly different, and that the 2F64C presents motion profiles largely in regions which MIL-STD-1472C counsel against if one is to avoid the nauseogenic features of VLF vibration. These results are dealt with more completely elsewhere (Van Hoy, Allgood, Lilienthal, Kennedy, & Hooper, 1987).

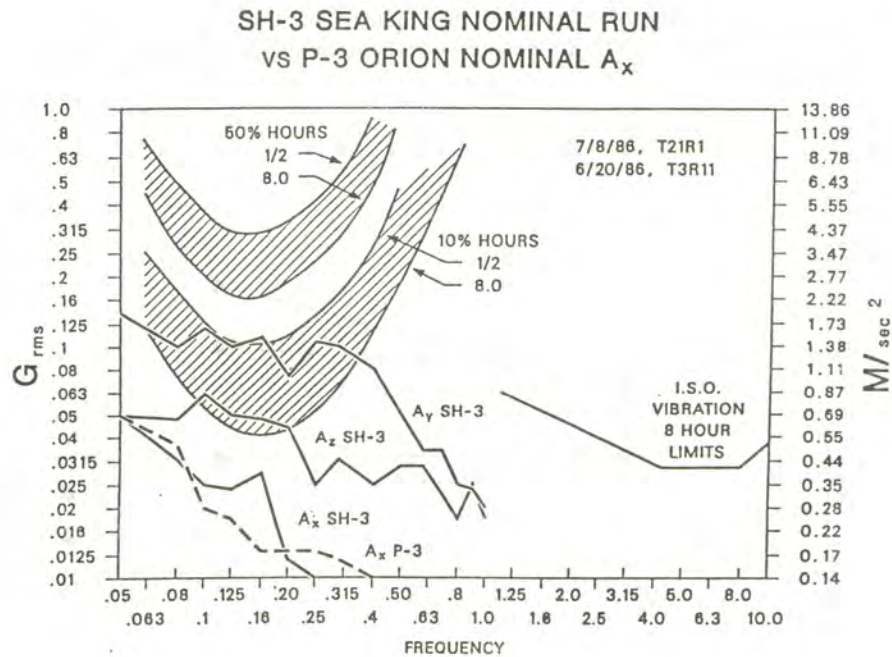


Figure 1. SH3 Sea King Nominal Run vs P-S Orion Nominal A_x

Motion Sickness Symptomatology.

Changes across pre-, mid-, and post-measures of symptomatology were assessed using the Wilcoxon Matched Pairs Signed Ranks Tests (Grauetter & Wallnau, 1985), which was designed for use with correlated ordinal data. Higher MSQ scores indicate increasing symptomatology with possible values ranging from 0 to 7 on an ordinal scale. For the 2F64C simulator, mid-MSQ scores were significantly greater than pre-scores ($Z = 5.479$, $p < .001$) as were post-MSQ scores ($Z = 7.322$, $p < .001$). The MSQ pre-score median of 0.0 indicates that virtually no symptoms associated with motion sickness were reported prior to the simulator training experience. The MSQ mid-score median of 4.0 and post-score median of 3.0 both represent dramatic increases over the MSQ pre-score median. The results show that pilots training in the 2F64C simulator experience a marked change in motion sickness symptomatology over the course of a training session. Differences between MSQ post-scores and mid-scores in the 2F64C simulator were not statistically significant.

Only pre-MSQ and post-MSQ scores were available from the 2F87 simulator. These scores were not statistically different ($Z = 1.7369$, $p = .08$). Inspection of the pre- and post-score medians shows that only minor symptoms associated with motion sickness were reported prior (median = 1.0) and following (median = 1.0) simulator exposure. This finding supports previous observations that the 2F87 simulator is associated with a low incidence of simulator sickness.

Equilibrium Testing.

Paired t-tests were used to assess changes from pre-scores to post-scores for both the WOFEC and SONLEC postural equilibrium tests. To partially control for practice effects, the average of the last two trials of the pretesting session were compared to the average of the first two trials after exiting the simulator. For 2F64C pilots comparison of post- and pre-WOFEC scores ($t = 0.15$, $df = 132$, $p = .88$), and post- and pre-SONLEC scores ($t = 1.59$, $df = 130$, $p = .115$) revealed no statistically significant differences. Similarly, for the 2F87 simulator subjects, no statistically significant differences were obtained between post- and pre-WOFEC scores ($t = 1.29$, $df = 42$, $p = .203$) or between post- and pre-SONLEC scores ($t = 0.45$, $df = 42$, $p = .658$).

In Figure 2, the pre- and post-means for the SONLEC scores are presented along with the means for a control group which was collected as part of another study (Jones, 1987, personal communication) where pre- and post-scores were collected with no intervening treatment and where approximately twenty minutes separated the pre-

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and post-testing. As may be seen in the figure, there is a tendency for the control group to improve from the pre- to the post-score while the simulator groups show virtually no improvement.

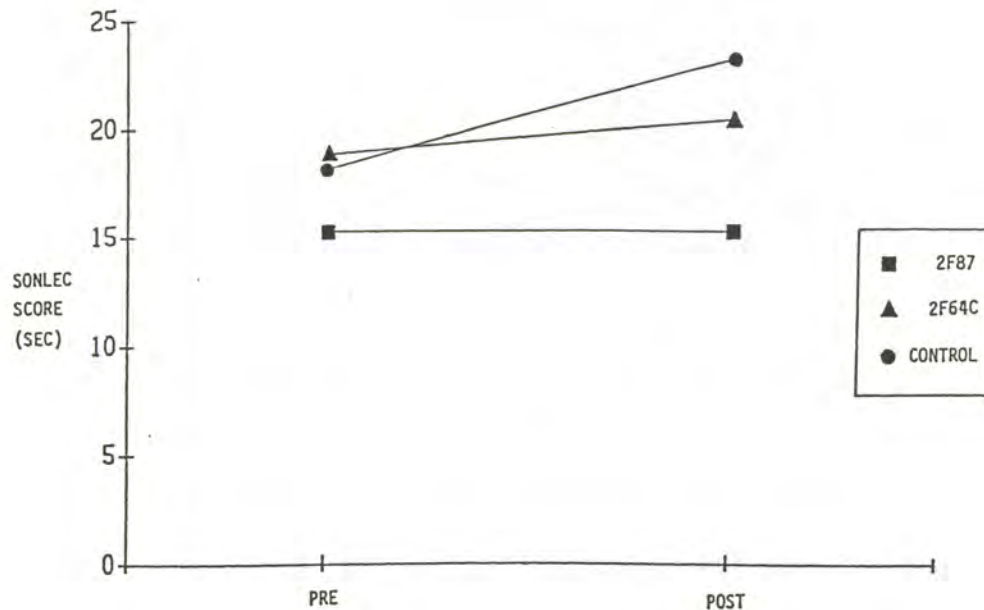


Figure 2. Pre- and Post-SONLEC Scores for 2F64C, 2F87F, and Control Groups

DISCUSSION

Nauseogenic motion profiles were evident in the 2F64C but not the 2F87 simulators. Not surprisingly, then, pilots' reports of sickness increased dramatically after exposure to the 2F64C simulator while exposure to the 2F87F simulator had virtually no effect on reports of sickness. There was no effect of exposure on ataxia scores. This was surprising in view of previous work showing significant ataxic effects of simulator exposure (e.g., Crosby & Kennedy, 1982). We believe the shorter exposures of the present study (usually less than two hours) may imply a break point for such effects. This suggests that motion sickness and ataxia may represent different processes and if restrictions of subsequent activity based on after effects are considered, perhaps both criteria need to be considered separately.

It was found that there were no increased in symptomatology beyond the midpoint in the hop. Perhaps the onset of symptoms occurs in the first hour, with little additional effect attributable to increased exposure, or perhaps adaptation to the environment occurs coincident with exposure, resulting in stable or even reduced symptomatology. However, more detailed analyses, incorporating reported time in the simulator, are required before final conclusions can be drawn. Whatever the explanation, exposure to the 2F64C simulated flight environment results in substantial and significant increases in motion sickness symptoms.

The success of our study, the demonstration that a generally nauseogenic simulator - the 2F64C - exposes pilots to acceleration at frequencies considered by MIL-STD 1472C to be nauseogenic, depends largely on the pilot-in-the-loop methodology. We suspect that no test and evaluation study which excludes the pilot and thereby fails to measure actual system behavior will be useful in understanding simulator sickness. Browder and Butrimas (personal communication, 1984) conducted a simulator study of "total system behavior" measuring "end-to-end system hardware and software," but used analytic functions (e.g. square waves) as the control input. Throughput delay, onset pulse duration and magnitude, and washout were found to be consistent with existing trainer standards and acceptable. The device tes-

ted was the 2F64C and 2F121. The difference between the results of this study and ours, we believe, has to do with methodology differences. Measuring exposure to nauseogenic acceleration/frequency requires pilot control signals and acceleration recording over an extended period. System performance and system behavior may be very different things; we believe that system behavior is more relevant to the effects simulators have on humans. We believe that in order to determine whether a simulator's motion base induces illness, the appropriate measures must include a pilot flying a training scenario to provide control input and acceleration recording over an epoch approximating a typical unit of simulator behavior — a simulator hop.

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