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Motion Cues in Flight Simulation and Simulator Induced Sickness

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.433

MOTION CUES IN FLIGHT SIMULATION AND SIMULATOR INDUCED SICKNESS

Papers presented at the Aerospace Medical Panel Symposium held in Brussels, Belgium
from 29 September to 1 October 1987.

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PREFACE

The purpose of the flight simulator is to provide a safe, readily available and economical means of training air crew in the operation of aircraft. Simulator training is potentially a safe substitute for part of the flight training that would otherwise be done in aircraft at higher cost and with greater risk.

Over the years a number of undesirable simulator effects, including a set of effects referred to as simulator sickness, have been reported. The frequency of these reports has increased as simulator usage has increased to offset the higher costs and risks of operating the complex modern aircraft. The goal of the symposium was to examine simulator-induced effects, their operational implications, and their etiology in order to develop ideas for reducing undesired effects. In general, symposium objectives were met. Areas for standardization of investigational methods and procedures were identified. Some apparent conflicts in results of different investigations were resolved, and avenues for future studies were ascertained. Several speakers provided recommendations for procedures to be followed to avoid some of the unwanted effects of simulator training.

* * *

Le simulateur de vol permet l'entraînement des équipages au vol en toute sécurité et à moindre frais, à l'aide d'un équipement qui est disponible en permanence. En effet, le simulateur de vol représente une solution de remplacement sans risque, qui permet de poursuivre une phase de l'entraînement au vol qui serait autrement effectuée à bord d'aéronefs, à plus grands frais et à plus grands risques.

Au cours des années, un certain nombre d'effets indésirables ont été constatés et notamment un ensemble d'effets connus sous le nom de "mal de simulateur". Le nombre de cas constatés de mal de simulateur a augmenté avec l'emploi des simulateurs devenu plus intensif dans le but de réduire le coût grandissant et les risques de plus en plus importants associés à la mise en oeuvre des aéronefs modernes, complexes. Le Symposium avait pour but d'examiner ces effets, leur incidence sur la conduite des missions et leur étiologie, afin de trouver des solutions permettant de réduire ces effets indésirables. La plupart des objectifs du symposium ont été atteints. Des domaines de normalisation en ce qui concerne les méthodes et les procédures d'investigation ont été repertoriées. Certains désaccords qui semblaient exister entre les résultats de différentes recherches ont été résolus, et des axes de recherche ont été identifiés. Plusieurs orateurs ont fait des recommandations concernant les procédures à suivre afin d'éviter certains effets indésirables de l'entraînement sur simulateur.

AEROSPACE MEDICAL PANEL

Chairman: Colonel K.Jessen
Director Aeromedical Services
Danish Defence Command
P.O. Box 202
DK-2950 Vedbaek
Denmark

Deputy Chairman: Mr Charles Bates, Jr
Director, Human Engineering Div.
AAMRL/HE
Wright-Patterson AFB
Ohio 45433-6573
USA

TECHNICAL PROGRAMME COMMITTEE

Captain W.M.Houk, MC, USN
Commanding Officer
US Naval Medical R&D Command
NMC/NCR
Bethesda, MD 20814
United States

Dr D.J.Benson
Head, Behavioural Sciences Division
RAF Institute of Aviation Medicine
Farnborough, Hants GU14 6SZ
United Kingdom

Colonel D.R.Price
Commander
US Army Aeromedical Research Laboratory
P.O. Box 577
Fort Rucker, Alabama 36362-5000
United States

Dr F.E.Guedry, Jr
Chief Scientist
US Naval Aerospace Medical Research Laboratory
Naval Air Station
Pensacola, Florida 32508
United States

HOST NATION COORDINATOR

Colonel Médecin A.Flion
Adjoint Médical Chef d'Etat-Major de la Force Aérienne (VSM)
Quartier Roi Albert 1er
Rue de la Fusée, 70
B-1130 Brussels
Belgium

PANEL EXECUTIVE

Major J.A.Winship, CAF
AGARD-NATO
7, Rue Ancelle
92200 Neuilly-sur-Seine
France

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TECHNICAL EVALUATION REPORT

by

Fred E. Guedry, Jr., M.S., Ph.D.
Chief Scientist
Naval Aerospace Medical Research Laboratory
Pensacola, Florida, USA

1. INTRODUCTION

The Aerospace Medical Panel Symposium on "Motion Cues in Flight Simulation and Simulator Induced Sickness" was held in Brussels, Belgium, from 29 September 1987 through 1 October 1987. The AGARD Conference Proceedings presented here consists of seventeen individual papers followed at the end of the Proceedings by a Round Table Discussion. Authors from six NATO countries presented papers.

2. THEME

The symposium was focused on the constellation of effects that represent problems encountered in the use of flight simulators to train air crew. Simulator-induced effects, resembling motion sickness, can interfere with progress in training. After-effects such as perceptual-motor aberrations and "visual flashbacks" can lengthen "down-time" between simulator training sessions or between a simulator session and readiness for actual flight. Relations between motor-control actions and the perceived response of the simulator, when discrepant with the remembered perceptions of flight conditions, can be a source of disturbance, particularly to the experienced aviator who may raise questions about negative transfer of training. The main theme of this symposium was chosen because of an apparent increase in the number of such reports; i.e., the symposium theme arose from the users of simulators, individuals being trained, and individuals responsible for training. The increased number of reports, in turn, may be related to 1) the increased use of simulators to reduce the costs and risks of training in modern aircraft; 2) the technological advances that have provided the designer with ever-increasing options for depicting the terrain, sky, and other aircraft in various degrees of realism, levels of visual contrast, amount of visual detail and sizes of the field of view; 3) inadequate maintenance of simulators and other factors brought out during the course of the symposium.

3. PURPOSE AND SCOPE

The purpose for this symposium was to disseminate information obtained in recent years on the incidence of effects in different simulators (or different units of the same model simulator) that might adversely influence the effectiveness of simulator training. An approach to obtaining information pertinent to etiology involves relating differences in incidence of effects to differences in simulator cues and motor responses in the context of theories of adaptation to sensorimotor rearrangement. Topics addressed included current and future trends in simulator design, variables influencing visually-induced self-motion (vection), use of models for the design and evaluation of simulators, procedures for overcoming vertigo in patients, procedures for reducing disorientation in space flight, some challenges presented by helmet-mounted displays, and efforts to relate neurophysiological systems and physiological measures (including event-related cortical potentials) to simulator problems.

4. SYMPOSIUM PROGRAM

The program consisted of four sessions. Session I consisted of three presentations that provided a symposium overview and discussion. Session II consisted of four presentations. Effects revealed during evaluation of different simulators by different speakers were discussed. Session III comprised eight presentations covering a range of topics. Due to time constraints, discussion was restricted following each of the last five presentations in this session. Session IV consisted of two presentations, one related to reduction of unwanted effects resulting from clinical disorder, and the other related to an effort to use simulated cue mismatches to preadapt individuals to stimulus rearrangement in weightlessness. These presentations were followed by a Round Table Discussion involving four panelists, a moderator, and the audience. The discussion centered on several points that had been raised during the course of the symposium.

5. TECHNICAL EVALUATION

The presentations of the three speakers of Session I provided a valuable overview for the symposium. The many simulation-induced effects, sometimes included in lists of signs of simulator-induced sickness, were the subject of lengthy discussion late in the symposium. Relevant to this in Kennedy's opening talk was his proposal that different symptom clusters may be related to different simulator equipment features, and he provided tables directly relevant to this point. The data base for Kennedy's presentation involved the evaluation of 10 flight trainers "before and after some 1200 separate exposures."

Current trends in simulation of motion cues, presented by Mooij, a member of the Flight Mechanics Panel of AGARD, provide insight into demands for large fields-of-view and high resolution visual images for simulators. It is probable that computegenerated imagery will be used almost exclusively in the future. Head-slaved or head/eye-slaved control may be used to provide high resolution in the area of visual interest while maintaining a wide field of view. However, Mooij believes that enhanced depiction of the outside visual scene creates simulator-induced sickness problems. Mooij regards quality control in the maintenance of flight simulators and in the training of individuals operating simulators as important determiners of simulator sickness.

Benson characterized simulator sickness as "another form of motion sickness," adducing as evidence the significant number of reports of stomach awareness, nausea, sweating, headache, dizziness, and drowsiness -- all common to other forms of motion sickness. Although vomiting is infrequent in simulator sickness, many other attributes of simulator effects resemble responses to stimulus situations that provoke motion sickness; e.g., severity of the effects and the after-effects are functions of the duration of the motion stimulus; adaptation occurs with repeated simulator flights, wide individual differences in the manifestation of malaise, disturbances of postural control after exposure -- all common to adaptation to sensory rearrangement conditions that produce motion sickness.

While Benson identified one of Kennedy's clusters of simulator effects as "just another form of motion sickness," he also clearly indicated that other simulator-induced effects are not specifically characteristic of motion sickness, e.g., some of the visual disturbances reported. Also, variations in the range of information collected by various investigators of different simulators compromised efforts to compare incidence of particular simulator-induced effects. A point emphasized during the course of the symposium is the need to consider simulator-induced effects in relation to effects induced by comparable flights in the aircraft.

The neural mismatch or sensory rearrangement theory was proposed to explain the cluster of signs and symptoms indicative of simulator-induced motion sickness. Motion sickness occurs when sensory information from the visual, vestibular, and somatosensory systems about whole-body movement is discordant with the pattern of sensory inputs expected on the basis of past experience. A model within the central nervous system of afferent and efferent neural activity is derived through daily experience "primarily during voluntary control of whole-body movement." A sustained change in the pattern of sensory input -- as, for example, occurs in some motion environments or when there is vestibular disease -- yields a continual mismatch between actual and expected sensory inputs. Thus, the internal model must be modified, but with two effects: 1) motion sickness, and 2) gradual modification of sensorimotor responses that provide adequate control of motion in the new environment. As the mismatch is reduced, motion sickness subsides, but then return to a "normal" environment produces after-effects as a result of readaptation to the normal environment.

The sensory rearrangement concept, as presented, emphasized the importance of past experience. I concur but with one reservation, viz, that some forms of conflict, wherein sensory inputs would elicit reactions in different directions simultaneously from the same muscle groups, may be an innate alarm signal that contributes to motion sickness. Nevertheless, it is clear that sensorimotor and perceptual reactions are altered during persistent exposure to unusual motion environments (1,2). The sensory rearrangement theory of motion sickness was generally accepted by the symposium participants who interpreted a number of the effects and after-effects of simulator training from this viewpoint.

The four papers of Session II dealt with incidence of simulator-induced effects and after-effects on simulators in four countries -- France, Canada, The United Kingdom, and the United States.

Results of the first paper in this group were based upon a retrospective survey, whereas results in the remaining three papers were based, at least partially, upon results obtained from more direct surveys. Chappelow, and later Kennedy during the Round Table Discussion, indicated that reported incidence tended to be lower in retrospective surveys. Each of these papers presented evidence of unwanted simulator effects. There seemed to be general agreement that there are reasons and methods to ameliorate unwanted effects, which in general were milder than anticipated and did not outweigh advantages that simulator training offers.

Reports of simulator sickness obtained from pilots in the Air Force of France were summarized in the paper by Leger et al. (presented by Leger). Of 164 pilots responding, 153 responses were judged suitable for general descriptive analysis, and 132 were retained for detailed analysis. In contrast to other studies in which on-site investigators evaluated effects induced by specific simulators, questionnaires were used by Leger et al. to obtain information on the past simulator experience of pilots (and motion sickness in general) from different units of the Air Force of France. Thus, the results were based upon questionnaires answered anonymously relating to past experience in different simulators over a number of years. Sixty-seven percent of the responding pilots had experienced simulator-induced sickness to some degree, but the majority of effects elicited were moderate and decreased rapidly after several sessions. After-effects were absent in 51%, insignificant in 34.8%, moderate in 9.[illegible], and severe in 3.8% of the responding subjects. In contrast with a study by Kennedy et al. (3), statistically significant relationship between simulator sickness and motion sickness in general (indicated by scores from a motion sickness questionnaire) was not found by Leger et al. Differences in this aspect of the results may be attributable to differences in approaches used and in the MSQ used.

In contrast with the preceding paper, which dealt with a number of simulators over a number of years, the paper by Magee et al. concentrated on one simulator, the C-130H (Hercules) flight simulator. Previous complaints about the simulator had included a variety of disturbing handling characteristics, unrealistic ground effects, and many symptoms such as vertigo, dizziness, disorientation, stomach disturbance, headache, nausea, and eye strain; at least two pilots vomited following simulator flights. The present study was conducted after shortcomings in handling characteristics had been addressed by computer modifications.

Simulator sessions lasted 4 hours, with a coffee break after 2 hours; the pilot and copilot switched positions after the break. No subject reported severe simulator sickness, but 95% experienced at least one symptom. Most commonly reported were eye strain, after-sensations of motion, fatigue, and drowsiness. Improved simulator handling characteristics may explain the lesser effects encountered in the present study. The flight experience factor in relation to simulator effects was also evaluated. Their experienced group had previous Hercules simulator experience as well as flight experience. The inexperienced group had previous flight experience, but none in the Hercules aircraft or simulator. Differences related to flight experience were not found; the authors do not regard their results as definitive but rather as a reason for keeping open questions regarding the role of flight experience in simulator sickness. The role of flight experience in simulator sickness was alluded to by a number of speakers in the symposium. It is an important point because it relates to the sensory rearrangement theory of motion sickness, which was generally accepted by symposium participants. A small median age difference (32 versus 29 years) between the "experienced" and "novice" groups in Magee's study was not a statistically significant variable in the effects recorded, but it was the subject of discussion later in the symposium.

Chappelow studied two simulators, both research simulators, one at Farnborough and one at Warton in the United Kingdom. A questionnaire provided information on effects experienced during the simulator sortie and, by readministration 3 days later, the same questionnaire provided information on post-simulator effects. Retrospective information was obtained by sending the questionnaire to other pilots known to have flown one of the two simulators. Concurrent surveys yielded more reports of simulator-induced effects than did the retrospective survey. A 70% return rate yielded 271 responses.

Both simulators were fixed-based with a projection dome and were used to simulate air combat maneuvering in this study. With the exception of concurrent questionnaires at Farnborough, about 40 to 50% of the respondents reported no symptoms at all. Effects at Farnborough were characterized by fatigue (mental and physical) and increasing symptoms as exposure lengthened. Results differed from those obtained at Warton. Pilots at Warton seldom mentioned fatigue; rather they reported dizziness, unsteadiness, and false perception of attitude. About 30% reported false perception of attitude, an effect that was less common at Farnborough.

Delayed symptoms (after simulator sorties) were uncommon; no delayed effects were reported in over 50% of the respondents from the concurrent survey and in over 90% from the retrospective survey. However, six subjects at Farnborough reported spinning sensations, usually on going to bed, and one of these canceled a scheduled flight the next day.

Differences in results between Farnborough and Warton are probably attributable to the simulator sorties scheduled. Farnborough simulator sorties lasted from 2 to 6 hours involving tests of different systems, whereas those at Warton were of 1 hour/day duration, each consisting of several 10-minute training sessions.

In general, the symptom constellations were similar to those reported in several other studies, but the data suggest a less severe problem than had been anticipated. An interesting feature of this study was that about 25% of all subjects found the simulator experience exhilarating; they enjoyed the experience. About 40% indicated that their simulator experience produced a positive attitude toward simulators, whereas less than 3% reported a negative attitude change. Chappelow found no relationship between previous flying experience and simulator effects.

Chappelow concurred with recommendations of Kennedy for reducing unwanted simulator effects; particularly he mentioned providing a night's rest between simulator training and real flight, limiting simulator exposure to 1 hour/day, avoidance of out-of-focus visual displays, avoidance of resets of the visual system, allowing those few pilots who have persisting effects to remove themselves from flight schedules, and assuring adequate simulator maintenance.

The final paper in this session by Gower et al. (Paper #8) provides a balanced background of advantages accrued from the use of simulators and problems encountered in their use. Gower, who presented the paper, summarized a number of studies, including investigation of Navy simulators by some of his co-authors. The methods employed are similar to those of the Navy studies.

The paper concentrates on evaluation of the U.S. Army's newest rotary-wing simulator, the AH-64 Apache combat mission simulator (CMS); it provides a good description of the Apache helicopter, particularly systems in the Apache potentially relevant to Apache CMS training effects. The study consisted of an on-site survey of pilots undergoing CMS training by means of a motion sickness history questionnaire (MSHQ) and a motion sickness questionnaire (MSQ). The MSQ provided evaluation of 1)prior flight time and simulator time (and recency of such experience); 2) use of medications, alcohol, tobacco, etc., and an estimate of well-being before entering the simulator; 3) post-flight symptoms; and 4) experiences with systems and symptoms in the simulator. In addition, a postural equilibrium test was administered before and after simulator training sessions.

Several samples of subjects (including student pilots, rated Army AH-64 pilots, and instructor pilots) were included in the study of 127 individuals whose combined experience totaled 434 CMS flights. Data were categorized in two symptom-clusters: 1) vision-related problems, difficulty concentrating, and headache; and 2) motion sickness; drowsiness/fatigue, sweating, nausea, dizziness, stomach awareness, and fullness of head.

Over-all symptom incidence was 44%, similar to prior U.S. Navy studies. Differences in symptoms between "student" and "rated" aviators were insignificant when subjects were flying in the copilot-gunner seats, but rated aviators exhibited significantly more symptoms when flying in the pilot seat. Postural equilibrium test scores dropped significantly from pre-test to post-tests (again similar to U.S. Navy data). In a student group, followed over 10 CMS flights, the pre-post ataxia difference scores increased over flight sessions even though other symptoms declined. The authors recommended follow-on studies of post-simulator effects beyond their 15-30 minute post-flight evaluations because of potential post-simulator risks in flying, driving, and so forth.

The eight papers comprising Session III represented a broad range of topics. Papers 9 and 12 dealt with the use of predictive models in relation to producing adequate simulation; however, the models were of very different types. Bussolari, Young, and Lee developed a model based fundamentally upon theory of how motions of the head are transduced into neural messages by the end-organs of the vestibular system. When values for parameters in differential equations appropriate for these kinds of sense organs have been obtained, then prediction of responses to any set of initial conditions and any set of accelerations can be made and tested through appropriate experiments. In this way, Bussolari et al. sought to minimize differences between perceived motions in selected aircraft maneuvers and simulated maneuvers. Thus, their model was generalizable to a number of motion conditions, although, as they indicated, more complex models would be needed to subsume the many effects of central adaptive mechanisms and integration of information from other sensory systems. The model of Frank and Casali was an empirical statistical model based upon regression equations and the empirical assessment of response variance accounted for by several independent variables. This model was based upon substantial data collected from a particular simulator. Frank and Casali suggested caution in applying their derived model to other simulators, although they anticipate that "the general relationship between the dependent variables and their regressors would be substantially the same" for other simulators. While these two approaches to modeling are very different, it is interesting to note that Bussolari et al. used results of an empirically derived model to validate their model.

The papers by Howard et al. (Papers 15 and 16) and Kriebel et al. (Paper 10) were somewhat related in that they dealt with information fundamental to understanding perceptual responses in simulators, but they did not deal specifically with simulators. On the other hand, Paper 11 by Casali and Paper 13 by DeMeyn et al. provided information on evaluation of simulators. Both of these papers could easily be grouped with the papers of Session II. The paper by Casali provided a substantial review of several topics important to this symposium. The paper by Ellis et al., Paper 14, dealt primarily with information transmission through novel display instruments, but it also discussed potential problems of head-fixed displays. Ellis' interest and background in this area were revealed by his earlier questions to Mooij concerning the practicality of head-slaved versus eye-slaved area-of-interest displays.

The third session began with the paper by Bussolari, Young, and Lee, presented by Young, on the use of vestibular models for design and evaluation of flight simulator motion. The fundamental idea is to use a model for predicting motion perceptions in order to reproduce (as closely as possible) in the simulator pilot the perceptions of the aircraft pilot. Values for parameters in the models for predicting semicircular canal and otolith responses were derived from studies of responses of vestibular primary afferents as opposed to selecting parameter values based upon endorgan mechanics or perceptual transfer functions.

Particular flight maneuvers were selected for simulation in two simulators, the Vertical Motion Simulator (VMS) and a Boeing 727-200 flight simulator, both located at NASA Ames Research Center. Four NASA test pilots, current in VTOL aircraft and with experience in the VMS, participated in a study evaluating simulation of selected VTOL maneuvers; and 18 air transport pilots, current in the Boeing 727, participated in a study of simulation of selected Boeing 727 maneuvers.

Within the limits of the observations, the model approach provided motion drive logic that was comparable in regard to pilot performance and ratings of simulator acceptability to an empirically optimized washout system previously developed at NASA Ames. An important point of this paper was that for some types of aircraft and for simulation of selected maneuvers, limited motion base capability appears adequate for training purposes.

Data reported in the paper by Kriebel et al., presented by Kreibel, related specifically to vestibular-evoked responses. Evoked responses recorded from normal subjects and from a subject without vestibular function were compared. Stimuli comprised whole-body sinusoidal oscillation at 0.4 Hz with peak velocities above and below subjects' perceptual thresholds. Absence of sinusoidal cortical-evoked responses in the patient led to the conclusion that the sinusoidal variation in cortical potentials recorded from normal subjects was mainly of vestibular origin. However, the authors were clearly aware of the convergence of kinesthetic and somatosensory projections in the area identified in earlier animal studies as the primary vestibular cortical projection area. The authors then described neurological systems and neurophysiological functions involved in the perception and control of motion in everyday life as a way of presenting the complexity of the systems challenged by adjustment to flight simulators.

The paper by Casali and Frank, presented by Casali, provided an excellent tabular summary of a number of simulator studies including studies of vehicular simulators. In considering etiology, the authors indicated that it is difficult to target simulator design characteristics that induce simulator sickness. However, they provided a summary of variables, some simulator-specific and others derived from evaluation of a number of simulators that have been identified as contributors to simulator sickness. The primary thrust of this paper was a review of symptomatology measurement with the objective of providing guidance regarding promising measures for future studies. Self-report measures, motion sickness questionnaires, physiological measures including cardiovascular activity, respiration, skin resistance/conductance, efforts to measure pallor, facial temperature, and measures of gastrointestinal activity were discussed along with postural stability measures.

Frank and Casali evaluated effects of transport delays of the motion system and of the visual motion system in a computer-controlled automobile simulator with a 4 degree-of-freedom visual system. Of particular interest in this study was whether or not the visual motion subsystem should lead or lag the motion base subsystem.

The results indicated "a linear relationship between increased vestibular disturbance, degraded performance and increases in delay," where delays were 0, 170, and 340 ms. With asynchronous delays, results indicated that the visual scene movement should precede motion base movement. Dependent variables included driving performance measures, physiological measures (skin resistance, pallor, respiration), measures of postural stability, and a simulator sickness severity index.

The paper by DeHeyn et al. (Paper #13 in the Program), the fifth paper of this session, examined two simulator scenarios for the presence of horizontal nystagmus and for simulator-induced sickness in 12 F-16 pilots during training in a flight simulator. In addition, 31 pilots responded to an anonymous questionnaire concerned with symptoms during and after simulated flight. Little or no nystagmus was detected during various maneuvers in the simulated flights. Many eye movements occurred during the engine start-up and landing segments of each scenario, very probably saccades associated with gaze shifts required to perform these particular tasks. The possibility that vertical and roll eye movements may have occurred during some segments of the scenarios would not have been sufficiently revealed by the recording procedures used. Eye movements apparently were not recorded in darkness before or after the simulator exposure.

Symptoms of simulator sickness during simulation were reported by 39% (12 of 31) of the pilots, age range 23-40 years, apparently with a preponderance of reports from older, more experienced pilots. Of the pilots reporting symptoms, 37% indicated persistence of symptoms (post-simulator) for about 15 minutes, 16% for up to 2 hours; one pilot had to interrupt his training program due to persisting effects.

Results of the symptom survey were comparable to results obtained by other investigators. No evidence was obtained for relationships between characteristics of oculomotor control and simulator-induced effects, although visual suppression could have prevented detection of anomalous eye movement patterns immediately following simulator exposure.

The sixth paper of Session III, Paper #14 in the program, was presented by Ellis. Technological advances permit high-performance 3D computer graphics, which provide aerospace designers with new flexibility for creating interactive information displays.

The authors provided examples of geometric enhancement and symbolic enhancement of "spatial instruments" and described an experiment illustrating how selected symbolic enhancements can provide qualitative and quantitative improvement in pictorial communication. Information enhancement in head-mounted displays is likely to yield results different from those that would be obtained from the same display information obtained from panel-mounted displays. With head-mounted displays, the normal vestibulo-ocular reflex (VOR) would be counterproductive unless VOR stabilization of the eye relative to a fixed point in space is somehow compensated by image movement in the display. Such a viewing situation requires "careful calibration to insure perceptual stability." Failure to achieve sufficient perceptual stability with head-fixed displays can produce nausea. This part of the paper by Ellis et al. should be considered in relation to Mooij's comments on head-slaved area-of-interest displays.

The authors suggested several forms of information enhancement that appear feasible for head-mounted displays, and concluded that "the development of spatial instruments is limited not by our manufacturing capabilities, but by our imagination and by our understanding of human spatial perception."

The last two papers of Session III, presented by Howard, dealt with sensations of self-motion (circular vection and linear vection) and tilt induced by moving visual fields. In the studies described in Paper #15, the moving displays filled the entire visual field, subjects were aware that their chairs and litters could be rotated independently of the visual surrounds, and efforts were made to minimise somesthetic cues. The apparatus permitted stimuli for pitch, roll, or yaw vection about either a vertical or horizontal axis. As expected, vertical-axis vection was consistently stronger than horizontal-axis vection. For both vertical or horizontal axes, yaw vection was stronger than pitch vection, which was stronger than roll vection. For horizontal-axis vection, there was a strong asymmetry of illusory body tilt in pitch with tilt backward stronger than tilt forward. There appears, however, to be discrepancy in the text and Figure 4 regarding asymmetry in the magnitude of pitch vection. Magnitude of perceived tilts about the horizontal axis during vection exceeded magnitudes previously reported, possibly as a result of the large visual field, the reduced somesthetic cues, and the subject being "primed to expect the body to rotate."

The second paper presented by Howard examined the contributions of various factors (such as background versus foreground motion, central versus peripheral motion) to vection generation with competing moving displays. In general, the authors explained their findings in both papers on a "common sense" basis, such as the frequency of occurrence and reliability of visual cues to whole-body motion in the daily experience of natural motion relative to the Earth.

The fourth session consisted of two papers and a Round Table Discussion. Neither paper dealt directly with problems of simulator sickness, but both were concerned with adaptation to conditions that produce sensory rearrangement. According to the theoretical viewpoint presented by Benson in Session I, motion sickness, including simulator-induced motion sickness, is one of the consequences of adaptation to sensory rearrangement.

The paper by Norre' (Paper 17) focused on sensory mismatch (i.e., sensory rearrangement) produced by peripheral vestibular disorder, in particular, peripheral vestibular disorders that produce vertigo provoked by movement. His method for treating selected patients consisted of repetitive exposure to the provocative motion that induces vertigo; it was based upon research indicating that vestibular adaptation or habituation is highly specific. Norre' reported success in the outcome of his treatment. From this, he recommended that sensory mismatches produced in simulators should closely resemble those in flight.

The paper by Parker and Reschke described an effort to readapt individuals to a sensory rearrangement that occurs in space flight. The inte[illegible]n was to closely reproduce visual-vestibular mismatches that occur in weightlessne[illegible] and, by preadaptation to this sensory rearrangement, to provide a method for reducing [illegible]sturbance in space flight.

Norre's recommendation and the fundamental idea pursued by Parker and Reschke are in many respects related to the work of Bussolari et al. (Paper 9), who sought to match perceptual experiences in flight by the use of vestibular models for the design (and evaluation) of flight simulator motions. As indicated above, both papers were also based upon the fundamental theoretical viewpoint presented by Benson (Paper 3).

The Round Table Discussion centered on several points that were raised during the course of the symposium. The points listed for discussion were:

1. Symptom checklists by various investigators used in evaluation of simulator sickness include symptoms that are also effects of conditions other than motion sickness. If nausea, stomach awareness, or vomiting are not among symptoms listed, should check marks on other symptoms be included as signs of simulator-induced sickness?

2. Simulator-induced after-effects have been reported and have been a cause of substantial "down-times" between simulator training sessions and return to real flight. If equivalent symptoms are present after real flight, is there reason for "down-times" after simulator sessions that are longer than those required after real flight?

3. In the past, there were a number of reports indicating that the "experienced pilot" is more disturbed than "the novice" by simulator training, yet we have had several papers that seemed to question this rather generally accepted belief.

4. Some studies have indicated relationships between motion sickness history questionnaires (MSHQ) and simulator sickness, whereas others have not found significant relationship.

5. Several speakers suggested that increased fidelity of the visual display in simulators is related to increased incidence of simulator sickness. Is this generally accepted?

6. Discuss visual versus motion-base phase leads in relation to time lags in visual perceptions and visual-vestibular interactions.

Because of the length of discussions of Points 1, 2, and 3, Points 4 and 6 were omitted from the Round Table Discussion.

In connection with Point 1, several speakers, e.g., Kennedy, listed clusters of symptoms that served to separate signs of sickness from effects that commonly accompany sickness (sometimes called covert indicators of motion sickness), but are also clearly associated with other causal conditions. Nevertheless, this point remained a concern of the audience, as is obvious from the comments in the Round Table Discussion.

The second point was repeatedly raised, particularly by Benson. Have the after-effects of real flight been studied sufficiently to place the after-effects of simulator training in proper perspective?

The third point is important because it is central to the neural-mismatch (synonyms: sensory rearrangement, sensory conflict, cue mismatch, sensory mismatch, conflict, etc.) theory of motion sickness. The experienced pilot would be expected to be more disturbed than the novice by inadequacies of the simulator. The Round Table Discussion served to resolve differences between studies on this point.

The fourth point was omitted from discussion. Differences in results between studies are probably due to differences in the MSHQ used and differences in the range of effects found in the simulators studied. Range of effects discerned may be attributable either to the simulator, kinds of subjects, or (perhaps more importantly) to the method of survey, as Kennedy indicated during the Round Table Discussion.

The fifth point, discussed thoroughly during the Round Table Discussion, will not be elaborated here.

The sixth point was not opened for discussion during the Round Table, although comments relevant to this topic were made by Young in the course of discussion of other points. Factors influencing latency and magnitude of perceived motion following onset of visual motion are important in simulation, and some fundamental information was provided in Papers 15 and 16 by Howard et al. Paper 12 by Frank and Casali dealt with this topic, but the door was only slightly opened in this symposium. Relative dominance of the visual and vestibular systems in regard to eye movement control, as well as perceptual effects, is frequency-dependent and, to some degree, magnitude-dependent. This point could easily be the topic of a major symposium.

6. CONCLUSIONS

6.1. Simulator-induced motion sickness and many of the effects of simulator training are areas of legitimate concern; continuing research is needed.

6.2. Examination of simulator-induced effects in clusters (e.g., vestibular, gastrointestinal, visual) appears to be a useful aid in the diagnosis of specific simulator problems.

6.3. Effects during and after simulator training sessions should be evaluated in relation to effects during and after real flight. Disturbing effects, such as fatigue, headache, and dizziness, are common covert signs of motion sickness, but when their incidence in simulators essentially reproduces incidence in real flight (of comparable duration and flight profile) then they are not necessarily signs of poor simulation and may be signs of good simulation. They also may be indications that new display instruments, whether in simulators or in aircraft, should be further evaluated.

6.4. In-depth studies of the duration and magnitude of the after-effects of simulator training in the course of a sequence of simulator training sessions are needed.

6.5. Efforts to standardize data gathered in simulator evaluations are desirable in order to enhance possibilities for shared data bases.

6.6. Unwanted simulator-induced effects tend to decrease with repeated simulator training sessions. (One study indicated increasing problems with ataxia while other symptoms diminished.) Usually, reduction of unwanted effects is advantageous for training. However, behavior during simulator training must be studied. For example, adaptation to a simulator by learning to restrict head movements would be dangerous training for a crew member whose combat performance depends upon wide-field visual scan.

6.7. Current and future trends in simulator design center around new developments in computer-generated imagery to meet demands for large fields of view and high-resolution visual images. High resolution, particularly when produced by head-slaved or head/eye-slaved area-of-interest techniques, must be carefully evaluated for unwanted simulator training effects, including simulator-induced motion sickness.

6.8. Eye-slaved area-of-interest displays are of particular concern due to artifacts in most feasible methods of eye movement measurement.

6.9. Shifts in gaze that yield apparent changes in depth may introduce discrepancies between reflexive visual focus mechanisms and feedback of cues from the visual display.

6.10. Area-of-interest shifts in gaze involving head and eye movement activate several mechanisms of oculomotor control. Together these mechanisms produce a gaze shift of remarkably constant velocity to the area of interest, and then stabilization of the eye on the area of interest despite ongoing changes in the angular velocity of the head and of the eye during the gaze shift process (4). Coordination between scientists, familiar with mechanisms of gaze control, and engineers designing area-of-interest displays is important for efficient optimization. Similar coordination is highly important for efficient development of head-fixed displays.

6.11. In general, pilots with substantial flight experience in the aircraft being simulated are more disturbed by simulation inadequacies than individuals without flight experience. Results seemingly at variance with this conclusion appeared to be resolved during the meeting.

6.12. To improve the science of simulation, more scientific information is needed on factors influencing the onset, magnitude, and direction of perceptions of self-motion and attitude relative to the Earth in aircraft and in simulator-feasible conditions. Important subtopics include the dynamics of perceived motion as influenced by a) visual-vestibular-somesthetic interactions, b) force fields encountered in aircraft, and c) voluntary initiation of motion.

6.13. Models of the dynamics of the human vestibular system appear to be useful in the design and evaluation of selected flight simulator motions. More complex models will be required for more general application.

6.14. Empirically derived models are useful in evaluation of the effects on performance of changes in simulator characteristics, in optimizing motion-base washout dynamics, and in validating predictions from models derived from a systems engineering approach.

7. RECOMMENDATIONS

7.1 An invited speaker from the AGARD Flight Mechanics Panel made a substantial contribution to this symposium. Future symposia of the AGARD Aerospace Medical Panel should continue the practice of inviting members of other AGARD panels whose missions are relevant to the symposium topic.

7.2. A working group to develop standards for evaluation of aeromedical simulator effects is recommended.

7.3. A symposium on factors influencing the dynamics of perceived motion and orientation relative to the Earth is recommended.

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ETIOLOGICAL SIGNIFICANCE OF EQUIPMENT FEATURES AND PILOT HISTORY IN SIMULATOR SICKNESS

R. S. Kennedy*, K. S. Berbaum*, G. O. Allgood,**
M. E. Lane*, M. G. Lilienthal***, & D. R. Baltzley*

*Essex Corporation, 1040 Woodcock Road, Suite 227, Orlando, Florida 32803
**Martin Marietta Energy Systems, Inc., P. O. Box X, Oak Ridge, Tennessee 37831
***Naval Training Systems Center, Human Factors Division (711), Orlando, Florida 32813-7100

SUMMARY

The U.S. Navy has conducted a survey in 10 flight trainers where motion experience questionnaires and performance tests were administered to pilots before and after some 1200 separate exposures. From these measures on pilots, several findings emerged: a) specific histories of motion sickness were predictive of simulator sickness symptomatology; b) postural equilibrium was degraded after hops in some simulators; c) self-reports of motion sickness symptomatology revealed three major symptom clusters; gastrointestinal, visual, and vestibular; d) certain pilot experiences in simulators and aircraft were related to severity of symptoms experienced; e) simulator sickness incidences varied from 10-60%; f) substantial perceptual adaptation occurs over a series of hops; g) in two moving-base flight trainers motion sickness incidence appeared to be related to the amount of acceleration (energy) experienced in frequency ranges around 0.2Hz.

The findings are discussed in the context of sensory conflict theory and recommendations are made for simulator design criteria. Suggestions are made for how to relate simulator and equipment configuration to the separate symptom clusters as an aid to diagnosis of specific problems within particular simulators. We believe this holds promise in diagnosing simulator equipment problems (e.g., alignment, inertial motion profile, cue asynchrony) since different symptom clusters may be related to different equipment features.

PREFACE

The use of ground-based flight simulators for training is growing rapidly because simulators permit training to occur safely and at lower cost [71, 72, 73]. Simulators may be used to train tasks which are difficult or impossible to train in the aircraft, and simulators are as much as 10-30 times more available. In the past 10 years, the U.S. Navy and Marine Corps have fielded many simulators incorporating sophisticated computer graphics, with wide fields of view and complex motion systems. With the increased availability of such devices, reports of simulator sickness also seem to occur with greater frequency, with armed forces in the U.S. [9, 33, 38, 82] and Canada [67].

Simulator sickness, a problem first recognized 30 years ago [26, 63], resembles motion sickness symptomatology. The problem has resurfaced in various reports since then, notably Barrett and Thornton [1], Reason and Diaz [77], Puig [76], Ryan, Scott, and Browning [78]. The history of simulator sickness research has been reviewed in several reports [5, 6, 13, 39, 40, 58]. These reviews generally partition the adverse effects of simulator sickness to three main classes:

- Safety and Health Implications - Examples include visual aftereffects [33], locomotor ataxia [8], physiological discomfort [38], and interference with higher order sensory-motor functions [57].

- Implications for Training - An increased occurrence of simulator sickness threatens the long-term utility of ground-based flight trainers as integral components in military and civilian flight training. Distrust and apprehension may develop among users of particularly troublesome simulators, limiting their training effectiveness. There is also a possibility that pilot trainees may adopt perceptual-motor strategies to avoid sickness in the simulator that will result in poor, even negative, transfer of training to the aircraft. Posteffects may restrict pilots in their subsequent training activities.

- Readiness Implications - It may also be necessary in some cases to restrict postsimulator flight activities of aircrew who experience sufficiently profound symptoms of sickness and disorientation, thereby diminishing their operational readiness. This, in turn, may limit overall operational effectiveness. Simulator aftereffects may even place the person directly at risk in other posttraining activities (e.g., driving).

Simulator sickness is defined both by the content in which it occurs and by the symptom clustering:

- Operational - Simulator sickness is that condition where pilots suffer physiological discomfort in the simulator but not while flying the same maneuvers in the actual aircraft. The presence of high incidence of simulator sickness implies that there is something wrong with the simulation (e.g., out of specification or alignment, dynamic visual distortion, cue asychrony).

- Psychophysiological - Simulator sickness is a malady which resembles other forms of motion sickness. Vomiting is the cardinal sign, while drowsiness, dizziness, and nausea are its chief symptoms [41, 42, 87, 88]. Less frequently reported, but often present, are postural changes, or ataxia, sometimes referred to as "leans" or "staggers" [8, 15, 17]. Other signs include changes in cardiovascular, respiratory, gastrointestinal, biochemical, and temperature regulation functions [7, 60, 61, 66]. Other symptoms include general discomfort, apathy, dejection, headache, stomach awareness, disorientation, lack of appetite, desire for fresh air, weakness, fatigue, confusion, and occasionally, flashbacks and incapacitation. Symptoms which are particularly characteristic of simulator sickness include pallor, sweating, salivation, and eyestrain.

Compared to other forms of motion sickness, visually related disturbances are more prevalent than the neurovegetative, yet symptoms are still present in fixed-based simulators as well as in simulators with motion bases. It is felt that vection, the visually induced impression of felt motion, is an important (and maybe a necessary) condition for sickness in fixed-base simulators. Simulator sickness resembles disturbances subjects experience when wearing reversing, displacing, or inverting lenses [64], and, to a lesser extent, astronauts' experiences with the space adaptation syndrome [29, 75].

Because of the similarity between simulator sickness and motion sickness, it would seem that characteristics of the motion environment may be a contributing factor. However, we were able to find only one study [25] which examined man-in-the-loop and recorded the motion profiles. These results showed the presence of very low frequency dynamics but did not connect their obtained findings with the acceleration profile of ships at sea [59], nor related data for recommended exposure limits for such vibrations [18].

When the Naval Aerospace Medical Research Laboratory began their studies of motion sickness in the Pensacola Slow Rotation Room [18, 20] they modified the history questionnaire of Birren [2] and validated them against the criterion of vomiting in connection with a standardized test [43]. Then, the same scoring key was employed in a study of student pilots to determine their willingness to be candid on such a questionnaire [24], and later this scoring key was employed to examine whether such responses were predictive of success in flight training [31]. In general, the two scoring keys (motion sickness, training success) contained overlapping items and produced appreciable contribution to a multiple regression prediction equation [31, 34].

This same questionnaire has been [illegible]d in several studies of motion sickness including hurricane penetrations [49] and ships at sea [illegible]wever, there has not been an opportunity for a large-scale validation effort against the cri[illegible] seasickness until the studies conducted on the Office of Naval Research Motion Generator [illegible] Factors Research, Inc. [69]. In these studies over 600 subjects (male and female college students) were exposed to standardized conditions and brought to a criterion of vomit versus requested nonparticipation. This data set has been item analyzed and cross-validated to produce a new scoring key [55].

An eight-step program has been initiated by the U.S. Navy to document, explain, and alleviate the problem of simulator sickness. First, the research literature was integrated and compiled to permit access and review [4, 5, 6, 39]. Second, a conference was convened by the National Academy of Sciences where the Committee on Human Factors in the Commission on Behavioral and Social Sciences and Education held a three-day workshop, 26-28 September 1983, at the Naval Postgraduate School in Monterey, California [58]. This workshop brought together experts from the three military services and the academic community to identify the initial research requirements for simulator sickness. The conference recommendations were: (a) to formally survey the occurrence of sickness in the various training devices, (b) to determine the actual incidence of symptoms in different simulators, and (c) to determine whether any equipment features are correlated with a disproportionate incidence.

Third, a survey was conducted of 10 Navy simulators and an attempt to create a permanent data base has begun. Fourth, preliminary analyses of some of these data were made available in a series of communications and to a conference of a cross-disciplinary team of experts in the areas of vision, vestibular function, simulator design, and simulator usage. The transcript of this latter conference [36] provided short-term solutions relevant to instructional strategies and operator usage, and longer term design modifications were suggested as the most promising means of preventing sickness in simulators in the near term. Fifth, the suggestions were synthesized into a Navy field manual [35] with recommended procedures to alleviate simulator sickness. Additional documentation of these findings is available in a series of more than 30 Naval Training Systems Center technical documents.

The purpose of the present report is to describe steps six and seven in the program, which entail complete analysis of the technical data base from the 10 simulators, and measurement of the influence of various inertial system profiles in two simulators in order to develop criteria for future Navy flight simulation. The eighth step is being planned and is concerned with the identification of characteristics of simulator visual displays that are nauseogenic.

GENERAL METHOD

<u>Experimental Plan</u>. The survey was conducted over a 30-month period. Methodological issues were addressed first. Specifically, it was necessary to: 1) develop a reliable measure of gait unsteadiness during and after simulator exposure [80]; 2) develop and adapt a motion sickness symptomatology self-report questionnaire to be employed for assessment of pattern and severity of symptoms [38]; 3) develop a procedure to identify whether human performance (cognitive vs. motor) was adversely affected and the extent of performance decrement [51]; and 4) improve and adapt the scoring key for a motion sickness history questionnaire [44].

<u>Site Selection</u>. For the survey, the simulator sites were selected to be representative of the Navy's current flight simulators which possess visual systems and with respect to geographical area, aircraft type mission, and equipment features. The sample included simulators with computer-generated imagery and model boards, light-source projection on domes, and CRT-based systems. There were approximately equal numbers of sites from each coast. A comparison between fixed-wing and rotary-wing systems was intended. Representative moving-base and fixed-base systems were surveyed. Both operational flight trainers and weapons systems trainers (and one weapons tactics trainer) were included, provided they had visual systems. Communication with the Navy basic training and advanced training commands revealed almost no reports of sickness in basic training flight simulators, perhaps because few, if any, have visual displays. Therefore, simulators for basic training were not studied.

<u>Subjects</u>. To the extent possible, all aircrew reporting for simulator training at the selected sites were asked to participate. Survey periods varied from three weeks to three months at a simulator site. During the course of the large survey and field study of over 1400 simulation flights, only one individual declined to participate. The resultant pool of participants included a highly diverse group of (mostly) designated Navy/Marine Corps aviators who flew these flight simulators as part of their normal duties. All participants were judged to be in good physical and mental health at the time of the study.

PROCEDURE

The participants were briefed (usually individually, but occasionally in groups) on the nature and purpose of the survey one to seven days prior to the beginning of the experiment. During the briefing the pilots were reassured as to the confidentiality of the results and completed the "Motion History Questionnaire." Each participant completed prehop measures just prior to the simulator session. Participants were cycled through their flight simulator session and posthop measures were then collected.

<u>Prehop</u>. Each participant completed the pretest measures 15 to 30 minutes before beginning his simulator flight. The pretest measures could include the "Symptom Checklist Questionnaire," three postural equilibrium tests, and the performance test battery of psychomotor and cognitive tests.

<u>Posthop</u>. Immediately after finishing the simulator flight, participants were administered the posttest which consisted of the same measures collected during the pretest session. Finally, each pilot was informally interviewed by the researcher. This interview invited the aircrew to discuss experiences in the simulator.

CANDIDATE MEASURES

<u>Motion Sickness Questionnaire (MSQ)</u>. The theory behind scaling motion sickness severity is that vomiting, the cardinal sign of motion sickness, is ordinarily preceded by a combination of symptoms [56, 62, 66, 85]. Studies conducted during World War II by Professor Wendt [86] form the historical basis for work in this field. In these studies, Wendt employed a self-report method which used a three-point continuum scale for grading sickness. This scale was used to assess motion sickness symptomatology, whereby vomiting was rated higher than "nausea without vomiting" which, in turn, was rated higher than discomfort. Navy scientists later developed a Motion Sickness Questionnaire (MSQ), a diagnostic classification system, and a five-point symptomatology scale for research in a Slow Rotation Room (SRR) [50].

In a series of experiments to assess the influence of actual vessel motion upon crew performance, physiology, and affective state [87, 88, 89, 90], the five-point MSQ was expanded to a seven-point symptomatology scale to query 15 participants aboard a 95-foot Coast Guard vessel regarding 34 symptoms normally associated with motion sickness. This is the approach used in the present study where symptoms were defined as either "Pathognomonic" (vomiting), "Major Symptoms," "Minor Symptoms," and "Other Symptoms" for current scoring (see Table 1). This classification scheme is similar to those used in previous experiments [44, 45, 88] and even to the 16-point scale [91], although one major change has been incorporated for simulator sickness work. A family of visual symptoms (including difficulty focusing, visual flashbacks, eyestrain, and blurred vision) was added to the "minor" category. As indicated previously, visual dysfunction seemed to occur with greater frequency in simulator sickness than in other forms of motion sickness. Lackner and Tiexeiria [52] have suggested that oculomotor conflict bears a strong resemblance to the perceptual problems of motion sickness. We followed their rationale by including eyestrain and related phenomena in our scoring. A facsimile of the recommended Motion Sickness Questionnaire is included as Appendix A. Additional information about these procedures appears elsewhere [48]. Based on our previous experiences in other studies of motion sickness [44, 47, 87, 88] with over 1,000 personally monitored cases we believe such an index is a meaningful way to express the level of discomfort.

<u>Motion History Questionnaire (MHQ)</u>. This questionnaire was used to determine each subject's history of exposure to various motion environments and susceptibility to motion sickness. It was patterned after the Pensacola Motion History Questionnaire developed by Kennedy and Graybiel [44] which is an omnibus anamnestic form that has been item analyzed, empirically validated, and cross-validated for the prediction of motion sickness against a laboratory procedure [44] and a ship motion simulator [55]. In addition, MHQ scores are related to flight training success [24, 44]. The MHQ gives each subject a "motion history" score that rates a subject's general motion sickness susceptibility. In a previous study involving simulators [40] MHQ scores were positively but not significantly related to experienced sickness. The recommended new form of the MHQ for predicting simulator sickness is shown as Appendix B.

<u>Automated Performance Test System (APTS)</u>. The explicit rationale for assessment of human capabilities in unusual or adverse environments is to predict fluctuations in the individual's capacity to perform his job. Other purposes are to monitor and diagnose the harmful/undesirable effects of the environment and to assess the effectiveness of practice, training, equipment, and system design. A Navy-sponsored research program titled Performance Evaluation Tests for Environmental Research (PETER) had a similar goal [23]. In that effort, a set of 30 tests of human cognitive, perceptual, and psychomotor capabilities used to study the effects of ship motion and other environments were subjected to an engineering analysis. Tasks were categorized as suitable for repeated means, variances, and correlations were statistically reliable under constant baseline conditions.

The "best" of these tests has been computerized on a portable microprocessor under development support from NASA. This microprocessor-based battery, called the Automated Performance Test System (APTS) [3] is the size of a notebook (9"x 12"x 2.5"), battery operated, sits easily on a lap or fits into a briefcase, and weighs only four pounds.

TABLE 1. MODIFIED DIAGNOSTIC CATEGORIZATION SCORE SHEET

PATHOGNOMONIC SYMPTOM
- Vomit

MAJOR SYMPTOMS (moderate or severe)
- Increased salivation
- Nausea
- Sweating
- Pallor
- Retch
- Drowsiness

MINOR SYMPTOMS (generally mild)
- Increased salivation
- Nausea
- Pallor
- Sweating
- Drowsiness

MENTAL SYMPTOMS ("minor" and "other" symptoms)
- Difficulty concentrating (minor symptom)
- Confusion (minor symptom)
- Fullness of head (other symptom)
- Depression (other symptom)
- Apathy (other symptom)

VISUAL SYMPTOMS ("minor" and "other" symptoms)
- Difficulty focusing (minor symptom)
- Visual flashbacks (minor symptom)
- Blurred vision (other symptom)
- Eye strain (other symptom)

"OTHER SYMPTOMS"
- Character facies
- Increased yawning
- Stomach awareness
- Anorexia
- Burping
- BM desire
- Headache
- Dizziness
- Aerophagia
- Vertigo
- General fatigue

The microcomputer was used to administer performance tests immediately before and after a person's simulator exposure. The specific tests were Pattern Comparison, Grammatical Reasoning, and Speed of Tapping. These tests have been field tested over several replications and have been shown to have the requisite metric properties for the present purpose. Specifically, the 7.5-minute battery: (a) achieves stability within 25 minutes of testing, (b) has six subtests with retest reliability coefficients equal to or greater than r = 0.85 for each three minutes of testing, and (c) assesses at least two different mental factors and one motor factor. The basis for the battery may be found in the early work on the PETER battery [23]. Additional information about the test battery may be found in a NASA-sponsored study [51].

The total time for all tasks was approximately 15 minutes. The computer has self-administered instructions for each of its tests. The computer battery consisted of the following tests: (1) three 10-second Tapping tests using the participant's preferred hand (the first 10-second test was practice), (2) Pattern Comparison for 1.5 minutes (with 20 seconds of practice before actual testing), (3) two 10-second Tapping tests with one finger from each hand (no practice -- format exactly like first Tapping test), (4) Grammatical Reasoning for one minute (with 20 seconds of practice), and (5) two 10-second Tapping tests using the subject's nonpreferred hand (no practice).

Equilibrium Tests. Two postural equilibrium tests, one static (Standing-On-One-Leg), and one dynamic (Walking Toe-to-Heel), were used to assess ataxia as a sign/symptom of simulator sickness. These are established tests derived from the Graybiel-Fregly Posture Test [19]. The tests were performed on the floor [16]. In a preliminary study, these tests were shown to be otherwise stable and reliable, although group performances increased continually over sessions [80]. In the "Standing-On-One-Leg" test, participants were asked to stand first on their "preferred leg" with arms folded across their chest and eyes closed for a maximum of 30 seconds. The experimenter used a stop watch to time how long the subject maintained the stance without losing balance or deviating from that position. The trial ended either after the 30-second time limit or when the subject lost his balance. Each subject performed the test for five consecutive trials on his preferred leg, then repeated the sequence on his nonpreferred leg. In the walking "Toe-to-Heel" test the subject walked a maximum of 12 steps with arms folded across his chest and eyes closed. If the subject did not touch his toe with his heel, he was told to stop. The number of steps up to that point was recorded and the test repeated. Both tests were administered to each subject pre- and posthop.

After completion of the main survey, simulators with differing incidences were sought in order to determine whether characteristics of the motion profiles could be identified which were nauseogenic. Both the SH-3 Sea King and P-3C Orion simulators, located at the U.S. Naval Air Station in Jacksonville, Florida (NAS JAX), met such criteria, since they possessed several characteristics implicated in simulator sickness (viz., w de fields of view, motion-base, and computer-generated imagery), and were representative of the many simulators operational within the Navy.

RESULTS OF THE SITE SURVEY

In combining the 10 different flight simulators of the survey and the two simulators for the motion profile study, 1200 exposures were obtained in all. Due to constraints on the availability of pilots, experimenters and simulators as well as other problems which attend field studies, all tests were not administered at all sites. This limited the results obtained to 1194 pre-/postmotion sickness questionnaires: 568 MHQ's; 711 pre-/postpostural equilibrium cases; 464 pre-/postperformance batteries; and 191 motion profile cases.

General Survey Findings

Overall Incidence. The overall incidences, based on 1186 separate simulator pilot exposures appear in Table 2a. It is to be recalled that the criterion for discomfort in this table is "the percent of persons who were sick enough upon exiting to report at least one minor symptom ordinarily associated with motion sickness." By this criterion, incidences in the 10 simulators vary over a broad range (10-60%). In Table 2b we have collected the grand incidence of each symptom category over all simulators. Table 3 presents the distribution of post-MSQ scores across the 0-7 downward scale. (Fine-grained analysis of symptom clustering are found in Figures 1 and 2.)

Equilibrium Test Results. Pre-/postpostural and gait stability comparisons from all simulators combined revealed an overall decrement from before to after exposure ($p < 0.001$) and six of eight individual simulator comparisons were statistically significant when compared to a control group. These data are described in detail elsewhere [37].

Motion History Questionnaire Results. MHQs scored in the standard way [46], and with two new methods [55] were compared. All three score keys obtained low but statistically significant correlations with incidence of simulator sickness (correlations ranged from $r = 0.16$ to $r = 0.23$), and thus were mildly predictive of reported symptomatology. A combined key for predicting simulator sickness was derived based on the best items from the three extant keys. The combined key obtained a correlation of $r = 0.32$ and $r = 0.43$ with reported symptomatology in the validation and cross-validation samples, respectively.

Automated Performance Test System Results. Pre- versus postperformance changes were studied in only six different simulators. In no simulator were group performances poorer after exposure, and indeed, most changes showed learning effects from the first (pre) to the second (post) session. Based on interpolations from other experiments on nonpilot subjects, these changes appear within the range of improvements due to practice which are to be expected over two sessions [51].

Special Survey Findings

Simulator Sickness Symptoms. Table 4 shows overall pre-exposure and postexposure mean scores for diagnostic simulator sickness symptoms. These are composite scores summarizing many symptoms.

A preliminary inspection of the individual MSQ forms suggested that there were two symptoms that resulted from exposure to the simulators surveyed (motion sickness-like symptoms and symptoms related to eyestrain). This was later confirmed statistically; indeed, a third was revealed through a factor analysis [53] but has not yet been applied to these data. Using the symptoms from Table 1 with the scoring criteria from Table 2, all MSQ forms were scored two ways, with or without visual symptoms associated with eyestrain. A single t-test was performed on the pre- vs. postdata from each simulator. Performing multiple t-tests in this manner increases Type I error probability (the chance of finding a difference where none exists). Note, however, that all "significant" tests yield p values of .001 or less, and those that are "not significant" are not close to any reasonable significance threshold. These findings are likely to be invariant under any method of protecting against type I error rate. The results of these t-tests agree well with the incidence rates of motion sickness-like symptom development in Figure 2, and in six out of nine simulators these differences are shown to be statistically significant. Note that the outcome of omitting eyestrain-related symptoms ordinarily lowered the obtained t statistic but did not change the p value from a significant to a nonsignificant level. Therefore, while eyestrain is not ordinarily a major symptom of motion sickness, omitting it is largely without effect from an interpretive standpoint. Eyestrain, however, appears to contribute to overall discomfort. There is also sufficient evidence entailing adaptive changes in oculomotor control which are related to conditions of simulator sickness, particularly recalibration of the oculomotor system based on perceived error signals [11, 52] that in the special circumstance of simulator sickness, it will be more helpful to include this symptom complex to the diagnostic classification.

TABLE 2a. DESCRIPTIVE INFORMATION CONCERNING 10 NAVY AND MARINE CORPS FLIGHT SIMULATORS*
(At least one minor symptom checked off on the POSTHOP Symptom Checklist)

SIM-ULATOR	N	AIRCRAFT	SIM-TYPE	LOCATION	VISION/MOTION	FIELD OF VIEW (deg)	INCIDENCE	MSQ SCORE
2E7	94	F/A-18	WTT	Lemoore	Yes/No	360H/150V	31%	1.34
2F132	26	F/A-18	OFT	Lemoore	Yes/No	48H/ 32V	27%	.58
2F112	52	F-14	WST	Miramar	Yes/No	350H/150V	10%	.54
2F110	55	E-2C	OFT	Miramar	Yes/Yes	139H/ 35V	47%	1.84
2F64C	223	SH-3	OFT	Jacksonville	Yes/Yes	130H/ 30V	60%	2.44
2F87F	66	P-3C	OFT	Jax/Brunswck	Yes/Yes	48H/ 36V	39%	1.94
2F117	281	CH-46	OFT	New River	Yes/Yes	175H/ 50V	26%	1.13
2F121	159	CH-53D	OFT	New River	Yes/Yes	186H/ 40V	36%	1.48
2F120	230	CH-53E	OFT	New River/ Tustin	Yes/Yes	180H/ 40V	33%	1.5[illegible]

Total N=1186

*The New River and Tustin 2F120 simulators data are combined in order to increase N. Also, the 2E6 simulator was excluded due to small sample size (N=8).

TABLE 2b. OVERALL PERCENTAGES OF KEY SYMPTOMATOLOGY

"A" Symptoms	Percentage	"B" Symptoms	Percentage
Eye Strain	25%	Drowsiness/Fatigue	26%
Blurred Vision	3%	Sweating	16%
Difficulty Focusing	11%	Nausea	10%
Difficulty Concentrating	10%	Dizziness/Vertigo	5%
Headache	18%	Stomach Awareness	8%
		Fullness of Head	6%

TABLE 3. PERCENTAGES (FREQUENCIES) OF EACH MSQ SCORE

Air-craft	N	POST-[illegible] SCORE 0	1	2	3	4	5	6	7
2E6	8	37.5(3)	25.0(2)	0.0	12.5(1)	25.0(2)	0.0	0.0	0.0
2E7	94	50.0(47)	13.8(13)	5.3(5)	13.8(13)	17.0(16)	0.0	0.0	0.0
2F64C	223	28.3(63)	4.9(11)	7.2(15)	22.0(49)	32.7(73)	2.7(6)	1.3(3)	.9(2)
2F121	159	45.3(72)	13.8(22)	5.0(8)	19.5(31)	15.7(25)	0.6(1)	0.0	0.0
2F120	230	44.8(103)	11.7(27)	11.3(26)	14.3(33)	15.7(36)	2.2(5)	0.0	0.0
2F117	281	54.8(154)	13.5(38)	6.0(17)	11.7(33)	12.8(36)	0.7(2)	0.4(1)	0.0
2F87F	66	27.3(18)	18.2(12)	15.2(10)	12.1(8)	27.3(18)	0.0	0.0	0.0
2F132	26	50.0(13)	15.4(4)	7.7(2)	11.5(3)	15.4(4)	0.0	0.0	0.0
2F110	55	40.0(22)	9.1(5)	3.6(2)	21.8(12)	25.5(14)	0.0	0.0	0.0
2F112	52	73.1(38)	13.5(7)	3.8(2)	5.8(3)	3.8(2)	0.0	0.0	0.0

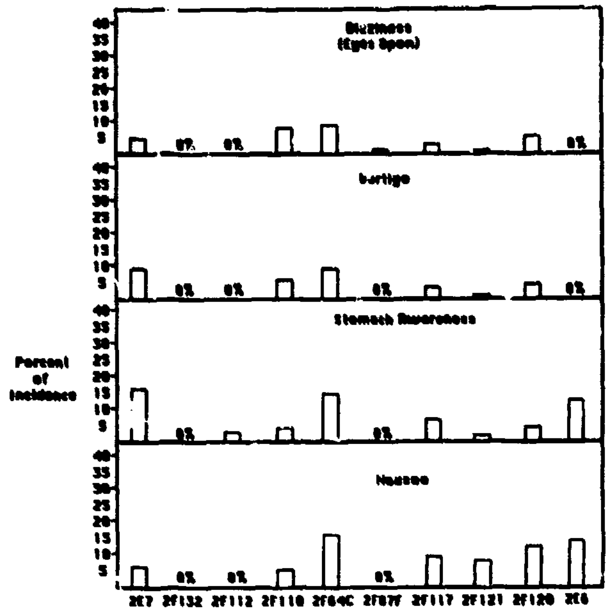

Figure 1. Primary motion sickness symptoms (Percentages of those not reporting a symptom before exposure).

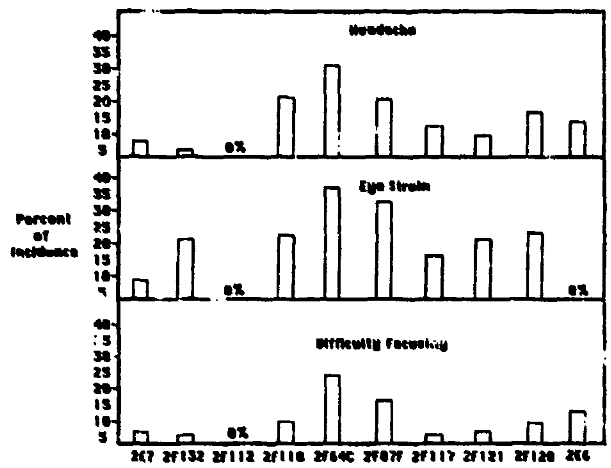

Figure 2. Eyestrain related symptoms (Percentages of those not reporting a symptom before exposure).

TABLE 4. PRE- AND POSTSIMULATOR EXPOSURE DIAGNOSTIC SIMULATOR SICKNESS SYMPTOMS*

Simulator	N	@	Pre-Mean	Post-Mean	Difference Mean	t	p
2E7	94	W	0.5106	1.3404	-0.8298	-4.50	0.000
		W/O	0.4787	1.1809	-0.7021	-4.00	0.000
2F132	26	W	0.6923	1.2692	-0.5769	-1.58	0.126
		W/O	0.5000	1.1154	-0.6154	-0.202	0.054
2F112	52	W	0.4038	0.5385	-0.1346	-0.93	0.359
		W/O	0.3077	0.5385	-0.2308	-1.47	0.147
2F110	55	W	0.6545	1.8364	-1.1818	-4.08	0.000
		W/O	0.5273	1.6000	-1.0727	-4.41	0.000
2F64C	223	W	1.2422	2.4395	-1.1973	-9.28	0.000
		W/O	1.1166	2.0852	-0.9686	-7.47	0.000
2F87F	66	W	1.6818	1.9394	-0.2576	-1.03	0.307
		W/O	1.5758	1.6061	-0.0303	-0.12	0.901
2F117	281	W	0.6335	1.1779	-0.5445	-5.58	0.000
		W/O	0.5445	0.9786	-0.4342	-4.57	0.000
2F121	159	W	0.8742	1.4843	-0.6101	-5.00	0.000
		W/O	0.8113	1.2893	-0.4780	-3.89	0.000
2F120	230	W	0.5870	1.5087	-0.9217	-7.67	0.000
		W/O	0.5348	1.1652	-0.6304	-5.53	0.000

Total N=1186

* The data for the New River and Tustin 2F120 simulators were combined in order to increase N.

@ t statistics were calculated with (W) and without (W/O) scores of visual effects related to asthenopia ("eyestrain").

· See Table 1 for scoring criteria

<u>Characteristic Motion Sickness Symptoms</u>. Figure 1 shows the self-reported incidence of four characteristic symptoms of motion sickness -- dizziness with eyes open, vertigo, stomach awareness, and nausea for each of the 10 simulators surveyed. The samples for each symptom exclude individuals reporting the symptoms prior to simulator exposure so that the proportions and frequencies are limited to those individuals who did not have the symptoms entering the simulator but did have them when exiting. This particular method of presenting the data may underestimate the extent of the problem because different pilots may experience different symptoms. In addition, for our survey, measures of characteristic motion sickness symptoms generally result in conservative values that may underestimate the magnitude of the problem. There was no control for the number of times an individual used the simulator over the period of the survey so that prior exposures ranged from 1 to as many as 30 hops and some individuals may have already adapted or habituated to the simulation. Uliano, Kennedy, and Lambert [81] show that the incidence of sickness drops 50% each hop over these exposures. It was not possible to correct these data by using pilot's report of hop number because of the multiplicity of other variables which occur during regular training (e.g., there were different time intervals between hops, different kinematics are known to occur in the same syllabus hop number, pilots were not always sure of the hop number).

<u>Asthenopia</u>. Figure 2 shows the self-reported frequency of eyestrain symptoms -- headache, eyestrain, and difficulty focusing for each simulation. Again, the data reported here are for those who were free of the symptoms upon entering the simulator. We believe these symptoms are less likely than motion sickness symptoms to habituate during training. From these tables it is clear that some simulators elicit symptoms in few individuals, whereas other simulators elicit symptoms in many.

Using the data from Figures 1 and 2, the simulators may be classified into categories of high, medium, and low symptom frequencies. Tables 5 and 6 present these classifications for motion sickness and eyestrain symptoms, respectively. There is some, but not complete, agreement between the classification of simulators according to the two symptom types. Two simulators produced a high incidence of both motion sickness and eyestrain, two other simulators produced a low incidence of both symptom types, and one simulator produced medium incidence of both types. The other four simulators had a one-level difference (high/medium or medium/low) between production of the two symptoms.

From the characteristics of simulators listed for the devices grouped by symptom "incidence" in Tables 5 and 6, it is possible to hypothesize which simulator features appear to be provocative. It appears that the simulators more provocative of motion sickness-like symptoms tend to be helicopter rather than fixed-wing simulators, and to use multiple CRT-computer-image generation displays rather than projection-dome screen displays.

TABLE 5. CHARACTERISTICS OF SIMULATORS* THAT ELICIT MOTION SICKNESS-LIKE SYMPTOMS**

Aircraft	Simulator	Nausea	6 DOF Motion Base	FOV H/V (Degrees)	CRT/Dome	Helo/Fixed Wing	Image Generation/Display Character.
High Incidence							
SH-3H	2F64C	15.4%	Yes	130/30	CRT	Helo	Digital CGI/calligraphic CRT
CH-53E	2F120	11.1%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
CH-46E	2F117	8.9%	Yes	175/50	CRT	Helo	Full raster scanned CGI/6500 color edges 6-window segmented virtual
Moderate Incidence							
CH-53D	2F121	7.0%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
E-2C	2F110	5.5%	Yes	139/35	CRT	Fixed	Digital CGI/Hybrid calligraphic-raster scan CRT
F/A-18	2E7	6.0%	No	360/145	Dome	Fixed	Digital CGI/TV projectors
Low Incidence							
F/A-18	2F132	0.0%	No	48/32	CRT	Fixed	Calligraphic CGI/dome projection
P3-C	2F87F	0.0%	Yes	48/30	CRT	Fixed	TV camera-model board Calligraphic D/N CGI
F-14A	2F112	0.0%	No	350/150	Dome	Fixed	TV camera-carrier model. Pt. Lt. Background 4 AOI Projectors

Total N = 1111

*The 2E6 simulator was excluded because of the insufficient number of cases (N = 8).
**Incomplete forms were not included and resulted in a lower N for percentages.

New Way to Score Motion Sickness Symptomatology

The availability of this large Navy/Marine Corps data base permitted the opportunity to conduct a factor analysis of symptom data from all the MSQ's. This analysis indicated that reported symptoms formed three major clusters: Factor I - Vestibular (dizziness and vertigo); Factor II - Gastrointestinal (nausea, stomach awareness); and III - Visual (headache, eyestrain, problems in focusing). Although factors were clearly identified, there was some overlap (common symptoms) among clusters, particularly with respect to "global" symptoms such as fatigue and general discomfort. When this shared variance was rotated onto a "general" factor, factor overlap was sharply reduced. The analysis suggests that simulator sickness and its symptoms can be represented by the three independent clusters, along with the "General Discomfort" factor which is common to all reported symptoms. Scoring the MSQ with this structure is likely to be dramatically more diagnostic of the problems underlying a given simulator; General Discomfort scores would indicate the overall magnitude of the problem, while Visual, Gastrointestinal, and Vestibular scores should reflect more accurately the particular simulator system(s) causing the problem.

An alternative factor structure was also developed by extracting four factors (rather than three) in the analysis. When examined in this way, the Visual factor "split" into two factors, one involving the process of visual disturbance (blurring, out-of-focus) and the second the results of that disturbance (eyestrain, visual fatigue, loss of concentration). A similar general factor was also present for this analysis. Because each of these visual factors is based on fewer symptoms, resultant scores would be expected to be less reliable than those for the 3-factor scoring method, but the differential power could be useful for more refined analyses of visual problems, and scoring keys are being developed for this structure. These relations are discussed in greater detail elsewhere [53].

TABLE 6. CHARACTERISTICS OF SIMULATORS* THAT ELICIT EYE STRAIN RELATED SYMPTOMS**

Air-Craft	Simulator	Headache	6 DOF Motion Base	FOV H/V	CRT/Dome	Helo/Fixed Wing	Image Generation/Display Character
High Incidence							
SH-3	2F64C	30.5%	Yes	130/30	CRT	Helo	Digital CGI/Calligraphic CRT
E-2C	2F110	20.4%	Yes	130/35	CRT	Fixed	Digital CGI/Hybrid calligraphic-raster scan CRT
P-3C	2F87F	20.3%	Yes	48/36	CRT	Fixed	TV camera-model board calligraphic D/N CGI
CH-53E	2F120T	16.8%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
Moderate Incidence							
CH-46E	2F117	12.0%	Yes	175/50	CRT	Helo	Full raster scanned CGI 6500 Color edges 6-window segmented virtual
CH-53D	2F121	9.1%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
Low Incidence							
F/A-18	2E7	7.1%	No	360/145	Dome	Fixed	Digital CGI/TV projectors
F/A-18	2F132	4.2%	No	48/32	CRT	Fixed	Calligraphic CGI/dome projection
F-14A	2F112	0.0%	No	350/150	Dome	Fixed	TV camera-carrier model Pt. Lt. Background & AOI Projectors
Total N = 1111							

*The 2E6 simulator was excluded because of the insufficient number of cases (N = 8).
**Incomplete forms were not included and resulted in a lower N for percentages.

MEASUREMENT OF SIMULATOR MOTION WITH PILOT-IN-THE-LOOP

The SH-3 simulator is a rotary-wing aircraft (helicopter) simulator with computer-generated graphic displays that simulate twilight conditions, employing a "Vital IV" calligraphic dusk/night CGI. Visuals are displayed with a 7-window, 5-channel, folded on axis virtual image cathode-ray tube (CRT) with a 130 x 30 (H x V) field of view. Motion is generated with a six-degree-of-freedom, synergistic motion platform. In general, the simulator is 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 occurred during the study due to a major update of the simulator site air conditioning system.

The P-3C simulator is a fixed-wing aircraft simulator with visual displays generated with a TV camera/model board. Visuals are displayed with a 5-window, 3-channel CRT (off axis reflective) with a 48 x 36 (H x V) field of view. Motion is generated with a six-degree-of-freedom synergistic motion system. The simulator is operated on a 15 hours/day, 5 days/week schedule. In general, the scene content of the helicopter simulator (2F64C) appears to be more articulated and active (i.e., more edges, higher resolution and contrast, and much close contact with the ground) than in the P-3C flight simulator. Many P-3C flight syllabus hops are high altitude or seascape scenes, with low resolution displays on single projection video screens.

Very high sensitivity servo accelerometers with minimum temperature sensitivity and hysteresis were selected. These accelerometers operate with output current, so the gain is dependent on the size of a precision resistor used to develop a voltage from the current. The signal-to-noise ratio was no longer a concern when based on proper resistor selection to provide high-sensitivity voltage output.

The accelerometers were dc coupled to measure not only motion but also variance in the gravitational field where they are mounted. Since the earth's gravity is a constant of nature, an accelerometer tilted within its local set of coordinates will sense a variance in the local gravitational field. Because tilt is a very useful function of these transductors, they are sometimes used strictly for this purpose.

Another advantage of the accelerometer selected was that voltage output from the signal conditioners could easily be adjusted to match the limited dynamic range of a high-accuracy frequency modulation (FM) tape recorder. Initial planning allowed for this voltage range to be changed as necessary during each run because the accelerometers were dc coupled and, with a high gain range (10 volts/hold together 50m0), a small amount of continued tilt might overload one or more channels on the recorder. These procedures are discussed in detail in Van Hoy, Allgood, Lilienthal, Kennedy, and Hooper [83].

Motion Profile Studies

Changes of symptomatology in the two simulators were tested for statistical significance by the Wilcoxon Matched Pairs Signed Ranks Test [12], for use with correlated ordinal data. For the 2F64C simulator ($N = 140$), comparison of post/pre-MSQ scores ($Z = 7.3220$, $p < .001$) indicated that statistically significant differences were obtained. This suggests that exposure to the 2F64C simulated flight environment results in dramatic, significant, and adverse changes in motion sickness symptomatology. In the 2F87F simulator ($N = 43$), the mean differences were not statistically different ($Z = 1.7369$, $p > .08$). Indeed, there was a slight reduction from the pre- to the postscore.

Figure 3 shows the standard axes labels used in this study. Figure 4 incorporates Military Standard 1472C (MIL-STD-1472C) [64] for the low frequency end of the spectrum and typical vibration values from commonly known occurrences. It may be seen that man-in-the-loop motion profiles fall within the nauseogenic regions of 1472C.

Figure 5 shows maximum average vs. maximum peak values for this same nominal run. The values correspond to the low-frequency portion of MIL-STD-1472C. Although maximum peak values are expected to be larger than the maximum averaged values, the range of variance for this run was larger than expected. Thus, the magnitude of difference between the peak and average values for any frequency is significant. If only averaged values are used for analysis and correlation evaluation, the analyst would be led to erroneous conclusions.

Figure 5 also shows a comparison of the nominal mean run of the P-3 simulator with the nominal mean run for the SH-3 simulator, for the 3 axes in the case of SH-3 and for the strongest simulator (gx) in the P3-C, overlaid on MIL-STD-1472C. The force environment of the two devices is markedly different; the SH-3 presents motion profiles within regions to which MIL-STD-1472C predicts nauseogenic reactions.

DISCUSSION

Observed Symptomatology

The objectives of this research followed from a definition of the problem [14] and the suggestions for research of a panel of vestibular scientists and training equipment technologists [58] to determine the extent to which simulator sickness occurred in Navy systems. Some of the results are clear-cut. There was almost no vomiting or retching (.2%), but some severe nausea, and significant amounts of drowsiness, eyestrain, and disequilibrium. Approximately 100 pilots (i.e., 10%) experienced disturbances that may be considered severe enough to warrant restriction of subsequent activities for as much as 24 hours.

Many of these individuals exhibited postural disturbances. Such individuals may be considered to be at risk to themselves and to others if they drive themselves home or return to demanding activities at work. Activities to be avoided include driving and flying, as well as those which entail attention to balance (mountain climbing and roof repair).

Using the report of at least one minor motion sickness-related symptom (e.g., salivation, nausea, pallor, drowsiness, or sweating) but not accessory symptoms (e.g., fatigue, depression, or boredom) as the criterion of illness, the observed incidence of sickness in the various simulators ranged from a low of 10% to a high of 60% for the total data base. If this were the only sign or symptom, the risk might be no more severe than an extended aircraft flight, perhaps with heavy "g" forces. However, adverse conditions produced in a simulator must be justified by their training effectiveness. Ordinarily, the symptoms of simulator sickness overlap only slightly with those which result from the environmental stress of flying aircraft, and their training relevance is dubious. Furthermore, some of these symptoms, particularly those related to eyestrain, may be remedied by engineering changes in future systems and to some extent by better maintenance in existing systems.

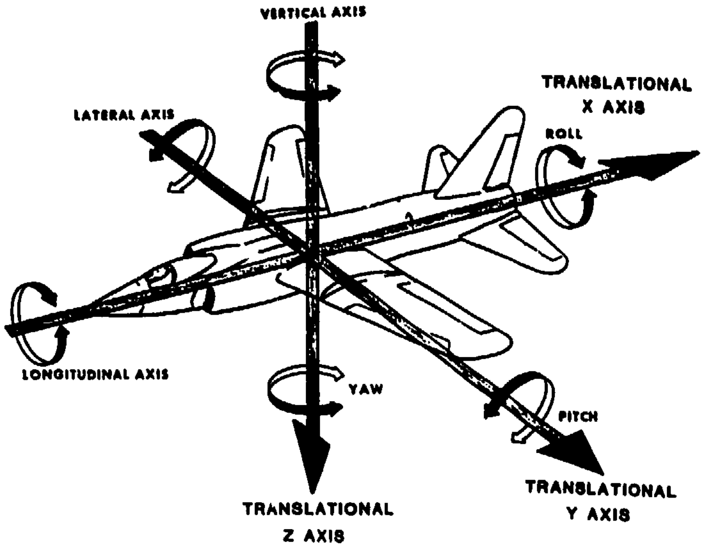

Figure 3. Translational aircraft measurement axes orientation.

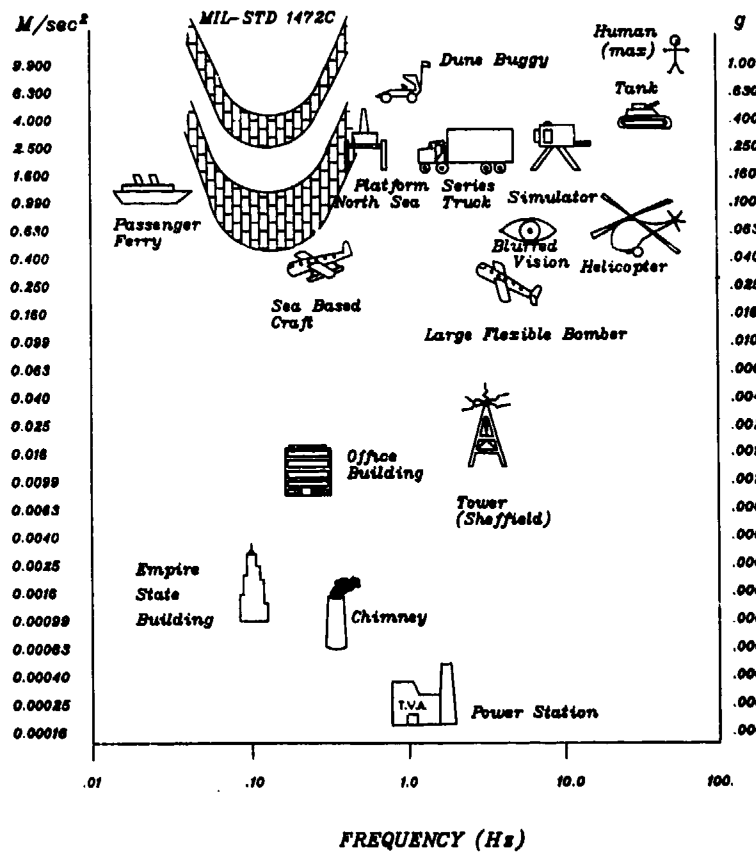

Figure 4. Relative vibration levels of familiar items to MIL-STD 1472C.

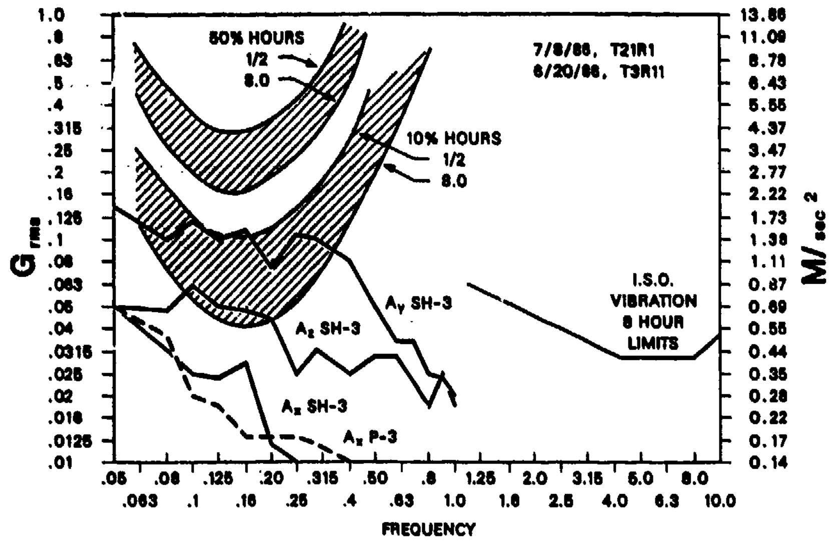

Figure 5. Comparison of X axis of the SH-3 helicopter simulator mean run vs. the X axis of the P-3 aircraft simulator mean run.

It appears from our data that simulator exposure does not significantly interfere with a person's cognitive or simple motor abilities, but some simulators do induce unsteadiness for some time afterwards. These conclusions are based on the use of floor walking and standing tests after the pilots' simulator exposures, rather than the use of more sophisticated apparatus and techniques at specific times after exposure, which might have been more sensitive. Further work needs to be conducted in this area in order to clarify the magnitude of the risk of the pilot population and the duration of effect. It is not known to what extent exposure to aircraft and surface vehicles might occasion similar effects nor how long those effects may last.

The duration of these postural posteffects was not monitored, and it is not known how long they might persist. Similar posteffects have been reported elsewhere [17, 21] following long-term (days) exposure in centrifuges, and are a cause for some concern following space flight [22, 30]. It is well known [68] that related closed loop integrated circuitry exists within the human nervous system for walking, and standing [54] as well as for eye hand coordination employed in tracking and steering [32]. This implies that disturbances manifested by postural instability may also transfer to manual tracking tasks (e.g., driving and flying). Therefore, the extent of postural aftereffects should be carefully researched with far more sensitive and sophisticated tests than we employed (e.g., force platforms) and data should be obtained for an extended period following exposure to the simulator (perhaps hours). Studies of perceptual modifications [84] imply that the adaptation period (viz, posteffects) is proportional to time spent in practice. There are few more consistent findings in the behavioral sciences than that the greater the learning or adaptation, the greater are the aftereffects, and the more resistant they are to extinction. The strength of these aftereffects, whether they will adversely effect the performance of other activities (e.g., driving) and how long effects may persist, are all empirical questions which should be studied in order to answer questions about safety and health influences of simulator usage. Explicit studies should be undertaken to establish reasonable adaptation periods before driving or flying are resumed.

The findings from the MHQ are encouraging since they permit the capture of approximately 10-15% of the reliable variance independent of simulator, age, and flight profile. This implies that simulator sickness is very individual and considerable predictive power (and with it the likelihood of protection) can be obtained by the identification before exposure of those persons who have higher than average likelihoods of sickness. The success of the Navy simulator sickness field manual [35] suggests strongly that it should be possible to identify who will have problems. To this end, it is recommended that the combined MHQ key be published in relevant military service publications in order to inform pilots about their individual risk of simulator sickness. These findings are dealt with more extensively elsewhere [47].

Presently, if effects are noted following exposure to simulators, we would recommend that pilots be limited for some time subsequent to simulator flight (depending on the simulation used). This constraint can be a serious impediment to operational readiness, but may be warranted. It is suggested that operators who experience any unsteadiness and symptoms equivalent to a score greater than 3 (cf. Table 1) should remain of the simulator building until symptoms dissipate and their flying should be restricted for one day.

Problematic Simulators

In connection with this survey, one simulator revealed an unexpectedly high incidence of illness (CH-53E-2F120). The Naval Training Systems Center subsequently conducted an inservice engineering assessment in order to evaluate the optical alignment and other characteristics of the system. This evaluation revealed several equipment features which appeared to contribute to the high incidence [74]. Some of these (distortion, color balance, alignment) are considered to be routine maintenance and "out-of-specification" problems. Others, short of major redesign, may not be easily modified.

The simulators which exhibit the highest incidences of sickness (Tables 5 and 6) are helicopter simulators with CRT infinity optics systems which have six-degrees-of-freedom moving-base systems. These equipment features all appear to interact in the etiology of simulator sickness in ways that are inadequately understood at this time. For example, fixed-wing, fixed-base, dome displays characterize the low incidence systems. These data suggest areas of future research. For example: (1) two of the widest field-of-view simulations (2E7 and 2F112) present very low incidences, and (2) recent quasi-experimental studies have shown sickness in two moving-base simulators to be related to the physical 0.2 Hz motion profile [83]. If the visual problems of the computer-generated imagery (CGI) systems are covaried, would domes be as nauseogenic? Comparison of Tables 5 and 6 provide some support for this view. Converging survey studies should be conducted where it would be possible to compare CRT versus dome displays with the motion base either enabled or disabled. Other combinations should be attempted. Such a program would likely need to combine field studies with laboratory work. Other important questions include determining whether the helicopter syllabus which occasions the motion profiles, the pilot's training, aerodynamic models, or the hydraulic systems responses are nauseogenic?

The Dependent Variable Problem

The above issues await further research. However, before such work can proceed, it will be necessary to improve the way motion sickness severity is scored. In the present study, data were dropped from some pilots who reported excessive symptoms before the simulator hop. A better method for screening the participants must be developed -- perhaps with closer personal contact in the field, and maybe after more comprehensive discussion either through the Commanding Officer, Executive Officer, Training Officer, Flight Surgeon, and Safety Officer. Next, a better scoring method is presently under study and will be developed [53] to permit better diagnosis of the level of sickness and perhaps specific diagnosis of symptom complexes. The slightly different ordering of simulators in Tables 5 versus 6 when a criterion for sickness rather than eyestrain is used suggests that this may be feasible in the future. Additionally, there are three newly developed physiological measures: pallor [70], gastric motility [28, 79], and dark focus [12] which show promise.

It is possible to incorporate Military Standard 1472C [64] in an algorithm for a microprocessor-based biocybernetic instrument that, with further refinement, could become a digital human vestibular system dosimeter and biomechanical motion analyzer. Such a device is likely to have application for many other vehicles.

Summary

Incidence data were available from surveys of simulators at six different Naval/Marine Corps Air Stations. For the survey alone, 1200 exposures were recorded in 10 different flight simulators. Approximately 200 more were recorded when the motion profile studies were conducted. Some of the results are clear-cut:

(1) The simulators which appear to exhibit the highest incidences of sickness are helicopter simulators that employ six-degrees-of-freedom (DOF) moving-base systems which use multi-window CRT's to provide the wide fields of view. But these equipment features are not independent. Therefore, while fixed-wing, fixed-base, dome displays distinguish the low incidence systems, insufficient converging operations are available in the technical data base to establish which of these factors is the determiner of the sickness rates.

(2) There was almost no vomiting or retching (2/1186), but some severe nausea and drowsiness. Such individuals may be considered to be at risk to themselves and to others if they drive themselves home or return to demanding activities at work. While simulator exposure in general did not produce gross changes in a person's cognitive or simple motor abilities, some simulators do induce unsteadiness afterwards. We suggest in regular simulator operations in the future, pilots should be indoctrinated to identify whatever postural and symptom changes are occasioned by their simulator exposures. Pilots exhibiting identifiable unsteadiness and symptoms greater than a criterion value should remain in the simulator building until symptoms dissipate and perhaps restrict their flying for one day. These data suggest areas of future research.

CONCLUSION

It may be stating the obvious to say that the ultimate aim of science is prediction and control. In the context of simulator sickness we believe that perhaps as much as 50% of the incidence is either predictable or controllable. These known relations are:

- A particular motion history, measurable with the five questions of the Orlando Motion History Questionnaire can account for 10-15% of the incidence. Adding pilot rank can improve the strength of this relationship.
- Eyestrain is a significant portion of the reported incidence data and much of this we believe is controllable by proper display arrangement or design (e.g., domes).
- Motion sickness symptomatology after a flight should probably be used by the pilot to restrict his activities that day and perhaps the next.
- Simulator usage, alignment and maintenance are probably major contributing factors to sickness incidence. Some of the rules which govern this are known and should be followed.
- Postural equilibrium after flight should perhaps be used as a sign to limit activities, particularly if the individual also has other motion sickness or eyestrain symptoms.
- If the simulator is a moving-base device, it would be best to avoid linear oscillations in the range of 0.2Hz.
- Different mixtures of symptomatology are likely to be predictive of the origins of the problem in a simulator.

But much of the problem still remains, and while a portion of the simulator sickness prediction question is likely to be due to error, we believe that significant improvements can be made to our understanding of the mechanisms which govern this malady. It should be pointed out that even if the first 50% is presently available, it is likely to be the "easy" 50%.

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APPENDIX A

Serial No. ____________

POSTHOP SYMPTOM CHECKLIST

Instructions: Please fill this out BEFORE you go into the simulator. Circle below if any symptoms apply to you right now. (After your simulator exposure, you will be asked these questions again.)

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.	Eyestrain	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	No	Yes		
18.	Faintness	No	Yes		
19.	Aware of breathing	No	Yes		
20.	**Stomach awareness	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				

* Visual illusion of movement or false sensations similar to aircraft dynamics, when not in the simulator or the aircraft.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

APPENDIX B

MOTION HISTORY QUESTIONNAIRE FOR SIMULATOR SICKNESS

1. Have you ever been motion sick other than aboard ships or in aircraft?

   No_0_ Yes_1_

2. Listed below are a number of situations in which some people have reported motion sickness symptoms. In the space provided, check any SYMPTOM(S) you may have experienced at any time, past or present.

SITUATIONS	SYMPTOMS												
	VOMITED	NAUSEA	STOMACH AWARENESS*	INCREASED SALIVATION	DIZZINESS	DROWSINESS	SWEATING	PALLOR	VERTIGO	AWARENESS OF BREATHING	HEADACHE	OTHER SYMPTOMS	NONE
AIRCRAFT													
FLIGHT SIMULATOR													
ROLLER COASTER													
MERRY-GO-ROUND													
OTHER CARNIVAL DEVICES													
AUTOMOBILES													
LONG TRAIN OR BUS TRIPS													
SWINGS													
HAMMOCKS													
GYMNASTIC APPARATUS													
ROLLER/ICE SKATING													
ELEVATORS													
CINERAMA OR WIDE-SCREEN MOVIES													
MOTORCYCLES													

* Stomach Awareness refers to a feeling of discomfort that is preliminary to nausea.

Any symptom checked: 1   Else: 0
Any symptom checked by Aircraft or Flight Simulator: 1   Else: 0
Symptom "Stomach Awareness" checked by Simulator: 1   Else 0
Any symptom checked by Roller Coaster, Merry-Go-Round, or Other Carnival Devices: 1   Else: 0

DISCUSSION

PRICE: How do you define eye strain?

KENNEDY: The definition is strictly operational; subjects, pilots in this case, report eye strain or difficulty focusing and so forth.

PRICE: Could you give me an example of a subjective description of eye strain?

KENNEDY: It is just a check in the box labeled "eye strain." This is not measured in any way.

LANDOLT: You mentioned visual flashbacks. How important are visual flashbacks in the scheme of things? Are they a cause for worry? How frequent are they? What is the genesis? What are their characteristics?

KENNEDY: Of 1200 cases in our data base, we have 20 reports of flashback that we consider rich enough to deserve complete description. There are perhaps 200 responses that might be considered flashbacks, but there is not enough information within the person's self-report form for us to say that those 200 are all good cases. So in terms of a base rate, we would suggest that somewhere between 20 and 200, and more like 50, of the 1200 are likely to have identifiable flashback type reports. Those may have occurred with one hour and as long as 24 hours after the simulator exposure. The incidence is low in our total data base. As far as what they are or what causes them, I think that the best I can do is give you a theoretical answer. They are perhaps related to state-dependent learning. They appear to occur in perceptually impoverished situations and in situations similar to the simulator experience.

TECHNOLOGY INVOLVED IN THE SIMULATION OF MOTION CUES: THE CURRENT TREND

by
H.A. Mooij
National Aerospace Laboratory NLR
Amsterdam, The Netherlands

SUMMARY

The subject of motion cue generation is a topic that requires serious attention from all involved in the design, development and manufacture of flight simulators. The enhanced realism in the depiction of terrain, sky, and other aircraft available in current visual systems has been associated with an increasing number of instances of simulator sickness. This form of sickness is the constellation of symptoms which may be experienced by pilots as a result of flying a simulator.

As one of the introductory papers of the AGARD Aerospace Medical Symposium on "Motion cues in flight simulation and simulator induced sickness" this paper presents observations concerning the current trend in visual and motion systems.

After an introduction of basic cuing methodology in flight simulation, the overview concentrates on developments in image generation, image display, platform motion cue generation and motion hardware mechanisms. The paper concludes with some observations concerning the importance of maintenance and calibration of flight simulator installations.

1. INTRODUCTION

In recent years there has been an increase in the number of reports of simulator sickness, although the extent of the problem is still not clearly defined.

If sickness occurs in the simulator, but not in the real world, there is evidence of a bad simulation.

The implications of simulator sickness are:
- Compromised training
- Decreased simulator use
- Simulator aftereffects.

The problems are particularly serious among the more experienced aviators as a result of overt "sensory conflict". Less obvious but nonetheless serious is the possibility of negative transfer of training in the less experienced aviator (compromised training).

A study published by the Naval Training Systems Center in 1986, reference 1, provides possibly the most comprehensive background information on the simulator sickness problem. It discusses its parameters, implications in training and research applications and theoretical foundations. It also lists simulator design and procedural characteristics with potential for influencing pilot sickness. It is stated that the simulator sickness etiology is as yet not clearly understood largely because of the interacting effects which can produce uneasiness for specific combinations of independent variables.

A topic that requires serious attention in the design, development and manufacture of flight simulators is the aspect of motion cue generation. Motion cues are provided through the visual display of out-of-the-cockpit scenery and platform motion.

Motion cues are clearly related to the phenomenon of simulator sickness; in all documented cases of simulator sickness, a visual display of vehicle dynamics has been involved (Ref. 2).

The enhanced realism in the depiction of the outside visual scene combined with platform motion in flight simulation, or the perceived motion solely acquired from visual systems with enhanced realism in fixed-base simulators create problems in the field of simulator induced sickness.

A necessary factor in relation to the occurrence of simulator sickness is a large Field-Of-View (FOV) of the outside visual scene (FOV in excess of 60 deg in the horizontal plane).

In this paper some important physical parameters that characterise advanced visual and motion systems are discussed. The paper is limited to trends in Visual Systems and Motion Systems, being the most dominant motion cue generating systems in simulators for flight training. Therefore no attention is given here to control loading systems, cockpit instrument systems and sound systems, even though these three elements also produce sensations related to aircraft motion.

A flow diagram representing the operation of a flight simulator is depicted in figure 1.1. All subsystems, including the computational system, contribute to the important control loop lags and delays which play a role in the perceptual fidelity of the simulator. Reference 1 introduces clearly the role of these lags and delays as sickness-contributors. One interesting observation is that the pilot, as a result of such lags and delays, may adopt a control behaviour that leads to pilot-induced oscillations. Such oscillations may contribute to sickness-onset (due to their sinusoidal character). This type of oscillations may also be a result of incorrect damping in control loading systems. In general, proper modelling and displaying through a control loader system of all factors related to control "feel" is of direct relevance to simulator sickness.

2. BASIC CUING METHODOLOGY

The visual display of out-of-the cockpit scenery provides visually induced motion cues.
The degree to which the scenery generated and displayed by the visual system must reflect real-world scenery is highly task-dependent.

Platform motion in flight simulators is directed at providing cues especially in the area of:
- turbulence disturbances
- vibrations
- onset cues in support of visual sensations (high frequency platform motion)
- long term accelerations (very low-frequency platform motion: tilt).

Motion-detection capabilities

A brief summary is presented below of the role played by the principal sensory mechanisms in motion detection in relation to flight simulation. AGARD-AR-159 (Ref. 3) was the primary source for the overview presented here.

- SEMICIRCULAR CANALS together with the otoliths (to be mentioned below) called "the vestibular organ", form the balance mechanism located in the inner ear. In total, two times three roughly orthogonal canals exist. Their function is analogous to that of rate gyros.
  At frequencies below 0.1 Hz, however, their indications are close to angular accelerations. These low frequencies are normally sustained only in man-made vehicles such as airplanes and here the semicircular canal signals can be misleading.

- OTOLITHS play the role of sensors of specific force; one pair is oriented in the horizontal plane with the head in its normal position, the other pair is oriented primarily in the vertical plane. The otoliths are incapable of distinguishing between gravitational acceleration and linear acceleration with respect to inertial space.

- TACTILE OR SOMATOSENSORY RECEPTORS permit detection of a change of orientation (of the body) or a change of force on the body. An important characteristic with respect to simulation is that the output of these receptors tends to return to a reference level during sustained uniform pressure application.

- PROPRIOCEPTIVE AND KINESTHETIC SENSES signal the relative positions of parts of the body as well as their movements. All proprioceptive and kinesthetic senses together permit subjects to perceive body accelerations based on the biomechanical reactions of the head and limbs by measuring either the force required to keep them stationary or the resulting motions.

- THE EYES make it possible to create so-called self-motion sensations by uniform motion of a wide visual field (visually induced motion). This phenomenon is called "vection" and is based primarily on the motion detection capabilities of the peripheral retina. (The foveal area of the retina is the high-acuity central part of the retina associated with image scanning and recognition and thus the cognitive sense of self-motion).

Cuing methodology

Motion cuing can be realized through the stimulation of Vestibular organs, Tactile receptors, Proprioceptive and Kinesthetic senses and the Eyes. When a mechanization of the training simulator is selected without a motion system, as is presently the case for a certain class of fighter aircraft simulators of the USAF (Ref. 4), stimulation of the tactile, proprioceptive and kinesthetic senses is used to generate acceleration cues. Devices such as a g-seat, a g-suit and stick-shakers are used in those cases.

In the following attention will be focussed on motion cuing through stimulation of the Eyes and the Vestibular organ.

Wide-field visually induced motion.

The phenomenon of "vection" mentioned above based on uniform motion of a visual field becomes effective when the Field-Of-View (FOV) is larger than 60 deg and most effective with a FOV of 180 deg. Both linear vection and circular vection occurs.

The principal characteristics related to the application of visually induced motion in flight simulation are:

<u>characteristics of the visual field</u>

High contrast borders over at least 30% of the FOV, proper brightness and uniform velocity are all important in increasing the effectiveness of visually induced motion.

<u>background versus foreground</u>

The moving visual field should be presented as background, (preferably distant information). Fixed objects in the background, such as blemishes on the projection screen, can inhibit visually induced motion.

<u>linear vection</u>

Linear translation of an aircraft through a wide visual field also leads to visually induced motion effects. High-speed movement appears to saturate the perception of velocity.

<u>circular vection</u>

Visually induced motion in yaw is quite effective over the range of angular velocities up to 60 deg/sec (at yaw rates higher than 60 deg/sec the vection becomes "unsaturated"; the perception of self-rotation is less than that of field rotation). For visually induced motion about the pitch or roll axis during level flight, the effect is normally a paradoxical one of pitch or roll rate, without a corresponding continuous change in pitch or roll angles. If the roll or pitch is performed about a vertically oriented velocity vector, however, it will normally produce continuing and nonparadoxical visually induced rotation sensations.

Sensations due to Platform Motion.

The semicircular canals function as rate gyros over a limited frequency range. It is necessary to "wash-out" platform motion at very low frequencies, so that a measure of motion cues can be achieved while the actual space in which the platform moves (rotates) is limited. The adequacy of wash-out algorithms depends on an appropriate appreciation of the effective thresholds of the semicircular canals.

The otoliths give rapid response when stimulated by linear accelerations or sudden tilt. The perception of these motions show a considerable amount of dynamic lag (unless it is confirmed by some other cue, such as semicircular canal activity or vision).

The relationship of perceived to actual linear velocity can be modelled as a simple third-order system. At extremely low frequencies, below 0.1 Hz, adaptation effects come into play, and the magnitude of the perceived motion becomes less than that of the applied motion. Since the otholiths are incapable of distinguishing between linear acceleration and orientation with respect to the vertical, it is common practice to substitute a steady pitch or roll attitude, for sustained linear acceleration. It is, however, very important that the rate of pitch and roll utilized in performing the "g-tilt" manoeuvre be such as to avoid the generation of inadvertent (false) motion cues.

If one is restricted to "g-tilt" manoeuvres that rotate the cockpit at sub-threshold rates the time taken for the acceleration to be washed out is excessively long and leads to intolerable excursions of the motion platform. Compromises are generally applied by rolling or pitching at slightly super-threshold rates to tilt angles less than ideally required and relying on the influence of visual cues to minimize the importance of the discrepancy.

Interaction between sensations due to platform motion and wide-field visual stimulation.

- The principal limitation on exclusive reliance on visually induced motion in flight simulation is the situation of rapid changes in linear or angular velocity. When sudden changes in visual field velocity are not accompanied by confirming platform motion, there can occur a disturbing and often lengthy time delay in the development of self-motion.

- In the absence of confirming motion cues, such as might be generated by platform motion, there are constraints on the magnitude of visually induced motion effects as well as on onset times.

- Vestibular cues (semicircular canals and otoliths) are responses to accelerations. They are important when early detection of aircraft acceleration is required to avoid instability (of the pilot/aircraft system) or to react to critical failures. Through vestibular cues the pilot can perceive aircraft motion approximately 150 msec earlier than through vision.

- Visual cues are important for steady, slowly changing, velocity perception. Moving visual scenes are especially appropriate for low frequency motion simulation with quasi-steady-state velocity segments.

3. THE CUE CONFLICT THEORY

It is extremely doubtful that there is a single causal factor for simulator sickness, anymore than there is for motion sickness in general (Ref. 5).

Symptoms of simulator sickness include: disorientation, dizziness nausea, emesis, spinning sensations, motor dyskinesia, flashbacks, visual dysfunction, burping, confusion and drowsiness, among others. A number of these symptoms are also present occasionally in motion sickness experiences. For these reasons the SENSORY CUE CONFLICT THEORY (also recognized as the SENSORY REARRANGEMENT THEORY) of motion sickness has been generally accepted as a working model for simulator sickness (Ref. 2). The model postulates :
"a referencing function in which motion information signalled by the eyes, vestibular organ, tactile receptors or proprioceptive and kinestetic senses may be in conflict with these inputs' "expected" values based on a neural store which reflects past experience, or with how the system's circuitry is wired."

A conceptualization of the sensory conflict theory of motion sickness is shown in figure 3.1 (Ref.6).

4. VISUAL SYSTEMS

In all documented cases of simulator sickness a visual display of the external visual scene has been involved. In addition the occurrence of the sickness phenomenon is strongly related to systems with a FOV in excess of about 60 deg in the horizontal plane. Nearly all visuals of advanced training simulators exceed this number.

Out-of-the-window visual simulation is a formidable challenge because of the fantastic performance capabilities of the human eye and the inadequate understanding of how a human uses the visual information in a simulator. Reference 7 which has been produced by AGARD FMP Working Group-10 thoroughly identifies and defines physical parameters that characterise the simulator visual system and determines its fidelity.

Visual systems can be broken down in two subsystems:

- Image generation system.
- Image display system.

The image generation and display systems are basically independent and normally can be interchanged between manufacturers.

The trend towards mission simulators dictates the incorporation in the simulator of the capability for demanding tasks such as low-level navigation and air-to-ground attack for fixed wing aircraft and Nap-Of-the-Earth (NOE) operations and hover for helicopters.

This demands a large FOV in combination with very high resolution.

The trend in image generation for training systems is that Computer Generated Imagery (CGI) techniques will be used almost exclusively. The main thrust in the development of image display systems is less clear, though it is probably the most important element in the visual system.

One prospect for presenting high-resolution, large field-of-view scenes is the laser projector. One other prospect is the head- or head/ eye coupled area-of-interest approach.
The latter concept combines cost-effective image generation, because of balanced detail over the total field-of-view and at the same time potentially solves the "field-of-view versus resolution dilemma". Its application in the training field may be expected in the near future.

Image generation

Computer Generated Imagery or CGI systems have progressed enormously recently in the level of detail offered and the quality of texture which is an important aspect related to realistic depth perception.
The drivers behind the recent improvements in image generation have been the military with their requirements for mission simulators for low level flight and tank warfare as well as the airline industry with their requirements related to maximized usage of flight simulators in all aspects of the training and proficiency checking of their flight crews. The description of contemporary "daylight/dusk/night" visual systems used in the airline industry (Federal Aviation Administration, Phase III) is:
"A visual system capable of producing as a minimum, full color presentations, scene content comparable in detail to that produced by 4000 edges or 1000 surfaces for daylight and 4000 light points for night and dusk scenes, 6-foot lamberts of light at the pilot's eye (highlight brightness), 3-arc minutes resolution for the field of view at the pilot's eye, and a display which is free of apparent quantisation and other distracting visual effects while the simulator is in motion".

Future trends indicate that with increasing use of VLSI (Very Large Scale Integration) and eventually VHSIC (Very High Speed Integrated Circuits) technology, not only will generation capability continue to increase, but cost will tend to decrease.

CGI will make possible the generation of full-field-of view, high resolution imagery for fighter/attack type aircraft simulators.

A list of a number of state-of-the-art image generating systems is presented in figure 4.1.

Image display

Image displays in training simulators can be subdivided as follows:

1 Large azimuth, limited elevation field-of-view

1.a Infinity optics:
Multi-window, direct-view of CRT's plus infinity optics.

1.b Projection screen
Multi-projector system using a "back-projection-screen" and a concave mirror.

2 Very large field-of-view

2.a Dome projection system

2.a.1 Target tracked: air-to-air combat simulators and certain air-to-ground simulators

2.a.2 Head/eye tracked: Area-Of-Interest (AOI) approach

2.b Helmet mounted system
Head/eye tracked: Area-Of-Interest (AOI) approach.

Of the first group it may be of interest to indicate how the "projection screen" (1.b), the most modern of the two, works.
In these systems a field of view of 150 deg (or 200 deg) in azimuth and 40 deg (in elevation) is produced using three, four or five CRT projectors, each with red, green and blue tubes, driven from three, four or five CGI channels, and a back-projection screen and a concave mirror. Figure 4.2 depicts the principle.
Of the second group attention is directed towards the AOI approach (2.a.2 and 2.b). With regard to the target tracked dome projection approach (2.a.1) one should be aware of a novel form of visual and motion system integration for a simulator for fighter R and D work, reference 8. The motion system and the cockpit are housed within a fixed dome and associated projection equipment (contemporary devices use motion platforms carrying a dome and associated projection equipment).

The Area-Of-Interest (AOI) approach employs head/eye slaving and is tailored to match the psychophysical performance of the human visual system.
Its principle is based on generating and projecting the highest level of detail and resolution only in an area of interest coinciding with head position and the orientation of the eyes. This means that high resolution imagery is only required over the very small foveal field-of-view (typical 20 degrees).

At present the development of AOI systems is an area of great activity.
As an example of the AOI approach employed in a dome projection system, the ESPRIT (Eye-Slaved Projected Raster Inset) system of Singer Link-Miles can be mentioned (Ref. 9). Separate projectors for the foveal high resolution inset image and the peripheral low resolution ("background") image are used. An eye

slaving system is used to drive the foveal projector and to command the CGI system to generate the image for the instantaneous eye pointing direction.

A configuration with a foveal projector giving 1.5 arc minutes per pixel resolution (equivalent to 5 arc minutes per line pair) and three background projectors covering 270 deg in azimuth and 130 deg in elevation is under development. Figure 4.3 depicts the ESPRIT system.

An example of the AOI approach using a helmet mounted system is the binocular CAE Fiber-Optic Helmet Mounted Disply (FOHMD) (Ref. 10).

This image display system exists of lightvalve projectors, relay-combining optics, fiber-optic cables, helmet, helmet display and the helmet position and orientation sensing system.

The display for each eye has both a background and a high-resolution inset channel. A four-channel CGI system is used. True stereoscopic viewing is possible.

A sketch of the helmet plus associated components and the displayed field-of-view is given in figure 4.4.

The pilot's FOV in a modern high performance single seat fighter/ attack aircraft is approximately 300 deg azimuth and a nominally unobstructed upper FOV. For VTOL fighters or (attack) helicopters an additional downward view of 40 to 50 deg is of importance.

The required resolution of 2 arc minutes for effective (mission) simulation is obtainable with the AOI devices described above.

As is indicated above, high-quality displays (high-resolution and almost unlimited fields of view) are now being readied for use in research and development simulators. Application in the training field may be expected in the near future.

A list of a number of state-of-the-art display systems is given in figure 4.5.

5. MOTION SYSTEMS

It has been demonstrated in several studies that proper design of certain aspects of the platform motion system is quite critical to the avoidance of simulator sickness.

Motion systems are widely used as part of flight simulator installations in the military and the civil training fields.

The complete motion system consists of:

- motion cue generation
- motion drive logic
- motion hardware mechanism

The cue generation and drive logic are embodied in software. Below a closer look at cue generation and hardware mechanism will be taken because they determine the motion cue characteristics.

Motion cue generation

An essential transformation in relating a motion system's displacement, velocity, and acceleration capabilities to its cue-producing potential in various simulated flight situations is a consideration of the technique used to attenuate the motions of flight to the excursion envelope of the simulator. The commonly used technique is direct attenuation and linear high-pass filtering.

The characteristic frequency of each filter is directly related to the maximum amplitude of the lower frequency accelerations anticipated in the flight to be simulated, the excursion envelope of the motion system, and the degree to which direct attenuation is acceptable or neccessary.

As a result of the constraints just mentioned the characteristic frequencies of the "wash-out" filters quite often coincide with the frequency range for manoeuvres. This leads to phase advances in the motion cue.

The "g-tilt" manoeuvre as discussed in Chapter 2 is also generated within the cue generating algorithm. The limits of application of "g-tilt" should be studied through further research; a potential conflict with proper simulation of angular cues does exist.

A further role for the cue generation algorithms is to apply "limit logic" to keep the motion mechanism off its stops (and thus avoiding the activation of the ultimate hardware limit switches) and to allow a smooth recovery from any saturation of demands. The "limit logic" should act without undue disturbance to the pilot. As he continues to fly the simulator the motion should recover back to normal operation.

There is considerable opportunity for the improvement of motion cue generation; extensive research is needed in this area.

Recent treatises on flight simulator motion cue generation with emphasis on transport aircraft are given in references 11, 12 and 13.

Motion hardware mechanism

AGARD FMP Working Group-07 reported in 1979, reference 14, the first substantive attempt to measure performance of the multiple degree-of-freedom motion systems. The reference specifies a uniform method of measuring and reporting motion system performance characteristics.

The most obvious physical characteristics of the hardware are the system excursion limits. They are defined as the extremes for displacement, velocity and acceleration which can be reached during controlled single-degree-of-freedom operation.

It is anticipated that system excursion limits will not be increased and therefore no significant increase in motion cue magnitude or duration will be realised.

The motion cue capability obtainable with a system is probably best represented by two characteristics called the "operational excursion limits" (for sinusoidal input signals) and the "dynamic threshold".

Operational excursion limits:

These limits determine the motion cue magnitude the platform can provide without generatir. unacceptable acceleration noise. The operational (and the system) excursion limits can be displ yed in a diagram of velocity versus frequency for each degree of freedom; see figure 5.1.

Dynamic threshold

The dynamic threshold indicates how quickly the motion cue can be provided. For hydrostatic bearings and correct lead compensation, the dynamic threshold can be kept below 50 msec for acceleration step inputs larger than 0.02 g, see figure 5.2.

The timing of the various kinds of motion cues provided by the total system is of great importance. The timing of an acceleration cue is especially important to the pilot. It should be close to that experienced in real flight; the trend in improvements in computer update rates has a positive effect on the reduction of motion cue response time.

As one example of an advanced 6 degrees-of-freedom motion system figure 5.3 presents the specification of a second generation hydrostatic motion system produced by Hydraudyne (Boxtel, The Netherlands) for the Nation.l Aerospace Laboratory NLR. The specified accelerations and frequency response are well in excess of the capabilities of contemporary systems. Figure 5.4 presents the mechanical construction with six linear hydraulic servomotors.

6. QUALITY CONTROL

High quality maintenance/calibration of hardware and software is needed to safeguard continued operation of the simulator at the fidelity level at the time of its delivery.
A number of observed instances of simulator sickness had to do with residual digital program errors. Other instances could have been linked to not-properly calibrated hardware elements.

In the civil world one can observe that the introduction of simulators with powerful motion cuing capability (large field-of-view visual systems, 6 degree-of-freedom motion platforms) is paralleled by the issuance of documents for the approval of their use in training and checking of proficiency (Refs. 15, 16 and 17).
It is noted that while previously only qualitative checks were performed by the regulatory authorities, now a clear trend towards a continuous checking of the devices against the data used in the initial approval phase can be distinguished.
To give an impression about the severity of the recurrent evaluation scheme of simulators as required in the USA, it is noted that according to reference 15 they are evaluated every 4 months. In each recurring evaluation 1/3 of the performance tests in the Approval Test Guide (ATG) will be checked so that each year the complete ATG will be tested.

It is not clear what the present situation is with regard to requirements for recurrent evaluation within the military (simulator) training community. No documents (e.g. military specifications) concerning initial and continued approval could be located.

It is not known if the introduction of the systems based on the area-of-interest approach does not require a higher level of education and training of maintenance personnel than the level required for contemporary systems.

Inappropriate use of the powerful Vision and Platform Motion cuing devices by the persons charged with the task of running the training sessions can have devastating effects on the well being of the pilot. It must be clear that proper training of these persons is of utmost importance.

7. CONCLUDING OBSERVATIONS

Area-of-interest image displays show promise to be introduced alongside the type of systems presently in use. They may be of the dome projection or the helmet-mounted type. Head/eye tracking devices will be applied to expanded field-of-view visual systems and to insert high resolution detail into the area being viewed by the pilot.

Research should be directed to platform motion cue generation philosophy and embedded limit logic of motion bases in order to improve the art of flight simulation.

Quality control with respect to continued operation of flight simulators (maintenance/calibration) is essential with regard to simulator fidelity; a relationship with the occurence of simulator sickness exists.

Proper training of the persons who are in charge of the powerful Vision and Platform Motion cuing devices is of utmost importance.

May I conclude to say that the views I have expressed are my own, and do not necessarily reflect the views of the Flight Mechanics Panel of AGARD or the views of my employer, the National Aerospace Laboratory, NLR.

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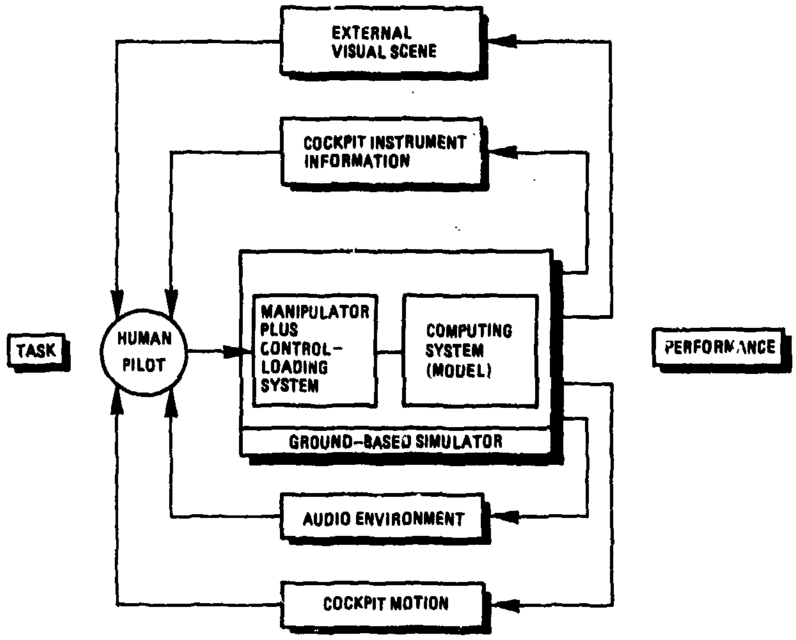

Fig. 1-1 Flow diagram of the pilot/flight simulator control loop

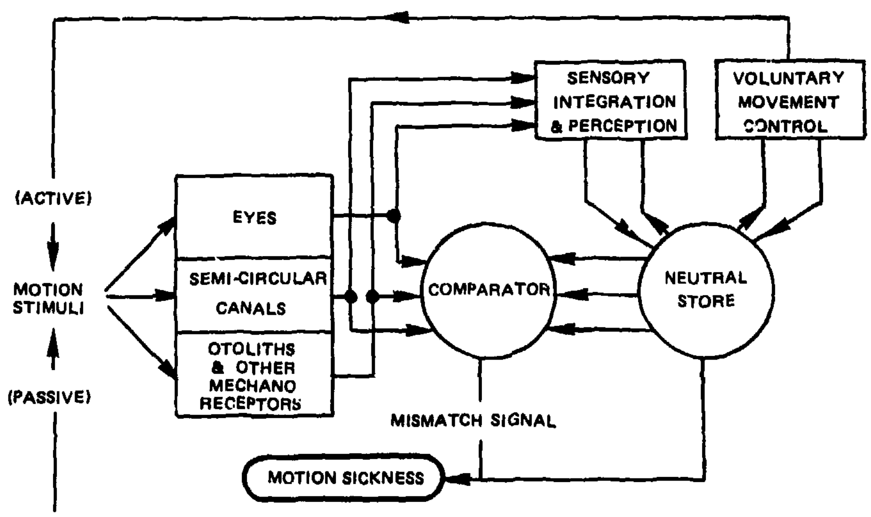

Fig. 3-1 Etiology of motion sickness

Company	Designation	Surfaces /Channel	No. of channels	Lightpoints /Channel	Stroke Raster	Resolution	Update Rate	Texture	Remarks:
General Electric	CompuSceneIV		8		S/R			full	
McDonnell Douglas Company	Vital IV								1978 dusk/night lightpoints, colored surfaces
	Vital V								1982 dusk/night Phase II FAA
	Vital VI								1982 day/dusk/night Phase III FAA
	Vital VII	500	8	1000	R	1,000,000 pixels	50	full	(1988)
Rediffusion (plus Evans and Sutherland)	SP1 (T)	224		4800	S/R		30	2D	texture optional
	SP2 (T)				S/R			2D	ditto dusk/night Phase II FAA
	SP3 (T)				S/R			2D	ditto day/dusk/night Phase III FAA
	SPX-100	250	3	5000	S/R	660,000	30	full	dusk/night
	-500	500	8	5000	S/R	720,000	30	full	dusk/night
	-500	500	8	1000	S/R	720,000	60	full	day
	CT 6	7500	8	20,000	S/R			full	light points traded off against surfaces
Singer Link-Miles	Image II(T)	250		4800	S/R	3 arcmin	30	2D	texture optional, dusk/night Phase II FAA
	Image III(T)	250		4800	S/R	3 arcmin	50	2D	dusk/night Phase III FAA
	Image III(T)	250		1000	S/R	,,	50	2D	day/dusk/night Phase III FAA
	Image IV	512			S/R		50	full	
	ATAC DIG							full	
	MOD DIG							full	
Sogitec	GI 10000	2500	4			1,000,000 pixels		full	
Thomson	VISA 4	5000	6		S/R	1,000,000	60	full	

Fig. 4-1 Examples of state-of-the-art Image Generating Systems

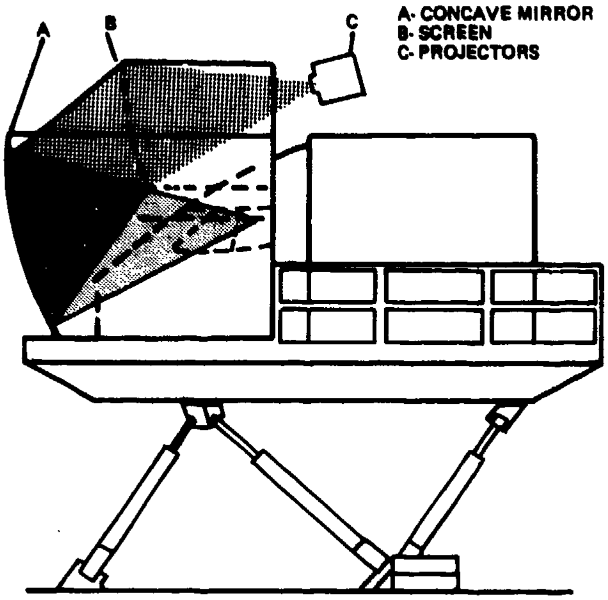

Fig. 4-2 Projection screen image display system

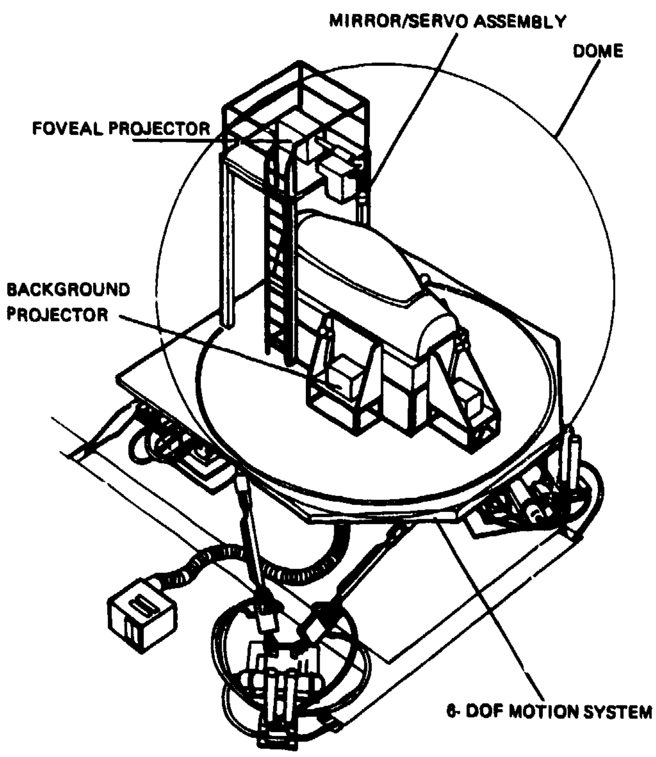

Fig. 4-3 Dome projection image display system (ESPRIT)

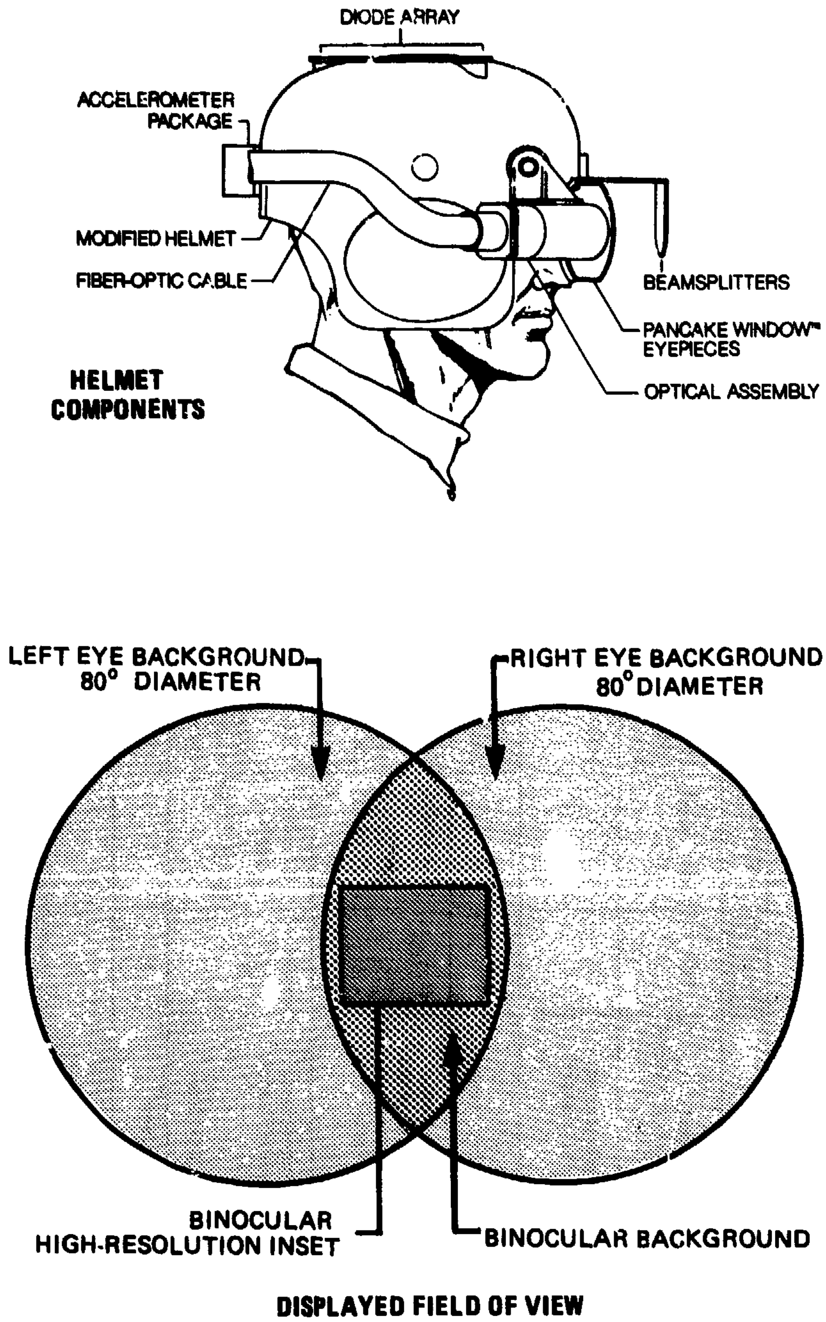

Fig. 4 Helmet mounted image display system (CAE-FOHMD)

Company	Designation	Type	No. of Channels	Luminance	FOV (degrees)	Resolution	Remarks
CAE	FOHMD	helmet, direct vision	2	100 cd/m^2	135x64 55x30 high res insert	4.6 arcmin/line 1.4 arcmin/line	developmental; see Chapter 4.
McDonnell Douglas Company (MDC)	Multiview	panoramic collimated	4		180x40		
MDC + Pacific Opt.		AOI 20ft Dome	2		instant 120x90 insert 40x30		AOI insert head-slaved, total coverage 300x180 possible
Rediffusion	WIDE SUPERWIDE WIDE II	panoramic collimated ditto ditto	3 3 5	20 cd/m^2 30 cd/m^2 >40 cd/m^2	150x40 150x40 200x40		Vertical view +15 deg, -25 deg for helicopters
Singer Link-Miles	AWARDS AWARDS 200 ESPRIT	panoramic collimated ditto AOI 24ft Dome	3 5	27 cd/m^2 peak 10-12 cd/m^2	150x40 200x40 270x130 insert 18,dia	 11 arcmin 2 arcmin	developmental; see Chapter 4.
Thomson	PHEBUS	Screen	5		150Hx100V 50 V	3 arcmin	100 deg V at edges 50 deg V in centre of field.

Fig. 4-5 Examples of state-of-art Image Display Systems

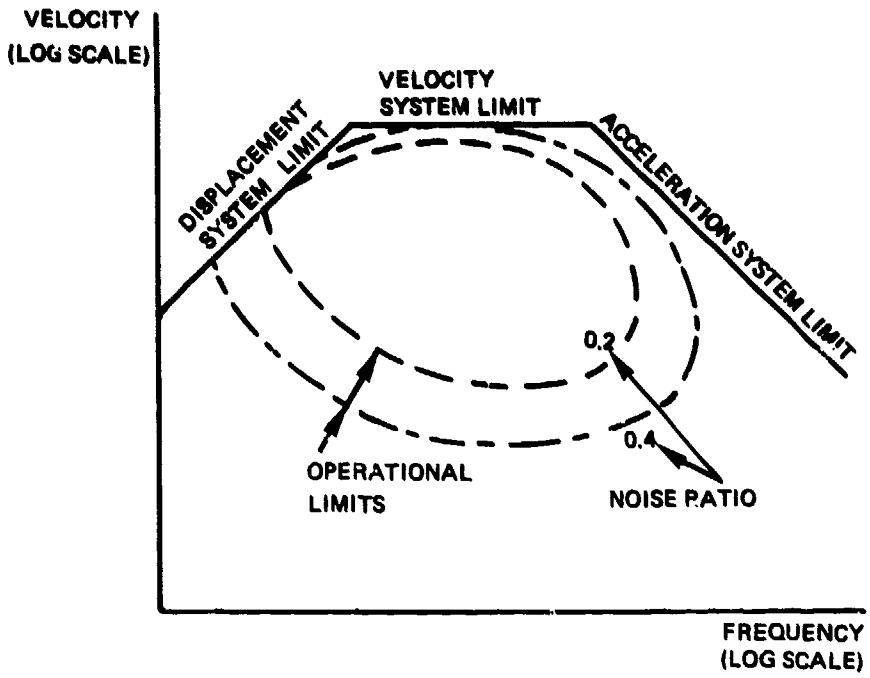

Fig. 5-1 Excursion and operational limits for sinusoidal input signals

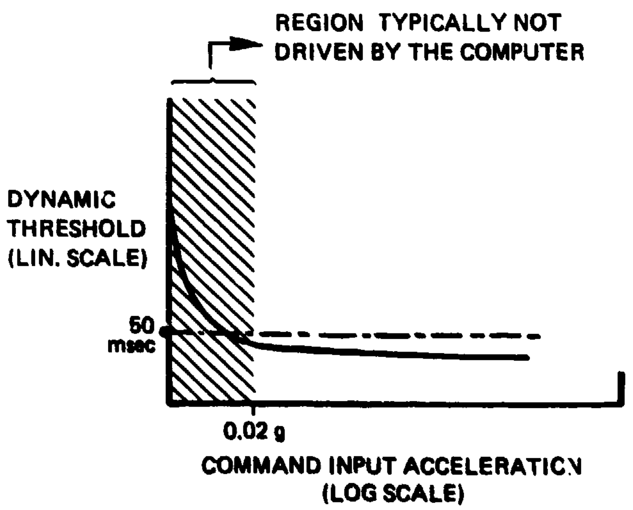

Fig. 5-2 Dynamic threshold

System limits

	Displacement			Velocity			Acceleration		
	pos	neg		pos	neg		pos	neg	
longitudinal	1.72	1.34	(m)	.8	.8	(m/s)	8	8	(m/s^2)
lateral	1.39	1.39	(m)	.8	.8	(m/s)	8	8	(m/s^2)
vertical	1.01	1.14	(m)	.8	.8	(m/s)	10	10	(m/s^2)
roll	30.5	30.5	(deg)	30.	30.	(deg/s)	200	200	(deg/s^2)
pitch	28.7	28.9	(deg)	30.	30.	(deg/s)	200	200	(deg/s^2)
yaw	41.4	41.4	(deg)	30.	30.	(deg/s)	150	150	(deg/s^2)

Frequency response

frequency (Hz)	max. phase angle (deg)	amplitude ratio
$\leq$ 1 Hz	2.0	1.0 ± 0.1
$\leq$ 4 Hz	45	between 0.7 and 1.0

*) with 5000 kg useful load

Fig. 5-3 Specification for the system limits and frequency response of the 2nd generation hydrostatic motion system at NLR

Fig. 5-4 Mechanical construction of the 2nd generation hydrostatic motion system of NLR

DISCUSSION

GUEDRY: Did you say that an eye-tracking system would be used to enhance the visual image? If so, what eye-tracking system would be used?

MOOIJ: The answer to the first part of the question is yes. I think eye-tracking will be used to make a clearer image in the line of sight. These particular devices require high resolution in a 20° circular field; therefore we need a number of image-generation channels. The technology of eye-tracking is still in a state of flux. There is experimentation with methods like infrared reflection upon the eyeball, but there are always training and calibrating problems involved. I assume that the eye-tracking problem will be solved. The helmet-mounted display shown on the slide, at the moment, is only head-tracked. This means that the high resolution part is set in the center of the right side of the helmet and not of the eyes; and that may be a big problem - I don't know - the particular system is just coming on line at NASA Ames, but the aim is to make it eye-slaved. The other one - the Singer-Link system on the platform shown on the slide - they claim that it is a fully eye-slaved system or combination eye/head-slaved system.

ELLIS: I'd like to ask another question along this same line. I think the idea of eye-track is at least 8 years old, maybe 10, and the typical problems with it have been the quality of eye-track. The eye-tracking techniques I've seen are probably not sufficient for particular tasks. I'm wondering if you have seen the performance of some of these systems, especially the one that actually, as you say, claimed to be eye-tracked and whether it seems to be working adequately.

MOOIJ: This is difficult to answer from my own knowledge. I am not acquainted with these systems. I took them from the literature because these are important trends at the moment. There are also indications that image generation, the computer part, will be growing so fast that in two or three years the high resolution solution (1.5 arc minutes) over the whole 180° will be available for the helmet-mount system.

ELLIS: I asked because I have heard very similar discussion with much the same impact. I've always been very skeptical as to how well the eye-track systems work because I've used two or three different systems myself, and I know they're highly volatile. In fact, I have come to believe that the head-track system would be better because of the greater stability of the image.

MOOIJ: To begin with, all those systems are head/eye-slaved so we have the head-track system anyway. The performance I've heard about in the Canadian system is good with the head-track system.

ELLIS: Yes, head-track works better.

MAGEE: I worry about head-slaved devices and eye-track devices because it seems that evolution has provided a tight coupling between head and eye movement control, and so I see these devices as presenting a real challenge to simulator design. This may make for more simulator sickness. Would you care to comment on this?

MOOIJ: No. I know that there was a big conference this past summer in Montreal, I presume, with a section on simulation sickness, and that would be a source of the most recent feedback on this. But I am not aware of the practical result with more than one pilot, let's say, in a training situation. It's really a question mark - I agree. It may make things worse, but from a standpoint of simulation and high resolution - on paper (from an engineering viewpoint) it seems "super" naturally. I don't want to go into a commercial talk (I'm from a government laboratory in Holland), but some people in industry are extremely enthusiastic about it, and they have claimed so far that, with their engineering pilots, there were no problems; but these pilots know the system and possibly they know not to move too fast. Therefore, such claims may not be relevant to the student pilot. I have one remark in addition to the paper that I would like to make about trends. I forgot to mention that the sizes of motion bases we have now in the 6-degree-of-freedom systems, are probably at a maximum (at least for the present). There are tremendous developments yet to be achieved in image generation and image display. On the other hand, the quality of motion reproduction on the motion base is very good these days if you do a proper job and the sizes of the motion bases will not go further than we see today. There are some more or less practical limits related to sizes of buildings, power, and costs.

Aetiological Factors in Simulator Sickness

by A J Benson
Royal Air Force Institute of Aviation Medicine
Farnborough Hants GU14 6SZ UK

Summary

The clinical features of simulator sickness are similar to the malaise induced by other motion stimuli. The essential aetiology of the condition is considered to be the same as in other types of motion sickness, namely, the mismatch between the motion information provided by the body's sense organs and the brain's internal model of 'expected' motion cues. The mismatch can be between concomitant inputs provided by the angular and linear acceleration transducers of the vestibular apparatus, or between visual and vestibular inputs. More significantly, in a fixed base simulator it is the absence of 'expected' inertial cues when the ambient visual system is stimulated by the external world, visual display that engenders neural mismatch. Even when the simulator has a motion base, quantitative and temporal disparities between visual and inertial cues commonly occur and can contribute, along with visual distortions and other anomalies, to the induction of the motion sickness syndrome.

Introduction

Simulator sickness is a term used to describe the syndrome of signs and symptoms that have been experienced by individuals during and after exposure to motion in simulators. The majority of the reports relate to symptoms induced in flight simulators (reviewed by Kennedy et al, 1984), but car driving simulators having dynamic visual displays also evoke the signs and symptoms which characterize simulator sickness (Reason & Diaz, 1971; Casali & Wierwille, 1980).

The varied manifestations of simulator sickness, described in papers reviewing the problem in flight simulators, are listed in Table 1. Apart from these data being drawn from several different types of flight simulators, ranging from helicopter to fixed-wing, air combat simulators, there is a lack of uniformity in the range of subjective information elicited by interview or questionnaire. Thus it is not possible to present meaningful figures of the incidence of particular signs or symptoms. What does emerge, however, is a clinical picture in which a significant, but variable, number of flying personnel experience the signs and symptoms of motion sickness during simulated flight - notably, stomach awareness, nausea, sweating, headache, dizziness and drowsiness, but rarely vomiting. In addition, they report other symptoms which are not specifically characteristic of motion sickness, in particular, false perceptions of attitude (i.e. spatial disorientation), physical and mental fatigue and disturbances of vision.

On leaving the simulator there is usually a rapid amelioration of symptoms, though in common with the sickness induced by other provocative motion environments (e.g. sea-sickness, swing-sickness), some symptoms may persist for several hours after the simulated flight. In addition, symptoms not present in the simulator may become manifest. Disturbances of postural equilibrium and ataxia are frequently reported, though they are usually short-lived. Less common are the visual 'flash-backs' and transient illusory sensations of bodily motion that can occur sporadically over several hours after the simulated flight.

There are features of simulator sickness, other than signs and symptoms, which strengthen the argument that simulator sickness is just another form of motion sickness. For example, the severity of the disability and its after-effects is a function of the duration of exposure to the motion stimulus. Another common feature is adaptation. With repeated flights in the simulator most individuals show an increased tolerance and reduction in symptoms. There is a clear parallel in the adaptation to provocative stimuli in the simulator with that seen in the adaptation to conditions of sensory rearrangement; whether this be the atypical sensory environment produced by actual (as opposed to simulated) flight, by a ship in rough seas, by a slow-rotation room, by weightlessness or by visual distortion (e.g. inverting goggles). In addition, there are wide individual differences in susceptibility and differences in the manner in which malaise is manifest.

The Neural Mismatch Theory

In order to explain why flight simulators may elicit the motion sickness syndrome, it is necessary, first, to

A. During simulated flight

Stomach awareness

Nausea

Vomiting

Pallor

Sweating

Headache

Dizziness

Drowsiness

Yawning

Anorexia

Increased salivation

False perception of attitude

Disorientation

Confusion

Eye strain

Blurred vision

Physical Fatigue

Mental Fatigue

Exhilaration

Difficulty with fine movements

B. After simulator flight

Persistence of signs and symptoms induced during flight

Ataxia

Visual 'Flash Backs'

Motion 'Flash Backs' (flying or spinning sensations)

Table 1. Signs and Symptoms of Simulator Sickness

(Sources: Chappelow, 1987; Kennedy et al, 1984; Kennedy et al, 1987; McCauley, 1984)

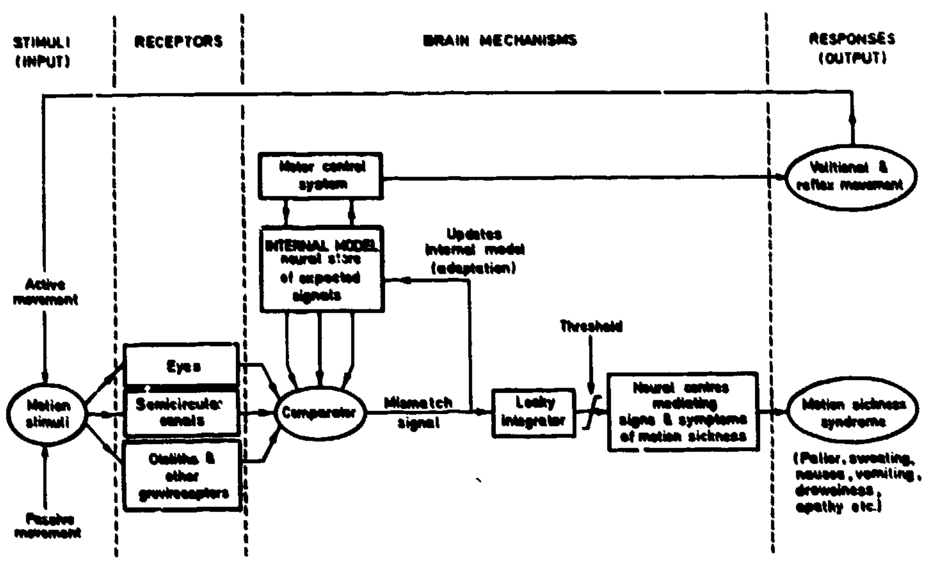

Figure 1. Heuristic model of motor control, motion detection and motion sickness based on the 'neural mismatch' theory.

(From Benson, 1984).

consider the broader problem of why certain motion stimuli induce sickness. The importance of conflicting sensory cues as the principal aetiological factors in motion sickness was suggested more than a century ago (Irwin, 1881), but it was Reason (1970, 1978) who first presented a coherent explanation in his neural mismatch or sensory rearrangement theory. The principal concept of this theory is that motion sickness occurs when the sensory information about bodily movement, provided by the eyes, the vestibular apparatus and other receptors stimulated by forces acting on the body, is at variance with the inputs that the central nervous system expects to receive. Essential to the theory is the postulated existence within the central nervous system of a model of afferent and efferent neural activity associated with bodily movement; a model that is derived through daily experience, primarily during the volitional control of body movement and the maintenance of postural equilibrium. In normal locomotor activity, disturbances of body movement, such as when one accidently trips, are typically brief and the mismatch between actual and expected sensory inputs from the body's motion detectors is employed to initiate corrective motor responses. However, when there is a sustained change in the sensory input - as occurs, for example, in atypical motion environments or when there is vestibular disease - then the presence of the mismatch between actual and expected sensory inputs indicates to the central nervous system that the internal model is no longer appropriate. The process of adaptation, initiated by the mismatch signal, involves the modification or rearrangement of the internal model so that it corresponds more closely with the contemporary sensory afference; consequently the mismatch signal is reduced to an acceptable level.

The presence of a sustained mismatch signal has two effects: one, it causes a rearrangement of the internal model; and two, it evokes the sequence of neural responses that constitute the motion sickness syndrome. There is clearly benefit to the organism to be derived from modifying sensory and motor responses, for this allows it to function more effectively in a novel environment. Whether motion sickness has any survival value is more problematical. Treisman (1977) has suggested that, in an evolutionary context, it does, though it may also be argued that motion sickness is a design defect which has only recently (in an evolutionary time scale) come to light with the use of mechanical aids to transportation (Oman, 1980).

Figure 1 is a diagramatic representation of the functional components and processes embraced by the neural mismatch theory. Motion of the body is detected principally by the eyes and the vestibular apparatus, although changes in the body's orientation to gravity and imposed linear accelerations are also transduced by mechanoreceptors in the skin, muscle, capsules of joints and supporting tissues, which may be considered to act synergistically with the otolith organs. It is postulated that within the central nervous system there is a neural centre that acts as a comparator of signals from the receptors with those from the internal model that stores the signature of 'expected' signals. The output of this comparator is the mismatch signal that, on the one hand, is responsible for modifying the internal model and, on the other, for activating the neural structures mediating the signs and symptoms of motion sickness. How this activation is achieved, that is, whether by purely neuronal or whether by neurohumoral mechanisms, has yet to be determined. It is necessary to postulate, however, the presence of a leaky integrator in order to account for the slow development of symptoms following exposure to provocative motion. In addition, the development of protective adaptation without induction of motion sickness and the large intersubject differences in susceptibility, require the presence of a threshold function in the system.

Identification of motion cue conflicts implicated in simulator sickness

Simulation of provocative flight environment. There are a few research flight simulators that have the capability of exposing the pilot to whole-body motion stimuli having angular and linear accelerations comparable to those achieved in actual flight. If these motion stimuli cause sickness in flight then it is not surprising that a reasonably accurate reproduction of the dynamic flight environment will evoke sickness in the simulator. In such circumstances the principal neural mismatch is between the information provided by the angular and linear acceleration transducers of the vestibular apparatus - the semicircular canals and otolith organs (O'Hanlon & McCauley, 1974). Linear accelerations at frequencies below 0.5 Hz are the dominant provocative stimuli, but head movements made during sustained turns and other rotational motion producing cross-coupled (Coriolis) stimulation of the semicircular canals may also be implicated (Guedry & Benson, 1978). It is not proposed, however, to discuss in more detail the nature of the mismatch produced by such motion stimuli in this paper, for our concern is primarily with the motion sickness occurring during simulation of flights which, in the aerial environment, do not induce the motion sickness syndrome.

Visual Cues. The simplest example of the role of visual cues in the aetiology of simulator sickness is provided by those simulators in which there is a dynamic, external world, visual display but no physical motion of the simulator base (e.g. the 2FH2 Bell HTL helicopter simulator (Miller & Goodson, 1950), the 2E6 F4 aircraft simulator (McGuiness et al, 1981), the UK Air Combat simulators (Chappelow, 1987) or the 'Simulcar' motor car simulator (Reason & Diaz, 1971)). In such simulators the external visual world moves in response to the control inputs of the pilot in a reasonably convincing way but the visual input to the pilot's central nervous system is not accompanied by the 'expected' neural signals from the body's inertial receptors of the vestibular apparatus and the more generally distributed mechanoreceptors. The importance of the 'expectation' of correlated signals from the visual and inertial receptors is supported by the fact that pilots with flight experience of the manoeuvres in the aircraft being simulated were more likely to develop symptoms than those who were not familiar with, or had little flight experience of, the aircraft or the manoeuvres being simulated (Kennedy et al, 1984).

The angular subtense of the visual display is another factor in determining the incidence of sickness (McCauley, 1984) for the condition is much commoner in those simulators having a wide field of view than in those in which the external visual world display is confined to a small window. The implication of this finding is that stimulation of the ambient visual system, rather than the focal visual system, is an essential feature for the generation of cue conflict. The ambient visual system is part of what may be termed an ambient orientation system in which there is convergence at centres within the brain of signals from the peripheral retina with those from vestibular and somatosensory receptors signalling body orientation and movement (Leibowitz & Dichgans, 1980). This system largely operates at a subconscious level in the control of body posture and equilibrium, but it is well established that moving patterns in the peripheral visual field can induce powerful sensations of bodily movement, the so-called vection sensations (Dichgans & Brandt, 1978). These may be angular or linear, depending upon the form of the dynamic visual stimuli. Such vection stimuli can induce the motion sickness syndrome if the sensed bodily motion is not in accord with information from the body's inertial receptors. The simplest example is the conflict produced by a roll vection stimulus presented to a subject standing erect. The visual stimulus engenders a sensation of body movement and tilt from the vertical position, whilst the otoliths and other graviceptors signal tilt in the opposite direction as a result of the compensatory adjustment of posture in response to the illusory sensation. Yet more provocative is the effect of head movement in roll when exposed to an angular vection stimulus in yaw - the "pseudo-Coriolis effect" (Dichgans & Brandt, 1973). In this more dynamic situation, involving active head movements and inputs both from the semicircular canals and the otoliths, the visual stimulus is almost as potent as actual bodily rotation in yaw in the induction of motion sickness.

There are many reports in the literature of the problems experienced by subjects who were required to wear optical devices that distorted vision (reviewed by Dolezal, 1982). Gross distortions, such as right/left reversal or inversion of the visual scene, are initially highly provocative of motion sickness when the subject attempts to move about and engage in normal locomotor activity. Yet even minor visual distortions such as the change in magnification of spectacles can cause symptoms, albeit less severe, on the first day or so that they are worn.

In common with other aetiological factors in simulator sickness the relative importance of distortions of the external visual world display is not known. There is anecdotal evidence, however, that geometrical and perspective errors in the visual display of the helicopter simulator studied by Miller & Goodson (1958) made a significant contribution to the incidence of sickness. Errors in the optical alignment of projected displays relative to pilot eye datum have also been implicated and we have experience of an RAF Lightning simulator which nauseated the instructors, rather than the students, until it was discovered that the display was misaligned.

Other characteristics of the visual display, such as its luminance and the degree of scene detail depicted, may also be of aetiological significance. It may be argued, however, that the ambient visual system is adequately stimulated by low spatial frequencies having low contrast and luminance. Hence, the quality of the image providing visual information on spatial orientation and movement is not important; rather it is the angular subtense of the image that determines the strength of the visual cue and its ability to engender sensory conflict. On the other hand, the quality of the imagery has a direct impact on the difficulty in performing focal visual tasks, such as target location and identification, which the pilot may be required to carry out in the simulator. Such deficiencies in the display are thus more likely to be the cause of, or at least contribute to, the eye strain, headache and "visual problems" reported by simulator pilots, rather than of simulator motion sickness per se.

Whole-body motion cues. In the preceding section of this paper it is postulated that the principal cause of simulator sickness is the conflict engendered by powerful ambient visual motion cues in the absence of the expected motion cues from vestibular and somaesthetic receptors. The corollary to this concept is that sickness should be reduced if, in the simulator, these non-visual receptors are stimulated by linear and angular movement of the body in a manner which is compatible with the visual display. Experiments conducted in a VSTOL simulator (Sinacori, 1967) and a driving simulator (Casali & Wierwille, 1980) have shown that the use of a motion base providing onset acceleration cues did lead to an improvement in the acceptability of the simulation and to a decrease in the incidence of sickness.

The limited angular and linear excursion of motion bases necessitates the introduction of motion 'washout' having time constants considerably in excess of those of the vestibular receptors that transduce angular and linear movement. Accordingly, the afferent vestibular stimuli during a simulated manoeuvre generally do not correspond with those generated when the same manoeuvre is performed in flight. The lack of correspondence may be small when, for example, minor changes in roll attitude are simulated. Lateral tilt of the motion base generates an appropriate angular acceleration, an effective stimulus to the semicircular canals, and a commensurate change in orientation of the head relative to the gravitational acceleration, an effective stimulus to the otolith organs. More commonly, however, the pattern of stimulation in the simulator differs from that occurring in flight. A simple example is the simulation of the change in direction of the resultant force vector, associated with acceleration in the line of flight, by a backward tilt of the motion base - an angular movement causing inappropriate stimulation of the semicircular canals.

Appreciably more serious mismatches between the expected inertial cues and those achieved by the motion base occur during simulation of the flight of high performance aircraft, particularly the large and frequent changes of the force environment and of attitude associated with air-combat manoeuvres. The inability of the motion base to achieve high linear and angular accelerations and roll rates which are in any way comparable to those occurring during such manoeuvres in flight, probably accentuates the conflict with visual motion cues and increases the incidence of sickness. The ineffectiveness of the motion base has led to it being disengaged in at least one air-combat simulator (Seevers & Makinney, 1979) and most simulators of this type in the US and the UK are now of a fixed-base design.

Temporal incongruity of motion cues Apart from what may be termed the quantitative and qualitative mismatch of motion cues produced by visual and inertial stimuli in simulators, differences in the timing of these cues also contribute to the conflict. Two types of temporal incongruity can be recognised; one between the control inputs made by the pilot and the motion cues provided by the visual display and motion base, the other between the visual display and motion base. The experienced pilot will have an expectancy of the temporal relationships between control stick and throttle demands and the dynamic response of the aircraft. Any time difference, between the perception of the motion cue(s) from that which he expects to receive, represents a mismatch capable of contributing to the development of motion sickness in the simulator.

In those simulators with motion bases there is also the potential for temporal incongruity of visual and inertial cues, which may be compounded by the differing dynamics of the visual and vestibular sensory systems in the perception of motion (reviewed by Young, 1984). Retinal receptors signal position and velocity of a visual target from which acceleration may be perceptually derived. In contrast, the otoliths (in company with somaesthetic mechanoreceptors) are sensitive to linear acceleration and rate of change of acceleration (jerk) and hence give information about body movement which is phase advanced upon that provided by the visual system. Sensory integration of these gravireceptor signals is required in order to perceive transient linear velocity and displacement. The semicircular canals signal, for transient angular movements, the angular velocity of the head and provide cues which allow the change in angular position or angular acceleration to be perceived by integration or differentiation of the afferent signal within the central nervous system. The implication of these differing sensory dynamics is that sensory conflict is likely to be the greater if mechanical movement of the simulator (and hence the operator) lags movement of the visual display than if the visual display lags the motion base.

In addition to a motion base, other devices, such as G-seats, G-suits and helmet loaders, have been used to provide pseudo-inertial cues to the pilot and to enhance the realism of the simulators. Whether they contribute to the induction of simulator sickness remains to be determined, although it is not improbable that the dynamics of the actuating mechanisms can introduce lags which conflict with visual cues or with other inertial cues. However, the role of somaesthetic cues in the aetiology of motion sickness, in general, is uncertain. Unlike ambient visual stimuli, somaesthetic signals do not converge at the level of the vestibular nuclei and are poorly represented in those areas of the cerebellum whose ablation of which protects experimental animals from motion sickness.

Post-exposure effects

As noted above, post-exposure effects fall into two categories, those that are a continuation of the signs and symptoms of motion sickness and others that become manifest only after leaving the simulator, notably ataxia and 'flash backs' in the visual and vestibular/proprioceptive sensory modalities.

The persistence of symptoms is a normal feature of motion sickness and, like other aspects of the condition, exhibits wide variation between individuals. Some experience a rapid amelioration of the signs and symptoms on withdrawal of provocative stimuli; in others, malaise, drowsiness and a feeling of depression may persist for several hours after leaving the simulator (Reason & Brand, 1975). The neural events mediating the motion sickness syndrome are not understood, but the slow development and decay of symptoms probably is the manifestation of the accumulation of some neurotransmitter within the central nervous system during exposure to provocative motion, and its subsequent removal or return to a normal level on withdrawal of the stimulus.

The other after-effects, in particular the disturbance of postural equilibrium, are, most probably, the manifestation of adaptive processes, in which new patterns of sensory-motor co-ordination are elaborated that are appropriate to the altered sensory environment of the simulated flight. Most of the experimental studies of adaptation to altered sensory environments have involved gross visual distortion, such as reversing or inverting goggles, or substantial alteration of the motion environment as in, for example, the Pensacola Slow Rotation Room (reviewed by Welch, 1978). The sensory rearrangement imposed in these experiments is substantially greater than that achieved in flight simulations, but they illustrate the remarkable ability of man's central nervous system to modify both the perception of signals from sensory receptors and the temporal and spatial configuration of voluntary and involuntary (reflex) motor responses (Melvill Jones, 1977). The magnitude of the adaptive change is dependent, inter alia, on the extent of the rearrangement, on the duration of exposure and on whether the operator is active (i.e. within the control loop) or passive in the rearranged sensory environment (Reason & Benson, 1978). It is probably this last factor, the active involvement of the pilot, whose motor responses directly influence the visual and inertial cues received, that is responsible for the rapid modification of sensory-motor reflexes which are disadvantageous on leaving the atypical environment of the simulator and returning to a stable visual world and a stable, 1g, force environment.

The 'flash backs' in which the pilot has brief, but powerful, recall of the simulator visual display or of the motion of the simulator are comparable to the transitory sensory disturbances that occur in more everyday situations in which there has been sustained exposure to comprehensive visual or inertial stimuli. For example, there are few who, having been aboard a boat in moderate seas for a few hours or more, will not have intermittently perceived an illusory sensation of the boat's motion on return to land. This sensation may also be accompanied by a corresponding motion of the visual scene. Although this type of phenomenon has long been described (Darwin, 1801) its neural mechanism remains covert, though in psychological terms one may speculate that it represents the recall of memory traces laid down during the period of exposure to the rearranged sensory environment.

Conclusion

Simulator sickness, in common with other forms of motion sickness, has several causes and affects different people in different ways; it is, to quote Kennedy et al (1987), "polygenic and polysymptomatic". In this paper an attempt has been made to discuss some of the more important aetiological factors within the framework provided by the neural mismatch theory of motion sickness.

An extensive list of possible causal factors is to be found in the proceedings of the National Research Council Workshop on Simulator Sickness (McCauley, 1984), though, unfortunately, the present state of knowledge allows only very approximate weightings to be given to the potential of each factor to cause simulator sickness. An understanding, incomplete as it is, of the aetiology of the condition does, however, allow rational recommendations to be made (Kennedy et al, 1987) relating to simulator hardware and utilisation that should reduce the incidence of simulator sickness and increase the operational effectiveness of simulator training.

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ETUDE HORIZONTALE DE L'INCIDENCE DU MAL DES SIMULATEURS DANS LES FORCES AERIENNES FRANCAISES

par

*A. LEGER, *P. SANDOR, **R.P. DELAHAYE

*Laboratoire de Médecine Aérospatiale
Centre d'Essais en Vol - 91220 - BRETIGNY-AIR, FRANCE

**Inspection du Service de Santé pour l'Armée de l'Air
26, Bd Victor - 75996 - PARIS ARMEES

RESUME

L'utilisation systématique du simulateur de combat pour l'entraînement a favorisé la mise en évidence du problème du mal des simulateurs. Une enquête destinée à évaluer l'incidence des troubles a été menée au sein de plusieurs unités de l'Armée de l'Air. Les résultats obtenus montrent globalement que 67 % des pilotes interrogés ont présenté des symptômes à des degrés divers. L'analyse statistique des données montre une absence de corrélation entre la susceptibilité générale aux cinétoses déterminée au moyen d'un questionnaire et la sensibilité au mal des simulateurs. Cette dernière constatation amène à envisager la nature du conflit en cause.

INTRODUCTION

Depuis le début des années 80 un intérêt croissant s'est manifesté, principalement aux Etats-Unis, à l'égard du mal des simulateurs. Cet intérêt, qui semble suscité par des considérations opérationnelles, fait suite à des préoccupations antérieures fondamentales (3).Suivant en cela l'opinion de REASON (3) on peut replacer ces phénomènes dans le cadre plus général des cinétoses induites visuellement. C'est bien, en effet, la généralisation de visualisations en champ large et de simulateurs à base fixe utilisant le principe de la vection pour l'entraînement des pilotes qui donne son ampleur à un problème plus ou moins latent.

Le premier simulateur à base fixe utilisant le principe de la vection a été opérationnel en France en 1975. Il s'agit d'une installation destinée aux études techniques et tactiques liées à l'emploi des missiles de combat aérien rapproché. Peu après, un simulateur utilisant une sphère de 10 m de diamètre a été mis en service au Centre d'Essais en Vol. La mise en oeuvre de ce type de simulateur à des fins d'entraînement au combat s'est effectuée à la fin de l'année 1984 sur la Base Aérienne 102 de DIJON et au Centre d'Entraînement au Combat de Mont-de-Marsan. Ces simulateurs sont essentiellement destinés à l'entraînement des pilotes de Mirage 2000.

Il est intéressant de constater qu'avant 1984 les descriptions faites par les pilotes des symptômes de mal des simulateurs sont restées au stade d'anecdotes. Ce n'est finalement qu'à partir de la mise en service des simulateurs d'entraînement que le problème des implications touchant à la sécurité des vols s'est réellement posé. Les observations effectuées par les pilotes utilisant les simulateurs de combat ont amené l'Inspection du Service de Santé pour l'Armée de l'Air à demander une étude sur l'incidence des effets secondaires de la simulation.

METHODE

Il n'est pas contestable que la meilleure méthode d'évaluation de l'incidence du mal de simulateurs aurait consisté à effectuer une étude sur le site. L'intérêt de cette démarche ressort nettement des travaux entrepris par KENNEDY et coll. (5). Cependant ce type d'opération nécessite une préparation importante. Compte tenu de l'organisation des différents services mis en cause, elle n'était pas envisageable, du moins dans un premier temps.

Il a donc été procédé à une enquête portant sur l'expérience passée des pilotes de différentes unités de l'Armée de l'Air.

Protocole

Un questionnaire anamnestique simple a été conçu en tenant compte de l'expérience acquise dans le domaine du mal des simulateurs par d'autres auteurs (4,5).

Procédure

Le questionnaire anonyme a été diffusé dans les différentes régions aériennes et remis aux pilotes par l'intermédiaire du médecin du Personnel Navigant des bases concernées.

Après collecte des réponses et centralisation au niveau des Directions Régionales du Service de Santé pour l'Armée de l'Air, les dossiers ont été adressés à l'Inspection du Service de Santé pour l'Armée de l'Air. Enfin, le Laboratoire de Médecine Aérospatiale a été chargé de l'exploitation des données.

Questionnaire

L'objectif du questionnaire consistait à permettre l'étude d'une large population de pilotes. Il n'était donc pas envisageable d'utiliser un questionnaire très détaillé, ceci en vue d'obtenir un niveau de coopération satisfaisant du plus grand nombre possible de sujets.

Le document remis au pilote se composait de quatre parties :

- une courte note d'introduction exposant le but de l'enquête ;
- un questionnaire d'information générale ;
- un questionnaire "mal des simulateurs" ;
- un questionnaire "mal des transports".

Le questionnaire d'information générale portait sur l'âge, l'expérience aéronautique, l'expérience des simulateurs de combat. Cette première partie ciblait donc l'étude sur un type particulier de simulateur. Cependant des consignes verbales ont été données afin d'inclure l'expérience provenant d'autre type de simulateur (mission, entraînement).

La partie concernant le mal des simulateurs se divisait en deux thèmes principaux :

- les symptômes ressentis pendant les séances ;
- les troubles survenant à l'issue des séances.

Dans tous les cas il était demandé d'indiquer la sévérité à l'aide d'une échelle numérique en quatre points :

0 Absence

1 Intensité faible

2 Intensité modérée

3 Intensité forte.

Pendant les séances, les questions portaient sur :

- Les signes digestifs pathognomoniques : inconfort épigastrique, nausées, vomissements ou spasmes.

- Les signes d'accompagnement : sudation, sensation de chaleur, étourdissement, salivation, céphalées.

A l'issue des séances les questions portaient sur la sensation de malaise général, les troubles de l'équilibre et de la locomotion, les céphalées, la disparition ou la persistance des signes avec la répétition des séances.

Cette partie du questionnaire se terminait par des remarques libres concernant le mal des simulateurs.

La dernière partie du dossier consistait en un questionnaire explorant la susceptibilité générale au mal des transports inspiré du M.S.Q. de REASON (7). Ce questionnaire avait préalablement été validé au Laboratoire au cours de la sélection de candidats cosmonautes.

Traitement des données :

Les données recueillies ont été traitées au Laboratoire de Médecine Aérospatiale du Centre d'Essais en Vol. A partir des données brutes on a pu calculer un indice reflétant la sévérité globale des troubles rapportés ainsi que le score de susceptibilité au mal des transports.

Une analyse de correspondance multiple a ensuite été effectuée avec l'aide du Centre de Sélection de l'Armée de l'Air.

RESULTATS

Dans l'ensemble des unités ayant participé à l'enquête, 164 pilotes ont répondu au questionnaire. Dans un premier temps 153 réponses ont été jugées exploitables pour l'analyse descriptive globale. 132 dossiers ont été retenus en finale pour l'analyse statistique détaillée.

Si l'on considère l'ensemble des dossiers on constate que tout type de simulateurs et niveau de sévérité confondus, 67 % des pilotes ont ressenti des troubles lors de séances de simulation. Un seul pilote décrit un épisode de vomissement.

Ces résultats se rapportent essentiellement à l'utilisation du simulateur de combat. Cependant un certain nombre de réponses concernent d'autres types de simulateurs (simulateur de mission Mirage F1 CR, simulateur Alpha-Jet, simulateur C 160 TRANSALL).

Nous envisagerons en premier lieu l'analyse descriptive des résultats puis l'analyse statistique qui en a été faite.

Analyse descriptive :

Cette analyse comporte deux volets :

- Les troubles rapportés pendant et après les séances de simulation

- La susceptibilité aux cinétoses évaluée à l'aide du questionnaire mal des transports (QMT).

. Troubles liés à la simulation

Parmi les signes pathognomoniques du mal des simulateurs on a distingué l'inconfort épigastrique et la sensation de nausée, de l'envie de vomir. Il s'agit là d'une distinction quelque peu artificielle mais qui a été adoptée pour introduire un élément de sévérité supplémentaire. Ces signes apparaissent dans 18,9 % des réponses pour la nausée simple et 9,8 % des pilotes admettent avoir eu envie de vomir au cours d'une séance de simulation.

Les signes d'accompagnement apparaissent beaucoup plus fréquemment et dans bon nombre de cas sont seuls présents. Ainsi une sudation inhabituelle a été relevée dans 18,9 % des cas. La sensation de chaleur anormale est présente dans 21,2 % des réponses. Le symptôme le plus fréquent reste cependant la sensation d'étourdissement ou de vertige qui apparait dans 26,5 % des questionnaires. Ce symptôme est suivi de près par les manifestations à type de céphalées et de tension oculaire qui atteignent 22,7 %.

L'intensité des symptômes est bien sûr extrêmement variable selon le sujet.

L'indice d'intensité globale, déterminé à partir de l'intensité des différents symptômes, fait apparaître que dans 47 % des cas les troubles restent à un niveau faible. Par contre ils sont modérés (intensité 2) dans 12,1 % des cas. Le niveau de sévérité 3 n'apparait que pour 3,8 % des troubles. En définitive sur les 132 dossiers ayant été soumis à l'analyse statistique seul 37,1 % des sujets n'ont présenté aucun signe.

Cette proportion de sujets indemnes apparait beaucoup plus importante pour ce qui concerne la période post-simulation. 51 % des sujets ne relèvent aucun trouble. Parmi les troubles les plus fréquemment rencontrés à l'issue des sessions on note la sensation d'étourdissement, les troubles passagers de l'équilibre et les céphalées. L'intensité de ces symptômes reste faible dans 34,8 % des sujets. Elle est modérée dans 9,8 % et sévère dans 3,8 %.

Pour la plupart des pilotes interrogés les symptômes disparaissent rapidement, généralement après 3 ou 4 séances. On note cependant que sur l'ensemble des réponses, 8 sujets signalent une persistance de la symptomatologie au delà de la dixième séance de simulation. Parmi les 47 pilotes des escadrons de Mirage 2000, qui sont les utilisateurs privilégiés des simulateurs de combat, 4 pilotes déclarent la persistance des troubles bien qu'ils aient été exposés répétitivement. L'intensité des symptômes est faible dans 3 cas, modérée dans le dernier.

. Susceptibilité générale aux cinétoses :

La figure 1 présente l'histogramme des scores de susceptibilité calculés à partir des questionnaires pour 153 pilotes. La distribution des scores ne diffère pas sensiblement de celle rencontrée, par exemple, dans une population de candidats cosmonautes. Un groupe de 3 pilotes se détache cependant avec des scores élevés, supérieurs à 90 ce qui signe habituellement une susceptibilité importante aux cinétoses. Deux de ces pilotes sont des chasseurs, le troisième est un pilote d'hélicoptères.

D'une manière générale, dans cette population essentiellement composée de pilotes de chasse on retrouve un peu plus de 20 % à 25 % des individus qui peuvent être considérés comme assez susceptibles au mal des transports.

- **Analyse statistique**

L'analyse statistique des données s'est revélée relativement décevante dans la mesure où elle dégage peu de grandes lignes directement exploitables.

La matrice d'intercorrélation présentée à la figure 2 a été établie sur les variables représentatives de la population et du mal des simulateurs. Les variables sont pour la population le nombre d'heure de vol (HDV), l'âge, la sensibilité aux cinétoses (SENS), le nombre de séances de simulateur (NSES). Les variables prises pour le mal des simulateurs sont le nombre de signes pendant la simulation (NSIP), l'intensité de ces signes (ISIP), le nombre et l'intensité des signes post-simulation (NSIA, ISIA).

L'examen de cette matrice ne permet pas de dégager de corrélation très intéressante en dehors de la liaison entre le nombre et l'intensité des signes pendant et après la simulation. Cette corrélation n'est cependant pas très surprenante. En fait c'est une constatation négative qui apparaît la plus intéressante, dans la mesure où l'on n'observe pratiquement pas de corrélation entre la susceptibilité générale aux cinétoses et le mal des simulateurs.

Ces premiers résultats permettent de comprendre assez facilement que l'analyse de correspondance multiple effectuée par la suite n'a pas apporté d'éléments plus attrayants.

DISCUSSION

Les résultats obtenus lors de cette enquête sont cohérents avec les travaux menés par d'autres auteurs (1,5). En effet selon KENNEDY et Coll. l'incidence, selon la sévérité du critère choisi, se situe entre 70 % et 20 % des sujets. Ces chiffres sont à comparer aux 67 % et 15 % qui ressortent de cette étude ; pour sa part CROWLEY trouve une incidence légèrement inférieure puisqu'elle se situe à 40 % des sujets.

L'étude que nous avons mené est une étude globale. C'est à dire qu'elle incorpore différents types de simulateur et parmi les simulateurs de combat différentes installations. Ce fait peut expliquer des différences qui pourraient apparaître avec des études menées spécifiquement sur un type de simulateur.

L'un des points qui ressort nettement est le manque de corrélation existant entre la susceptibilité générale aux cinétoses évaluée à l'aide d'un questionnaire et la sensibilité au mal des simulateurs. Ce résultat n'est pas fondamentalement en désaccord avec les données de la littérature puisque REASON et DIAZ (7) avaient déjà souligné la faible valeur prédictive de ce type de questionnaire pour le mal des simulateurs. De même CROWLEY rapporte que la sensibilité au mal des simulateurs dans le simulateur de l'AH-1 cobra n'est pas associée avec une histoire antérieure de mal des transports. Cependant, pour KENNEDY et FRANK il existerait une corrélation quoique faible.

Ce manque de prédictivité des questionnaires anamnestiques, par ailleurs bien corrélés avec les résultats d'épreuves vestibulaires, amène donc à envisager le problème de la nature des stimulations causales.

Il ne fait pas de doute que les manifestations observées, tant au cours qu'à l'issue des séances de simulation, sont liées à un processus d'adaptation au niveau du système nerveux central. On peut parler ici "d'actualisation" du modèle interne de la dynamique du corps, tel qu'il est présenté par YOUNG (9).

Les troubles observés dans les simulations de combat à base fixe peuvent être rattachés sans trop de problème aux cinétoses induites visuellement dont les mécanismes ont été largement étudiés par DICHGANS et BRANDT (3). Pour d'autres simulateurs, comme les simulateurs de mission à base mobile dotés de visualisation en champ large, les mécanismes en cause sont sans doute plus complexes.

Pour leur part les questionnaires anamnestiques explorant la susceptibilité individuelle au mal des transports font appel à des questions portant principalement sur des conflits comportant des stimulations vestibulaires de poids fort. Il serait alors tentant de considérer que ces questionnaires, adaptés approximativement au mal des transports dans des conditions "naturelles" terrestres, ne correspondent pas à des applications plus spécifiques. Il faut toutefois noter que les résultats obtenus par DAUNTON et coll. (2) ne vont pas dans ce sens. Il semblerait en effet chez l'animal que les sujets sensibles aux stimulations vestibulaires soient ceux qui répondent également aux stimulations visuelles. Par contre les résultats présentés par MONEY et Coll. (6) sont plus cohérents puisqu'ils montrent que les sujets sensibles aux tests vestibulaires classiques peuvent se révéler insensibles à des cinétoses induites par un conflit visuo-vestibulaire (prisme de DOVE). Le faible nombre de sujets inclus dans cette expérimentation exclut cependant toute généralisation.

Le problème de la susceptibilité individuelle aux diverses formes de cinétose reste de toute façon un obstacle épineux pour la compréhension des mécanismes du mal des transports.Il dépasse d'ailleurs largement le cadre de cette étude et du problème du mal des simulateurs.

CONCLUSION

L'incidence du mal des simulateurs observé dans les unités de l'Armée de l'Air Française apparaît relativement identique aux observations effectuées dans d'autres pays. On doit souligner que dans la grande majorité des cas ces manifestations restent modérées et s'estompent rapidement après quelques séances. Sur le plan opérationnel deux problèmes peuvent être envisagés. Les implications dans le domaine de la sécurité des vols ne semblent pas vraiment très cruciales. Les mesures de bon sens qui ont été proposées jusqu'à présent semblent régler le problème d'une manière satisfaisante.

Le problème avancé par FRANK et KENNEDY de la fiabilité de la simulation apparaît beaucoup plus complexe. Les résultats obtenus au cours de cette étude ne permettent pas d'apporter d'éléments en cette matière.

Il faut toutefois remarquer que toute simulation repose par principe sur la génération d'illusions sensorielles.

Plus ces illusions sensorielles sont fortes, plus la simulation reste réaliste comme c'est le cas pour la simulation de combat. L'intérêt opérationnel semble évident pour les pilotes et nous n'avons recueilli aucun avis négatif sur ce point dans notre enquête. Plutôt que de considérer ce type de simulation comme "mauvais", peut-être vaut-il mieux prendre ses effets secondaires comme "la rançon du progrès".

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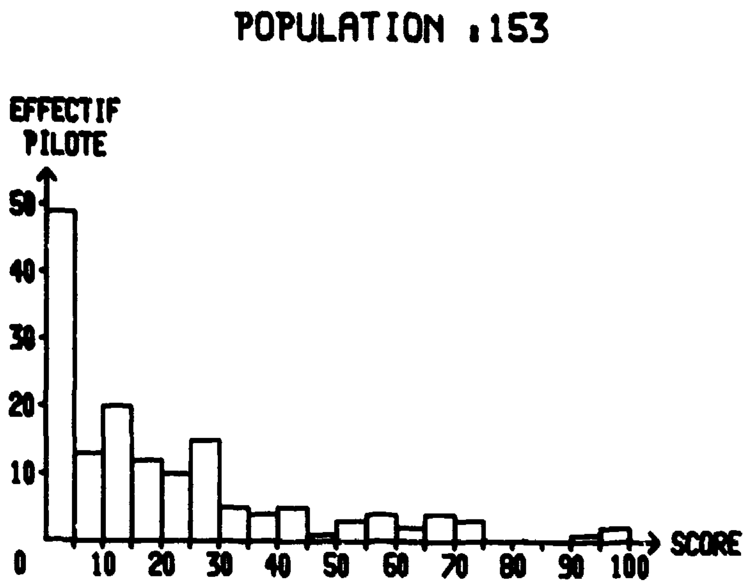


Fig. 1 : Histogramme des scores de susceptibilité aux cinétoses déterminés par le questionnaire pour une population de 153 pilotes.

HDV	1,00							
AGE	0,88	1,00						
SENS	-0,06	0,03	1,00					
NSES	0,27	0,16	0,01	1,00				
NSIP	0,00	0,04	0,18	-0,09	1,00			
ISIP	0,06	0,06	0,16	0,04	0,79	1,00		
NSIA	0,08	0,14	0,23	-0,12	0,36	0,41	1,00	
ISIA	0,07	0,07	0,22	-0,05	0,44	0,47	0,80	1,00
	HDV	AGE	SENS	NSES	NSIP	ISIP	NSIA	ISIA

Fig. 2 : Matrice d'inter-corrélation des variables représentatives de la population et de l'incidence des troubles.

DISCUSSION

PRICE: Did you obtain data relative to how long after simulated flight the post-simulator-run symptoms persisted?

LEGER: Yes, we gathered some data but it was not presented in this paper. I would say that most of the after-effects occurred within 13 minutes. Most after-effects stopped very rapidly. I do not recall any late post-run effects like some of those reported by Dr. Kennedy.

SIMULATOR INDUCED SICKNESS AMONG HERCULES AIRCREW

L.E. Magee, L. Kantor and D.M.C. Sweeney
Defence and Civil Institute of Environment Medicine
1133 Sheppard Ave. West, Downsview, Ontario, M3M 3B9 Canada

SUMMARY

The purposes of this study were to investigate the incidence, severity and time-course of simulator sickness among pilots and flight engineers training on a C-130H (Hercules) flight simulator, and to assess the influence of flight experience on susceptibility. Evidence of simulator sickness was collected by questionnaire, tests of balance, and observation. The questionnaires were completed at the conclusion of a four-hour training session and 20 hours later. The balance tests were performed immediately prior to and immediately following the training session. Overt signs of pallor, sweating, drowsiness and visual nystagmus were also recorded at these times. Thirty-five of the 42 aircrew (i.e., 83%) tested reported characteristic symptoms of simulator sickness. The most prevalent were eyestrain, mental and physical fatigue, and after-sensations of motion. Some effects persisted following simulator training for many hours although most were not severe. Few had delayed onset. Although eleven subjects (26%) reported loss of balance at the end of the training session, performance on the balance tests improved; this suggests a practice effect which masks ataxia. With the exception of occasional nystagmus, no overt signs of simulator sickness were evident. The relationships between aircraft experience, both general and type-specific, and diagnostic scores based on symptoms were examined. There was no evidence to indicate that experience influenced susceptibility to simulator sickness.

INTRODUCTION

The Defence and Civil Institute of Environmental Medicine has begun to determine the incidence, severity, and time-course of simulator sickness resulting from the use of flight simulators within the Canadian Forces. The purposes of this work are (i) to provide a rational basis for flight restrictions following simulator training, (ii) to make interim recommendations to alleviate the problem, and (iii) to identify salient characteristics of Canadian Forces flight simulators that seem to instigate sickness and that possibly limit training effectiveness.

In the present study symptoms experienced by aircrew training on a flight simulator for a multi-engine transport aircraft, the C130(H), are reported. This simulator was suspect as a result of pilot reports accumulated during the acceptance period following its installation at Canadian Forces Base Trenton in February, 1985. Pilots had been given a questionnaire by instructional staff to help validate the simulator. Complaints about the handling characteristics of the simulator were obtained. Jerkiness in nose wheel steering, overbraking, oversensitive throttle, oversensitive rudder/aileron and instability despite trim were typical comments on simulator handling characteristics. "Ballooning" on round out during landings and unrealistic ground effects were noted. Accompanying these complaints were those of vertigo, disorientation, dizziness, headache, stomach disturbance, nausea and eye strain. Two pilots had vomited following simulator flights. Shortcomings in the handling characteristics of the simulator were subsequently addressed by software modifications to the computer algorithms, but the extent to which they were corrected and the extent to which simulator induced sickness remained were uncertain.

Sensory conflict prevails as an explanation of simulator induced sickness. Sickness is thought to be generated as a result of conflicts among existing inputs from the spatial senses and those expected from memory (for a review, see McCauley (1)). The basic assumption, that uncorroborated sensory signals give rise to sickness, has found support in experimental findings which suggest that experienced operators are more susceptible to simulator sickness than students, or those with little or no previous experience with the vehicle (2-6). Casali and Wierwille (7) suggest that kinematic modelling of the vehicle is perhaps the most fundamental and critical factor underlying the dynamic fidelity of a simulator. In a comprehensive summary of the literature (1) temporal discrepancies between the response characteristics of the simulated and actual aircraft are identified as a prime source of simulator sickness. Response lags and temporal asynchronies were known to exist for the visual and motion systems of the C130(H) simulator. On these grounds it was hypothesized that C130(H) aircrew familiar with the flight characteristics of the aircraft would be more susceptible to simulator sickness than students with no experience because the experienced personnel would be sensitive to additional conflicts between sensory expectations derived from long term memory and the immediate sensations derived from the simulator session. Consequently, empirical data were sought to compare the susceptibility of experienced and novice aircrew. Greater susceptibility among experienced aircrew would implicate the simulator's dynamic features as a cause of simulator induced sickness and would provide further support for the theory of sensory conflict.

METHODS

Participants

Thirty-one pilots and eleven flight engineers scheduled for training on the C-130H (Hercules) simulator participated in this study. Both experienced (7 flight engineers, 19 pilots) and novice (4 flight engineers, 12 pilots) aircrew, all males, participated. The experienced group consisted of aircrew that had come from their squadrons to the simulator facility for advanced training. Some members of this group had already used the simulator. Their experience on the simulator ranged from 20 to 124 hours, with a median of 90 hours, but at least three months had elapsed since their last session on the trainer. This group also had accumulated between 450 and 5500 hours of flight time on Hercules aircraft (E and H models) with a median of 1250 hours. These estimates for the number of hours of training on the simulator and the number of hours of Hercules flight experience are based on data provided by only eleven of the 26 experienced aircrew. The remaining data were missing. Complete data from all members of the group indicated that the number of hours they had logged on all types of aircraft ranged from 845 to 10,000 hours, with a median of 3166 hours. The median age of this group was 32 years. Those in the novice group had no previous training on the Hercules aircraft or Hercules simulator. This group of subjects was undertaking initial training for type certification. Their flight experience on other aircraft types ranged from 50 to 4340 hours, with a median of 1465 hours. Their median age was 29 years.

Equipment

The major components of the C-130H simulator include an instrumented flight deck, an instructor station, a visual display system, and a motion platform. The physical components of the simulator cockpit faithfully duplicate those of the aircraft. Hydraulic loaders with hydrostatic bearings are used to provide force feedback to the primary flight controls.

The motion platform, a 500 series design built by CAE Electronics Ltd., is a six-post, synergistic system providing motion in six degrees-of-freedom (DOF). The posts, arranged in pairs as inverted Vs, also have hydrostatic bearings; each post is about 3.4 meters long. Some motion system performance characteristics are given in Table 1.

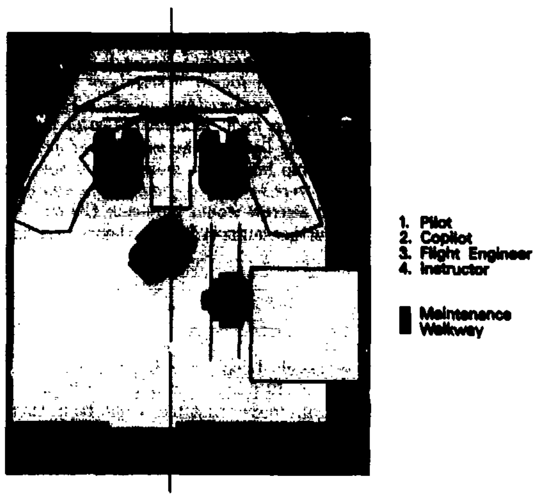
Table 1: Motion System Performance Characteristics

DOF	Displacement	Velocity	Acceleration
Pitch	+33° -37°	±24° sec^{-1}	±250° sec^{-2}
Roll	±28°	±24° sec^{-1}	±250° sec^{-2}
Yaw	±37°	±24° sec^{-1}	±250° sec^{-2}
Vertical	1.73m	±0.61m sec^{-1}	±1.0g
Lateral	2.44m	±0.71m sec^{-1}	±0.6g
Longitudinal	2.84m	±0.71m sec^{-1}	±0.6g

The resonant frequency of the motion platform is recognized for its importance to simulator sickness. Sensitivity to motion sickness is greatest about .2 Hz (8). To characterize this aspect of the C130(H) simulator a three-axis accelerometer was used to record vibrations at a pilot's seat while he flew a typical circuit. Power spectral analysis of the data indicated that the magnitude of frequencies between 0 and 2 Hz did not exceed .01 g RMS. There was no evidence that the resonant frequency of the simulator resided within this range or that the energy levels within this range approached hypothetical thresholds for simulator sickness (9).

The visual display system consists of six separate "windows": the front, quarter and aft (side) windows of the pilot and co-pilot. Only five of the six windows are active at the same time. Either of the aft windows, but not both, is active depending on whether the pilot or co-pilot is flying the simulator. Four separate "channels" of computer-generated imagery drive the 5 active windows. One channel drives both front windows so that the imagery displayed to the pilot and co-pilot is identical. In other words, there is no parallax between the two forward windows; pilot and co-pilot see exactly the same scene as if they are at the same vantage point. A resulting visual effect is that both pilot and co-pilot, for example, may simultaneously perceive themselves to be centered on the runway, although they sit on opposite sides of the cockpit. The seating positions of the aircrew are shown in Figure 1.

Figure 1: Seating positions of the aircrew



A Rediffusion Novoview SP2 system generates the computer imagery. This imagery is displayed on high resolution CRTs (780 x 1000 pixels) through a beam splitter and collimating mirror. The computer generated imagery (CGI) system is capable of producing about 4000 light points and 200 surfaces. Day, dusk, and night scenes may be seen. Maximum brightness of the displays are 2.5 foot-lamberts (ft-L) for day scenes, 1.5 ft-L dusk and 0.5 ft-L night. The field-of-view for the three active windows on the pilot's side of the cockpit subtends about 120 degrees horizontal and 40 vertical. System reaction times to discrete control inputs are shown in Table 2 for the attitude display indicator (ADI), motion and visual systems.

Table 2: Throughput Delays For ADI, Motion And Visual Systems (milliseconds)

Axis	Delay (ms)		
	Take-off	Cruise	Landing
PITCH			
Visual	210	210	220
ADI	260	230	260
Motion	170	180	180
ROLL			
Visual	200	210	230
ADI	240	260	250
Motion	190	190	200
YAW			
Visual	250	240	240
ADI	240	240	230
Motion	180	200	200

Unfortunately, it is not possible to determine the extent to which the control loop display lags shown in Table 2 differ from actual control response lags as the latter are unavailable. However, the visual display lags presented in this table are relatively large and appear to be more than sufficient to generate simulator sickness (6). It is also instructive to note (i) that the length of the lags vary with different stages of flight, (ii) that the lags vary with the type of control used (elevators, ailerons and rudder), (iii) that visual, motion, and instrument lags are out of phase, (iv) that the temporal asynchronies are inconsistent, and (v) that motion platform response precedes visual system response.

Procedures

The experimenter observed and tested each subject immediately before and immediately after the training session. The presence and severity of any overt signs of pallor, sweating, drowsiness and visual nystagmus were recorded at these times. Methods for these ratings can be found elsewhere (10). Two balance tests, the Walk On Floor Eyes Closed (WOFEC) and the Sharpened Romberg (SR) were given. Detailed descriptions of these tests are provided by Fregly, Graybiel and Smith (11).

The number of subjects in the simulator during any single session varied; there were always two pilots and sometimes one or two flight engineers. Each simulator session lasted four hours with a coffee break midway through the session. The pilots switched positions following the coffee break, allowing the person who was first co-pilot the opportunity to be aircraft commander and vice versa. Since the research literature indicates that aircrew adapt to the simulator within a few training sessions (eg. (6)), all subjects were tested on their first day. Following the training session each subject completed a symptom questionnaire to indicate the presence and severity of aftereffects. Subjects were requested to return twenty hours later to respond again to the questionnaire. They were assured that their performance and responses would not affect their career and that their results would be confidential.

RESULTS & DISCUSSION

Ninety-five percent of the subjects experienced at least one symptom listed on the questionnaire given to them immediately after their training session on the simulator. A summary of their responses is presented in Table 3.

The most commonly reported symptoms include eye strain, after-sensations of motion, mental and physical fatique, and drowsiness. Most symptoms were rated mild, some moderate, none severe. The types of symptoms and their severity are similar to those reported in the literature. No subject reported severe simulator sickness as might have been expected on the basis of the anecdotal reports of pilots who flew the simulator soon after its installation. This may mean that some of the more provocative characteristics of the machine were corrected by software modifications. It may also mean that instructional staff learned to avoid practices known to precipitate simulator sickness, such as freezing the visual display or rapidly repositioning the aircraft (9).

To determine whether the overall incidence and severity of the symptoms reported by each group differed reliably, diagnostic criteria established by Kennedy, Dutton, Lilienthal Ricard and Frank (12) were used to rate the responses. They have published explicit criteria for evaluating simulator sickness. The criteria provide a means by which symptomatology may be ordered according to severity. A zero to seven scale is used; seven represents emesis. This rating scheme was used to avoid exaggeration of differences between groups due to high correlations among the responses to some symptoms, possibly accounted for by overlap in symptom meaning.

Diagnostic scores based on the questionnaire data are given in Table 4. The Mann-Whitney U test was applied to these scores to determine whether the two groups differed. The result was found to be non-significant ($Z_U = -1.1$; $p \geq .05$). It is of interest to note that twelve per cent of the aircrew obtained a diagnostic score of 3 or more which is believed to represent a threshold for voluntary training on the simulator (12).

Table 3: Frequencies Of Immediate Symptoms

Symptom/Reaction	Novice (n=16)			Experienced (n=26)			Total (n=42)
	Mild	Moderate	Severe	Mild	Moderate	Severe	
1. GENERAL LOSS OF WELL-BEING	3			4	3		10
2. WARMTH				6	2		8
3. HEADACHE	2	1		4	2		9
4. PHYSICAL FATIGUE	6	1		9	5		21
5. STOMACH AWARENESS	3			3			6
6. VOMITED(EMESIS)							0
7. LOSS OF BALANCE	5			5	1		11
8. EYE STRAIN	7	1		15	4		27
9. BLURRED VISION	1			9	1		11
10. LOSS OF DEPTH PERCEPTION	2	1		3			6
11. INVERTED VISION				1			1
12. VISUAL FLASHBACKS	1						1
13. APATHY	3			4	1		8
14. MENTAL FATIGUE	7			13	2		22
15. DROWSINESS	5			12			17
16. CONFUSION	1			3			4
17. DIZZINESS	1			3			4
18. VERTIGO	1			2			3
19. LEANS				5			5
20. SPINNING SENSATIONS-ROTATION	1			7	1		9
21. TRANSLATORY SENSATIONS	3			5	1		9
22. DISORIENTATION	1			4			5
23. AFTER-SENSATIONS OF MOTION	4	1		17	3		25
24. DIFFICULTY IN FINE MOVEMENTS	1			8			9
25. LOSS OF APPETITE				2	1		3
26. EXCESSIVE SALIVATION		1		1			2
27. BURPING							0
28. MOVEMENT OF VISUAL SCENE	3			7			10
TOTAL	61	6	0	152	27	0	246

Table 4: Diagnostic Score Frequencies - Immediate Symptoms

Experience	Diagnostic Score						Total
	0	1	2	3	4	5	
Novice	4	4	7	0	0	1	16
Experienced	3	6	13	3	0	1	26
Total	7	10	20	3	0	2	42

When asked the next day, a large number (81%) of subjects indicated that their symptoms lingered or that new symptoms arose following training. Table 5 provides a summary of the responses. It shows that the most commonly reported symptoms for both the experienced and novice groups were physical and mental fatigue, eye strain, drowsiness, after-sensations of motion, and headache. Most of these symptoms were mild, few moderate, none severe. Some symptoms lingered briefly for a few minutes, others persisted for many hours. One subject said he had a headache for 20 hours. Subjects experienced lingering symptoms for a median of 2.5 hours. There were three reports of delayed onset. One individual (experienced) reported that physical fatigue set in two hours after ending the training session, lasting eight hours. Another (novice) reported that physical fatigue set in 1.5 hours following training and lasted approximately 1.5 hours. A third subject (novice) reported that he experienced visual flashbacks, translatory sensations and after-sensations of motion for a brief period of time (approximately 5 minutes), ten hours after training.

Table 5: Frequencies Of Delayed Symptoms

Symptom/Reaction	Novice (n=16) Mild	Moderate	Severe	Experienced (n=22) Mild	Moderate	Severe	Total (n=38)
1. GENERAL LOSS OF WELL-BEING	1	1		2	1		5
2. WARMTH				2	2		4
3. HEADACHE	2	1		5			8
4. PHYSICAL FATIGUE	8	1		9	1		19
5. STOMACH AWARENESS	1			1			2
6. VOMITED(EMESIS)							0
7. LOSS OF BALANCE	3			2			5
8. EYE STRAIN	7	1		8	1		17
9. BLURRED VISION	2			2	2		6
10. LOSS OF DEPTH PERCEPTION	2						2
11. INVERTED VISION							0
12. VISUAL FLASHBACKS	1			1			2
13. APATHY	1			2			3
14. MENTAL FATIGUE	8			7	1		16
15. DROWSINESS	5			3	1		9
16. CONFUSION				1			1
17. DIZZINESS				1			1
18. VERTIGO					1		1
19. LEANS				1			1
20. SPINNING SENSATIONS-ROTATION				1			1
21. TRANSLATORY SENSATIONS	1						1
22. DISORIENTATION				1			1
23. AFTER-SENSATIONS OF MOTION	2			5	1		8
24. DIFFICULTY IN FINE MOVEMENTS					1		1
25. LOSS OF APPETITE	1				1		2
26. EXCESSIVE SALIVATION					1		1
27. BURPING							0
28. MOVEMENT OF VISUAL SCENE				1			1
TOTAL	45	4	0	55	14	0	118

The pattern of responses to the delayed questionnaire was similar for the two groups. Diagnostic scores are shown in Table 6. The groups did not differ according to the Mann-Whitney U test ($Z_U = -1.1$; $p \geq .05$). On the basis of this evidence, and the negative result noted above, there is no reason to conclude that there is any relationship between diagnostic score and flight experience on the Hercules aircraft. The empirical data do not implicate the mathematical model as a primary cause of simulator induced sickness, nor do they affirm the notion that experiential knowledge of vehicular dynamics predisposes aircrew to simulator sickness.

Table 6: Diagnostic Score Frequencies - Delayed Symptoms

Experience	Diagnostic Score 0	1	2	3	4	5	Total
Novice	3	7	5	1	0	0	16
Experienced	9	8	4	1	1	0	23
Total	12	15	9	2	1	0	39

Since the numbers of flight hours logged by members of each group overlap considerably it is possible to examine more generally the relationship between flight experience and simulator sickness. Total flight hours on all types of aircraft were correlated with diagnostic scores obtained from the immediate and delayed questionnaires. Because flight experience and age were found to be positively correlated ($r = .67$), and because sensitivity to disorientation and vertigo is known to increase with age (13), it was necessary to remove variation with age to determine the relationship between flight experience and diagnostic score. A partial correlation between the two variables of interest was computed. Also, because the criterion measures are ordinal, and contain many ties, the ranking technique suggested by Ferguson (14) was used to calculate correlation coefficients. The coefficient of correlation between total flight hours and diagnostic score, accounting for age, is .03 for immediate symptoms and -.17 for delayed symptoms, clearly non-significant values. These values do not change if the data for pilots alone are used. The lack of a relationship between total flight hours and diagnostic score suggests that general flight experience is also ineffective in influencing simulator induced sickness. There is no reason to believe that experienced aircrew are differentially sensitive to simulator characteristics, including its dynamic features. Therefore, temporal asynchronies between visual and motion systems do not seem to predispose experienced aircrew to simulator sickness contrary to expectation.

The results of the balance tests confirm this conclusion. A split-plot analysis of variance using the scores obtained from the WOFEC test revealed a significant practice effect ($F(1,36)=11.1$, $p \leq .002$) in the absence of an interaction effect between group and replication, or main effect due to experience. Similarly, only a significant main effect due to practice ($F(1,36)=5.1$, $p \leq .03$) was found for the SR balance test. Subjects showed a general improvement in balance. This is an interesting result considering that 25 subjects (60%) reported after-sensations of motion upon leaving the flight simulator, and that 11 (26%) reported loss of balance.

We suspect that practice effects mask ataxia. Failure to find degraded performance as a result of simulator exposure has been reported by Kennedy et al (15). In attempt to reconcile this result with that of Crosby and Kennedy (16), who found significant ataxia problems following a four-hour training session, they postulated that insufficient exposure to the simulator was the reason why they did not detect loss of balance, maintaining that the postural equilibrium tests are sensitive enough to measure meaningful effects. In the present study the duration of the training session was as long as that of Crosby and Kennedy. With the exception of occasional nystagmus, no overt signs of simulator sickness were evident.

The association between flight experience and simulator sickness is a topic of longstanding interest. Havron and Butler (2), the first to document simulator sickness, said that "Instructors reported sickness somewhat more frequently and in a more extreme form than students". Havron and Butler suggested that instructor's expectancies are more firmly fixed; consequently, they may be more sensitive to simulator inadequacies. But, they also offered alternative explanations, noting that the students handled the controls more often, and that visual distortions may be more apparent to the experienced pilot who scans the entire visual scene rather than concentrating on a specific area.

Miller and Goodson (3) also suggested that experience may be an important factor in the genesis of simulator sickness. This suggestion was based on their finding that 60% of instructor pilots reported symptoms compared to 12% of student pilots. They suggested that a difference in willingness to report symptoms may be one factor that helps explain the difference in incidence between instructors and students. McGuiness, Bouwman and Forbes (5) found that aircrew with more than 1500 flight hours had a higher incidence of symptoms than less experienced aircrew, but they note that other characteristics of the subject populations complicate the interpretation of this result. Physiological changes resulting from aging may influence susceptibility, they say, because problems of disorientation and vertigo increase with the age of aviators (13). Paradoxically, the relationship between age and experience is used by Kennedy (17) to help explain a finding in apparent contradiction to the rest of the research literature. He found that more experienced flight engineers reported fewer symptoms of simulator sickness than seemingly less experienced personnel. He explains that loss of vestibular and visual sensitivity with age may afford some protection from simulator sickness by reducing the salience of conflicting cues.

In conclusion, the research literature provides a small amount of circumstantial evidence, often gathered incidentally, bearing on the significance of flight experience. A variety of confounding variables have been offered to cloud the establishment of a clear relationship between flight experience and susceptibility to simulator induced sickness. The significance of the present study is that it directly assessed the role of experience, examining the relevance of both type specific and general aircraft experience, and that it took into account age as a confounding variable. The results challenge the generality of the notion that flight experience predisposes aircrew to simulator sickness. However, we do not regard our results as definitive. One reasonable explanation for the apparent ineffective role of experience in the present study is that the experienced group possessed both simulator and aircraft experience. They may have learned to reduce simulator induced sickness by spontaneously practising techniques to alleviate its occurrence, such as minimizing head movements or avoiding the visual display (see (9)). Insufficient data were obtained in this study to dissociate these facets of experience. Clearly, additional experimentation is needed to clarify further the associations among simulator fidelity, flight experience and simulator induced sickness.

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DISCUSSION

UNIDENTIFIED QUESTIONER: Did you observe some nystagmus?

MAGEE: Yes, we did. It was a very rare event, but we picked this up on three or four different occasions, but we are unable to explain these responses. I should have mentioned that there were no overt signs of pallor, sweating, or drowsiness. Also, we saw nystagmus on a couple of occasions before the simulator run, so these data are not meaningful.

GUEDRY: Under what conditions did you observe the nystagmus?

MAGEE: We simply observed subjects' eyes as they followed our fingertips, i.e., as they looked to the left, to the right, up, and down. It was not sophisticated testing. (Note: Answer did not clearly distinguish between evaluation of quality of pursuit eye-tracking, presence of gaze nystagmus, etc., but this was obviously not a primary objective.)

PRICE: Did you say that 60% of the subjects experienced after-effects, or 60% of those who presented symptoms had after-effects?

MAGEE: 60% scored greater than 2 on the diagnostic scale. Twenty-five of the 42 subjects scored at least 2, 3, 4, 5 on our diagnostic scale.

PRICE: So that was not related to after-effects but rather percent having symptoms?

MAGEE: Yes. (Note: Magee's Table 5 shows that 12 of 39 subjects indicated Delayed Symptom Scores of 2 or greater.)

BENSON: Coming back to the problem of ataxia following exposure, do you have any idea of the incidence of ataxia following real flight?

MAGEE: No.

BENSON: I think we need this comparison between effects following real and simulated flights.

MAGEE: Yes, but I think it is more important to examine these ataxia tests - they seem very insensitive. I was alarmed by how easy it was to improve performance by practice, by simple things like distributing more or less weight across the two feet, locking one knee behind the other, etc. We need to improve our tests of ataxia before moving to the problem of comparing effects of actual flight and simulator flight. (Note: There are elaborate methods of evaluating ataxia as indicated by Parker later in the meeting.)

BENSON: The question is whether or not ataxia is a simulator effect or one that also occurs during real flight.

BERRY: If I understood you correctly, there was a coffee break in the middle of the 4-hour session?

MAGEE: Yes.

BERRY: Did you evaluate whether coffee or tea consumption during the break had any effect on performance?

MAGEE: No.

BERRY: I would think that there might be a significant effect.

MAGEE: I don't know. These fellows drink a lot of coffee all the time. If we deprived them of coffee, we may have found a larger effect.

DOPPELT: Although it was not the point of your paper, did you do any analysis as to training-effect activity relating to the symptoms?

MAGEE: None. I'd love to.

CASALI: Given the level of transport delay inherent in the simulator control loop, do you have any information on how the tracking performance in the simulator and control reversals correlate with what is actually experienced in the plane?

MAGEE: No, I did not measure performance. I know that we were not having problems with oscillation, but I have no measure of actual tracking performance.

SIMULATOR SICKNESS IN THE ROYAL AIR FORCE: A SURVEY

J W Chappelow
RAF Institute of Aviation Medicine
Farnborough
Hampshire GU14 6SZ

SUMMARY

A questionnaire survey was undertaken of pilots with experience of two air combat simulators. Two hundred and seventy one respondents completed questionnaires, some up to two years retrospectively and others immediately after a simulator session. There were, thus, four separate studies. The questionnaires sought information on the incidence of disequilibrium and other symptoms experienced in the simulator and after leaving it. The proportion of those suffering at least one symptom in the simulator varied between 50% and more than 90% across studies (53.5% overall). However, not all the symptoms reported were unequivocally ascribable to disequilibrium. The proportion of each sample reporting delayed symptoms was between 10% and 50% (13% overall). The effect on the respondents' motivation to use the simulator was negligible.

INTRODUCTION

The surveys reported in this document were undertaken at the behest of the Simulator Technology Research Liaison Committee of the Ministry of Defence. The interest in simulator-induced sickness was provoked by reports originating in the United States of America suggesting that modern simulators, particularly those with wide field of view visual systems and no motion platforms, could induce symptoms of disequilibrium both in the simulator and some time after leaving it. Delayed symptoms could pose a serious threat to flight safety. Symptoms experienced in the simulator could compromise training by direct interference or by reducing the trainee's motivation to use the simulator.

Kennedy et al (1) have provided a convenient summary of seven studies of simulator sickness between 1957 and 1982 involving four simulator types and exposures of 30 minutes to one hour for air combat simulators and up to four hours on other types. Among the generalisations they derived from these studies were the following:

- Nausea, dizziness and ataxia were the most commonly reported symptoms.
- Incidences ranged from 11% to 88%.
- Wide field of view was a factor.
- The likelihood of symptoms was related to the intensity of manoeuvring or the duration of exposure to the simulator.
- More experienced pilots were more susceptible.

They went on to investigate the incidence of simulator sickness among 64 aviators flying one of two helicopter simulators. They found that nearly 40% reported two or more symptoms and 80% reported at least one symptom. Kennedy et al (2) investigated 1008 aircrew members exposed to eleven simulators and found one or more symptoms in 13% to 55% of cases.

One of the more disturbing studies included in the summary was that by Kellog et al (3) on an air combat simulator. Of 48 pilots 87.5% exhibited some untoward effects. Nausea was reported by 79.2%. Sensations of spinning or pitching, vivid visual images of the simulator sortie and other symptoms were experienced after leaving the simulator - in some cases ten hours later. The pilots were engaged in an intensive programme of air combat training involving approximately 12 hours of simulator flying in one week.

Drawing on the extensive experience of simulator sickness recorded in these studies, Kennedy et al (4) have proposed guidelines for simulator use intended to minimize the untoward effects. These include:

- Avoiding freezing in unusual attitudes or slewing the visual system while it is visible to the pilot.
- Restricting the duration of simulator sessions to less than two hours and taking breaks during a session.
- Allowing at least one day breaks between simulator sorties.
- Reducing the duration and intensity of activities after long periods away from the simulator.

The Royal Air Force has an increasing requirement for air combat simulation. The combination of very wide angle field of view and fixed-base cockpits in the air combat simulators currently in use and projected for future use is, according to the evidence available, potentially provocative of symptoms. Most invidious would be delayed symptoms of disequilibrium engendered by adaptation to the simulator environment. The intention behind the current study was to draw on existing experience of air combat simulators in the RAF in order to gauge the size of the problem.

METHOD

Two air combat simulators were available for study. They had essentially similar designs (fixed-base cockpits within a projection dome) but the one at the Royal Aircraft Establishment, Farnborough was used exclusively as a research tool; the pilots surveyed had taken part in a variety of trials not directly linked to air combat flying. The pilots surveyed for their experience of the simulator at British Aerospace, Warton, had all been engaged in air combat training.

A questionnaire was devised in two forms: Form A was to be given to pilots immediately after exposure to a simulator for completion in two parts, the first (covering symptoms experienced in the simulator) during the debrief, the second (covering delayed symptoms) three days later. Form B was similar but was a retrospective inquiry sent to pilots who had been exposed to the simulators during the preceding two years. The Farnborough simulator was the subject of the first phase of the investigation; pilots with experience of the Warton simulator were surveyed later. As a result of experience in the first phase, one question ("For how long did you fly the simulator?") was slightly altered to permit a finer categorisation of responses. The questionnaires sought information in the following categories:

- Total flying experience
- Experience of the air combat simulator.
- Effects experienced in the simulator.
- Delayed effects.
- Activities after flying the simulator (flying or driving) and unusual effects experienced while engaged in those activities.
- Unusual symptoms experienced in other simulators.
- Changes of attitude towards the simulator.
- Other comments.

A full list of the effects for which a Yes/No response was sought can be seen in Tables 2 (immediate effects) and 3 (delayed effects).

RESULTS

The return rate for the two retrospective studies was approximately 70%. The results from the two simulator sites and two forms of the questionnaire are sufficiently different to warrant separate presentation in most of the tables and figures that follow. Table 1 contains a summary of the total flying experience of the respondents. Table 2 shows the incidence of immediate effects, and Table 3 that of delayed effects.

In Figure 1 the extent of exposure to the air combat simulators is summarised. Figure 2 records the proportions of respondents suffering one, two, three, more than three or no symptoms while flying the simulator; the effects "exhilaration" and "sense of well being" have been excluded from this and all other analyses in which the term "symptoms" is used in preference to the term "effects". Figure 3 presents a similar analysis of delayed symptoms.

Many of the comments added by respondents provided interesting qualifications to the rather bald statement that a symptom had been experienced. The following list paraphrases and summarizes most of those comments:

- Symptoms experienced as a result of standing in the dome next to the simulator cockpit: 29 comments (all from Warton); most of the reported symptoms were not included in the data but 13 immediate and eight delayed symptoms reported by ten respondents were in a sufficiently ambiguous context to warrant inclusion.
- Symptoms (particularly fatigue) ascribed to prolonged or high workload: 14 comments.
- Symptoms due to equipment deficiencies: These were mainly confined to criticisms of the visual systems, eg poorly defined horizon causing uncertainty about attitude, out of focus visual system or head-up display causing headache or visual problems and limited resolution of the visual system making target selection difficult: 9 comments
- Symptoms due to the realism of the simulation: 8 comments, eg difficulty with perception of attitude when near the vertical; feelings of instability (unsteadiness) at low airspeed.

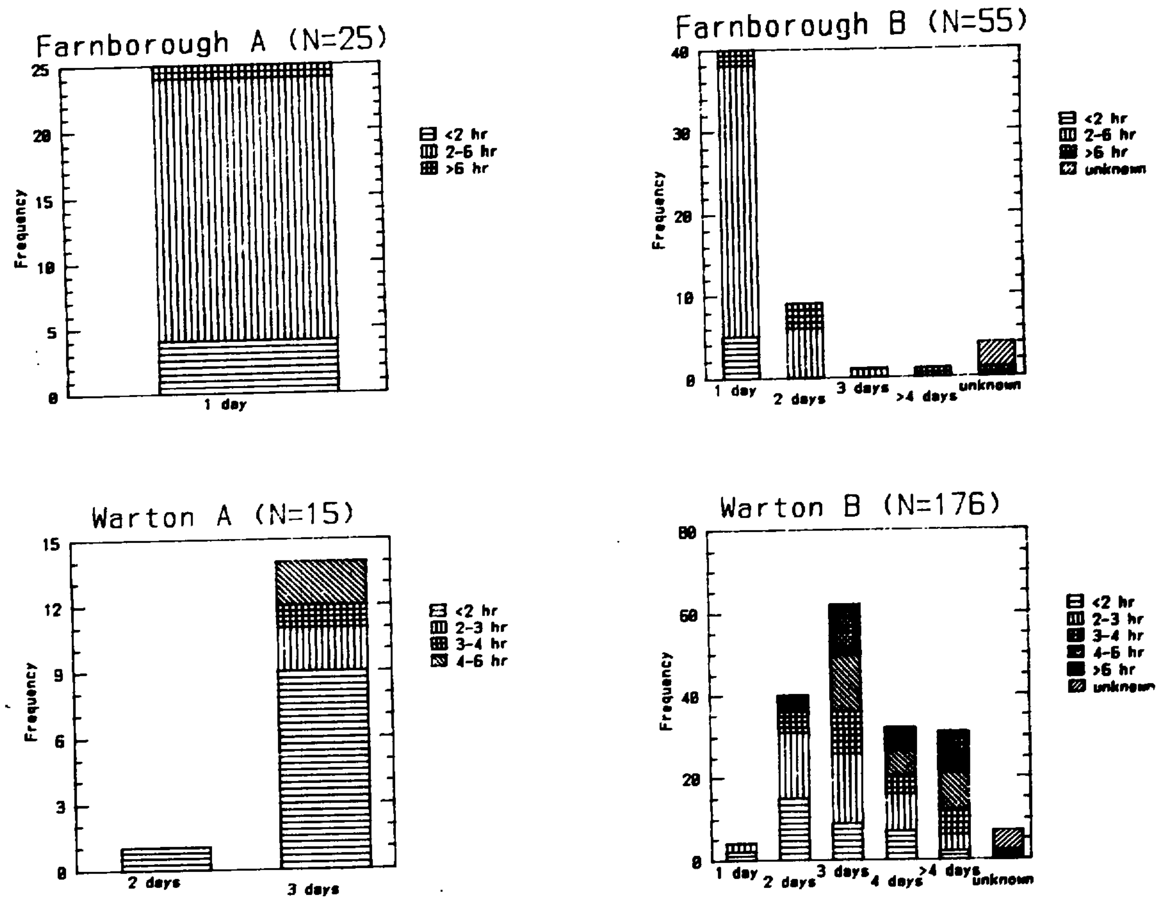

Figure 1: Time spent in the simulator

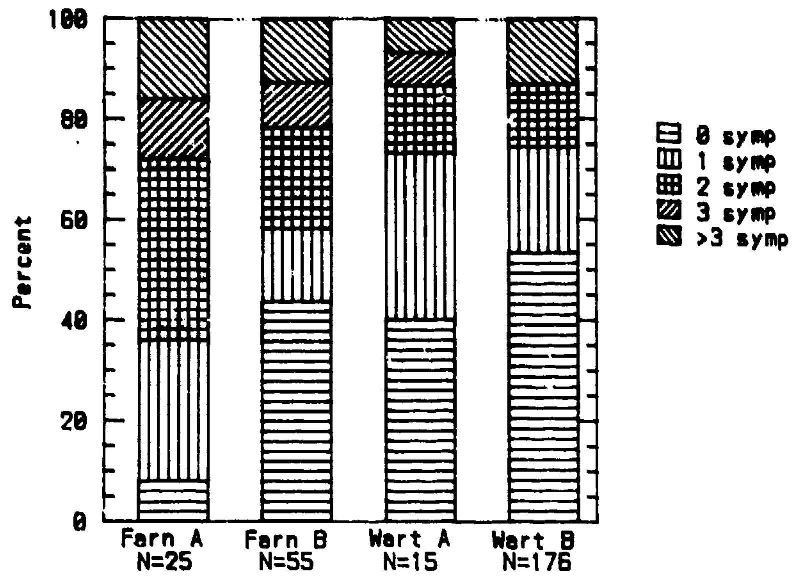

Figure 2: Incidence of immediate symptoms

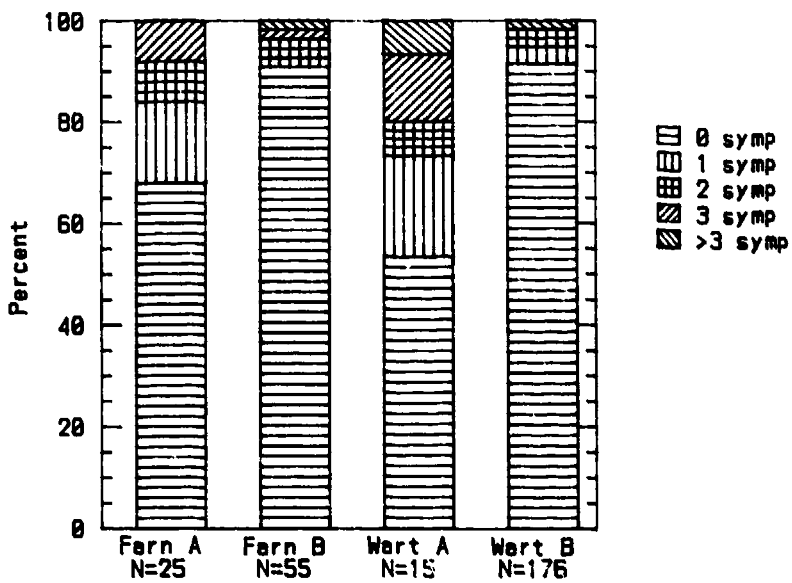

Figure 3: Incidence of delayed symptoms.

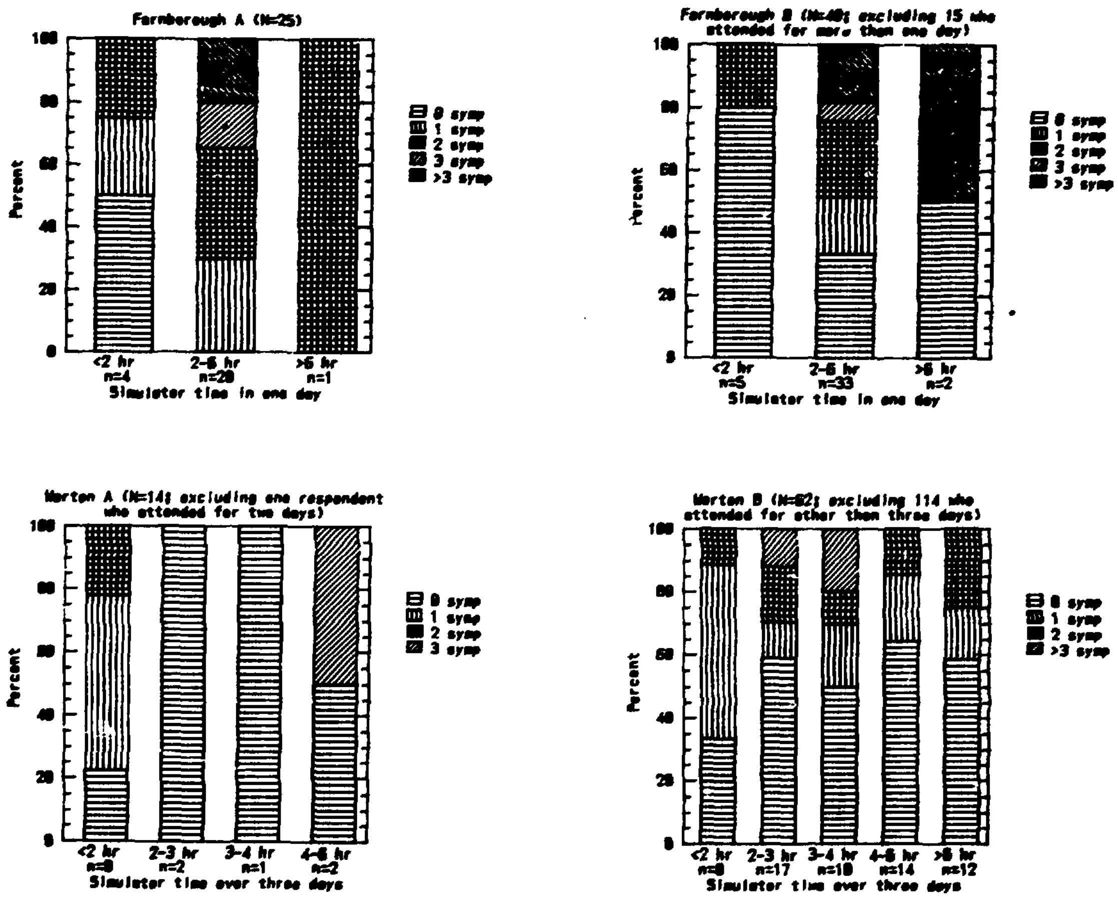

Figure 4: Immediate symptoms versus time in the simulator

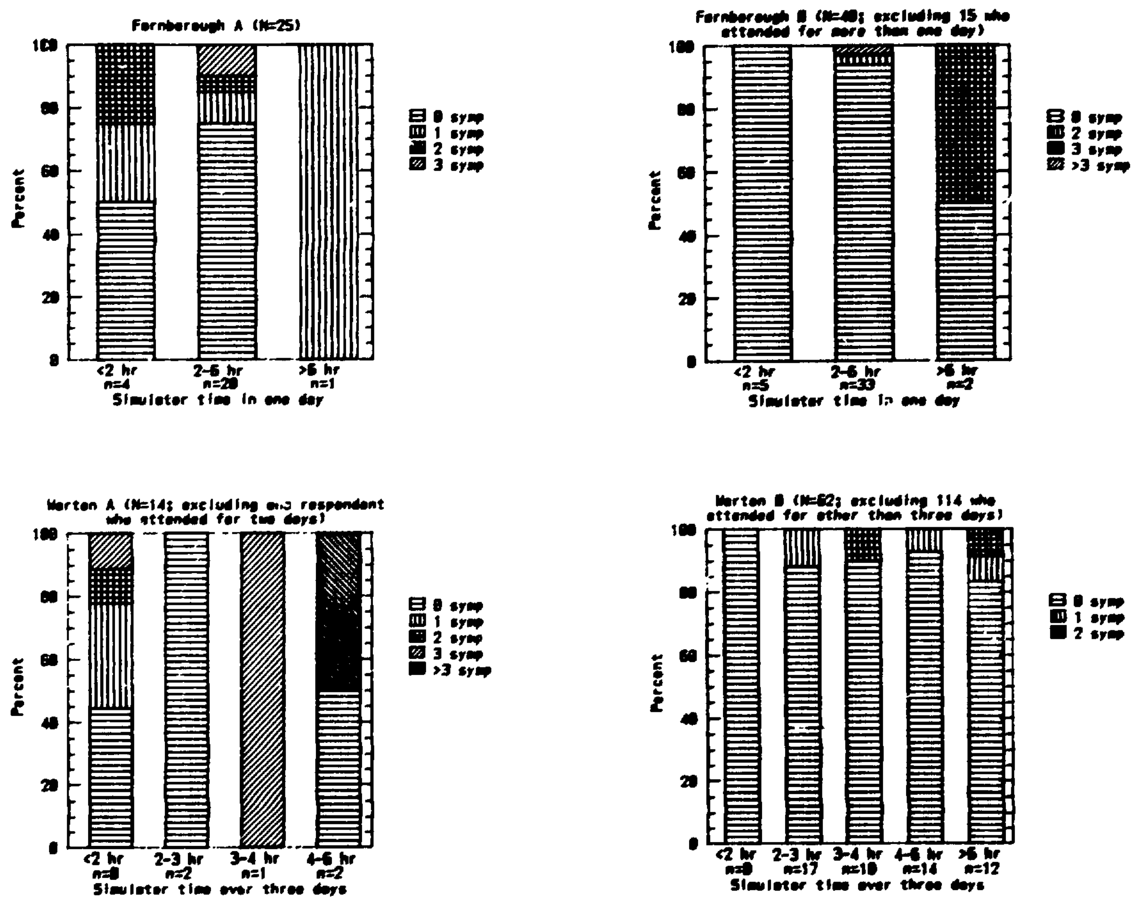

Figure 5: Delayed symptoms versus time in the simulator

- Symptoms only slight or very brief: 10 comments.
- Symptoms possibly due other factors (alcohol or food): 5 comments (all from Warton).
- Symptoms experienced mainly or only during visual system resets: 5 comments.

With the exception of the 15 Warton A-Form respondents, those who suffered more immediate symptoms appeared to suffer more delayed symptoms as well. The correlation (for the entire sample) between number of immediate symptoms and number of delayed symptoms reported is low, but significant ($r_s = 0.26$, $p<0.01$). There was no correlation between total flying hours and number of immediate or delayed symptoms.

In considering the effects of time in the simulator on the number of symptoms reported, analysis was restricted to respondents reporting the modal number of days of exposure (one for Farnborough, three for Warton). Figure 4 shows that longer exposure to the Farnborough simulator tended to produce more symptoms in the simulator. Combining respondents to Forms A and B for the Farnborough simulator yields a small, but significant correlation ($r_s = 0.28$, $p<0.05$). The relationship is not apparent in the Warton data for immediate symptoms (Figure 4) or in the delayed symptom data from either simulator (Figure 5).

Table 4 shows the number who flew an aircraft or drove a car after flying the simulator and, of those, the number who did so with symptoms.

Some respondents (nearly all of them in the Warton B sample) were known to have had more than one exposure to the simulator. Table 5 shows that a smaller proportion of these pilots reported symptoms, but the difference was not significant (Fisher Exact Probability tests for immediate symptoms p=0.12; for delayed symptoms p=0.36).

Respondents who had reported immediate or delayed symptoms were asked to assess the effect of the experience on their willingness to use the simulator. Table 6 summarizes these responses.

TABLE 1: Total flying experience (hours)

Location:	Farnborough		Warton	
Form:	A	B	A	B
N =	25	55	15	176
Mean	2372	2332	613	1533
Standard deviation	1105	1169	541	134
Minimum	400	400	200	100
Maximum	5000	4700	1700	6000

TABLE 2: Incidence of immediate effects (percentage)

Location:	Farnborough		Warton	
Form:	A	B	A	B
N =	25	55	15	176
false perception of attitude	28	13	20	35
dizziness	12	4	0	8
spinning sensations	4	5	7	6
unsteadiness	8	4	27	13
headache	12	11	0	1
pallor	0	0	0	1
stomach awareness	4	2	0	3
burping	0	0	0	1
lassitude/weakness	0	2	0	1
yawning	0	13	13	2
cold sweat	0	2	0	3
confusion	4	5	13	6
physical fatigue	48	25	0	3
mental fatigue	32	33	0	6
visual problems	8	7	0	7
difficulty with fine movements	12	2	13	7
exhilaration	24	11	27	24
sense of well being	4	2	0	5

TABLE 3: Incidence of delayed effects (percentage)

Location:	Farnborough		Warton	
Form:	A	B	A	B
N =	25	55	15	176
false perception of attitude	0	0	13	1
dizziness	0	2	40	2
headache	4	4	0	1
pallor	0	0	0	0
stomach awareness	4	0	0	1
loss of appetite	0	0	0	0
nausea	0	0	0	1
vomiting	0	0	0	0
unusual physical fatigue	12	4	0	1
unusual mental fatigue	8	5	0	1
yawning	0	2	0	1
burping	0	0	0	0
confusion	0	0	0	0
spinning sensations	16	4	7	2
unsteadiness	0	2	20	2
difficulty with fine movements	0	0	0	0
visual problems	0	0	0	0
vivid visual images	4	0	13	5
flying sensations	8	0	7	2

TABLE 4: Post-simulator activities (number reporting)

Location:	Farnborough		Warton	
Form:	A	B	A	B
N =	25	55	15	176
flew an aircraft...	0	9	0	7
...with delayed symptoms	0	2	0	0
drove a car...	20	44	8	110
...with delayed symptoms	2	6	0	1

TABLE 5: Incidence of symptoms and number of exposures (Warton B only)

	Immediate symptoms		Delayed symptoms	
Number of exposures	None	One or more	None	One or more
One	78	74	138	14
Two or more	16	8	23	1

TABLE 6: Effects on willingness to use the simulator. (Percentage)

Location:	Farnborough		Warton	
Form:	A	B	A	B
N =	25	55	15	176
Greatly increased	0	9	13	10
Slightly increased	12	4	7	5
No influence	44	27	47	28
Slightly decreased	4	0	0	1
Greatly decreased	0	2	0	1
No answer	40	58	33	55

DISCUSSION

General comments:

Few significant relationships were apparent in these data. The number of untoward symptoms experienced in the simulator or afterwards was not demonstrably related to the total previous flying experience of the pilots. There was no statistically significant change in the incidence of symptoms with repeated exposure to the simulators (Table 5). Length of exposure to the simulator was not demonstrably related to the number of delayed symptoms reported. However, pilots flying the Farnborough simulator were more likely to experience symptoms during a long session than a short one. It is probably no coincidence that physical and mental fatigue are the predominant symptoms reported from Farnborough; prolonged and heavy workload was, apparently, a more significant problem than disequilibrium (see Table 2) for reasons discussed below (under Immediate symptoms).

Pilots who reported many immediate symptoms were also more likely to report delayed symptoms. This finding is somewhat at variance with the notion that delayed symptoms of disequilibrium are likely to arise as a result of adaptation to the simulator environment, and is due to many of the reported delayed symptoms being continuation of effects experienced in the simulator (eg fatigue, some reports of dizziness and unsteadiness). Exceptions are flying and spinning sensations, which were most often experienced on closing the eyes when going to bed.

The delay (over a year in some cases) in reaching some of the retrospective respondents must, inevitably, have allowed a number of less noteworthy effects to be forgotten. The fact that the visit to the air combat simulator was an interesting and unique experience for many of the respondents may have reduced this memory loss. On the other hand, the administration of Form A questionnaires may, in itself, have drawn attention to symptoms that would otherwise have gone unnoticed. Overall, it is to be expected that the retrospective surveys (Form B questionnaires) should reveal a lower incidence of symptoms than the A Form questionnaires. In general this is so. The safest course is, probably, to regard the two sets of results as representing upper and lower bounds on an estimate of the incidence of symptoms to be expected in similar simulators. To the extent that the Warton simulator was used purely for air combat training, whereas the Farnborough simulator was used for research purposes, the data from Warton are a better guide to what should be expected from future use of training air combat simulators in the RAF.

The effect of untoward symptoms on the respondents' willingness to use the simulator (Table 6) was generally slight and only in a few instances negative. In view of the nature of the question (it was directed only at those who had suffered unpleasant symptoms), it is surprising that the balance of responses favoured an increased willingness to use the simulator. An explanation was evident in additional comments. These indicated that many respondents thought the simulators provided valuable training in important skills, and were fun to fly; the positive aspects outweighed the negative.

Immediate symptoms:

A clear difference between the Farnborough and Warton respondents is evident in Table 2. Pilots flying the Farnborough simulator reported physical and mental fatigue far more frequently than those flying the Warton simulator. The most likely explanation for this difference lies in the different purposes for which the pilots used the simulators: At Warton students received instruction in air combat often in short (10 minutes) sessions. At Farnborough pilots participated in experimental trials. The necessity for repeated and extensive measurement in equipment evaluation inevitably favours rather more arduous working conditions for the pilots. In addition, in some of the trials, pilots reported physical fatigue and difficulty with fine movements due to heavy stick forces. The different regimes at the two sites are reflected in Figure 1. Most of the Farnborough respondents had between two and six hours in the simulator in a single day. Very few of those attending the Warton simulator achieved more than two hours simulator time in one day; in general they spent two to four days at the site and only a small proportion exceeded six hours in the simulator in that time.

Leaving fatigue aside, there is some evidence of disequilibrium induced in both simulators, the main symptoms being false perception of attitude at Farnborough and false perception of attitude and unsteadiness at Warton (Table 2). However, the qualifying comments supplied by some respondents indicate that caution is required in interpreting these results. Symptoms such as confusion, headache and visual problems were often associated with comments about poor contrast or focus of the visual system or head-up display inadequacies. Some of the reports of dizziness, unsteadiness and false perception of attitude may have resulted from passive observation of the visual system. Some symptoms were reported as being only mild or short-lived, or as due to over-indulgence in alcohol or highly spiced food. Some were ascribed to the realism of the simulation, ie the respondents felt that they would have had similar experiences in the air, and a few resulted from system resets. Although a small proportion of respondents reported three or more symptoms (Figure 2), none appears to have been incapacitated or seriously discomforted by his experiences.

Bearing in mind the differences between the Farnborough and Warton results, it seems likely that most untoward symptoms in air combat simulators could be avoided by restricting the duration of training sessions to short periods and by avoiding certain provocative conditions. For example the visual system and head-up display should be carefully maintained in focus; resetting the simulator with the visual system illuminated should be not be permitted. Intensive repetition of training sessions over several days should be avoided. Inspection of Figure 4 suggests that if a maximum permitted exposure of one hour per day is observed over periods of one to three days, then at least half the pilots should experience no noticeable symptoms at all. Taking into account the numbers reporting fatigue or symptoms ascribable to other factors, the proportion experiencing symptoms unequivocally of disequilibrium should be small.

Delayed symptoms:

The results from the retrospective surveys indicate a very low incidence of delayed symptoms (Table 3); this is probably a fair indication of the salience of the symptoms as experienced by the respondents. The concurrent (Form A) results are less reassuring, though the small numbers involved should be borne in mind. Physical fatigue (mainly ascribed to long sorties and high stick forces) was reported by 12% of the Farnborough

Form A respondents. Four respondents (16%) also complained of spinning sensations; all four associated the symptom with closing the eyes on going to bed. One found his sleep disturbed (and cancelled his first flight the next day); one reported only mild sensations; one reported purely visual images of turning; and two thought that thinking about the questionnaire or the simulator ride had provoked the experience.

Six Warton Form A respondents (40%) reported delayed dizziness (Table 3). Three of the six (20% of the sample) also reported unsteadiness. One described his symptoms as "minor in nature" although they lasted for six hours. Three indicated that the dizziness lasted only a few minutes immediately after leaving the simulator. Interestingly, three of the six were among those who reported experiencing symptoms while standing in the simulator dome.

Few respondents flew an aircraft after the simulator (Table 4). The two who reported "symptoms" were actually commenting on a difference in head-up display presentation between the simulator and their aircraft. A total of nine respondents reported experiencing symptoms while driving a car after the simulator flight (about 5% of those who drove). The majority of these reports concerned fatigue. Two concerned detachment from reality, two disequilibrium, and one vivid visual images.

If, as suggested above, simulator air combat training is conducted in short sessions totalling not more than an hour a day, then the risk of delayed symptoms would probably be around 10% (taking Figure 5 as a guide). Allowing a night's sleep before recommencing flying duties should reduce residual risks to negligible proportions. Although it should be expected that the majority of delayed symptoms experienced under such a regime would be tolerable, being very short-lived or mild or occurring only on going to sleep, the possibility of a small number of pilots suffering more severe disturbance should be recognised, and allowed for. In view of the fact that several of those reporting delayed symptoms of dizziness, spinning sensations etc also reported experiencing symptoms while standing in the simulator dome, it would probably be wise to include time spent in such passive observation of the visual system in the one hour per day exposure limit.

Comparison with previous studies:

The incidences of symptoms experienced in the simulator found in this survey seem comparable with the rather broad range reported in previous studies. However, when the respondents' qualifying comments are taken into account, the overall impression is that disequilibrium may be rather less of a problem in these simulators than elsewhere. The low incidence of serious delayed symptoms supports this view. There are two main reasons why a difference might be expected. The exposure borne by the Warton respondents was considerably less intense than that suffered by, for example, the air combat pilots in the study by Kellog et al (2); to a large extent it would meet the guidelines suggested by Kennedy et al (4). Both the simulators in this survey were primarily research devices. This fact could have implications for the standard and amount of maintenance effort devoted to them in comparison with training simulators. As a result, there may be less scope for the minor misadjustments or drifting out of specification that can make the simulator feel unlike the aeroplane to an experienced pilot.

Although the data reported here give less cause for alarm than some previous studies, they do, nevertheless, provide support for many of the guidelines suggested by Kennedy et al (4). Specific modifications of current practice that seem to be justified are:

1. Avoidance or restriction of passive observation of the visual system by air combat pilots using the Warton simulator.

2. Finding some means of ameliorating the lot of pilots taking part in experimental trials at Farnborough.

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DISCUSSION

ELLIS: You mentioned false perception of attitude as a symptom. Could you elaborate on that? Are there any patterns to the errors in attitude perception?

CHAPPELOW: I'm afraid I can't. This was essentially a checklist and all we have is checks in boxes. I think the false perception of attitude reported as a delayed symptom may well have arisen when people stopped the simulator with a large angle of roll or pitch and then tried to step out. Some people did elaborate slightly. They had difficulty appreciating what their attitude was near the vertical.

ELLIS: If I might just follow up - the false perception of attitude refers to an experience upon just leaving the simulator?

CHAPPELOW: Not necessarily. It could be a false perception while still in the simulator or while engaged in flying, so there were two separate issues - whether it was experienced in the simulator or was a delayed symptom.

DOPPELT: Could you please describe what the scenarios were that were used in the two simulators; that is, how they differed technically, intensity of training and so forth, and secondly, was there a difference in the simulators in terms of the visual and control response characteristics?

CHAPPELOW: To some extent I can answer your question. At Warton, subjects were engaged in, to a large extent, basic air combat training. Most of them were pilots undergoing advanced flying training. As I said, most of them got short bursts of about 10 minutes, adding up to about an hour a day in basic instruction. At Farnborough, there was a variety of trials; not all of them really involve much maneuvering risk, but flying in air combat training. Some of them were air-to-ground, some of them were tests of helmet-mounted sights or infrared devices, so there was a wide variety. Low-risk maneuvers are certainly not as provocative as air combat. The simulators, while of the same basic design, were different in terms of control characteristics according to which aircraft they were simulating, and were different, I think, in terms of the visual displays used. At Warton there is a computer-generated background earth display which is "flat fields" with a superimposed aircraft model. Farnborough had a variety of devices, including models which a computer manipulates.

SIMULATOR SICKNESS IN U.S. ARMY AND NAVY FIXED- AND ROTARY-WING FLIGHT SIMULATORS

Daniel W. Gower, Jr., MAJ
Director, Biodynamics Research Division
U.S. Army Aeromedical Research Laboratory
P.O. Box 577
Fort Rucker, Alabama 36362-5292

Michael G. Lilienthal, LCDR
Branch Head, Training & Development Branch
Human Factors Division
Naval Training Systems Center
Orlando, Florida 32813-7100

Robert S. Kennedy, Ph.D.
Facility Director
Essex Corporation
1040 Woodcock Road
Orlando, Florida 32803

Jennifer E. Fowlkes, Ph.D.
Staff Scientist
Essex Corporation
1040 Woodcock Road
Orlando, Florida 32803

SUMMARY

As technology has been developed to provide improved visual and motion systems in operational flight trainers and weapons tactics trainers, there have been increasing reports of the occurrence of simulator sickness. Simulator sickness here refers to one or more symptoms which can occur while in a simulator, immediately postexposure, or at some later time following exposure. Flight instructors have complained these symptoms interfere with simulator usage. Some pilots have reported while driving following postexposure, they have had to pull off the road and wait for symptoms to subside. Instructor-operators have reported experiencing "the room spinning" when they went to bed. More critical is the potential for in-flight problems due to prolonged physiological effects. As a result, flight activities after simulator flight have been limited in some commands.

The U.S. Army Aeromedical Research Laboratory at Fort Rucker, Alabama, and the Naval Training Systems Center at Orlando, Florida, have conducted field surveys to document the extent of the simulator sickness problems at operational fixed- and rotary-wing simulator sites. Data are pooled from 10 different Navy flight simulators and the Army's AH-64 flight simulator. The total number of surveys is approximately 1500, with the number of subjects in each simulator type ranging from 28 to 280. The simulator sickness incidence rates and the relative frequency of specific symptoms are presented and correlational factors such as flight experience, simulator experience, and flight mode also are presented. Difficulties in assessing the duration of simulator sickness effects are noted, and attempts are made to present the symptom duration for the Army's AH-64 combat mission simulator (CMS). Unique to this CMS is its use of the helmet display unit (HDU) in conjunction with the other visuals in the simulator.

The combined Army and Navy simulator sickness database is an ongoing attempt to relate symptoms to specific equipment features, simulator instructional techniques, training procedures, and trainee characteristics. The study reinforces the need for continued research related to system design, training methods, and crew rest guidelines between simulator and actual flight.

INTRODUCTION

Training, the military's primary mission during peacetime, creates large and continuing demands on the financial resources allocated to the Department of Defense. For example, it costs about $3.6 billion per year for fuel and supplies to operate military aircraft in the United States. Much of this military flying is conducted for training purposes. However, flight simulators can be operated at 5 to 20 percent of the cost of comparable aircraft (Orlansky and String, 1979). Generally, pilots trained in simulators can acquire necessary skills with fewer flight hours than those pilots who are not training in simulators.

Advancing engineering technologies permit a range of capabilities to simulate the real world through very compelling kinematics and computer-generated visual scenes. Aviators demand realistic simulators. However, this synthetic environment can, on occasion, be so compelling that conflict is established between visual and vestibular information specifying orientation (Kennedy, 1975; Oman, 1980; Reason and Brand, 1975). It has been hypothesized that in simulators, this discrepancy occasions discomfort and the cue conflict theory has been offered as a working model for the phenomenon labeled "simulator sickness" (Kennedy, Berbaum, and Frank, 1984). In brief, the model postulates the referencing of motion information signaled by the retina, vestibular apparatus, or sources of somatosensory information to "expected" values based on a neural store which reflects past experience. A conflict between expected and experienced flight dynamics of sufficient magnitude can exceed a pilot's ability to adapt, inducing in some cases simulator sickness.

The nature of simulator sickness

Simulator sickness is considered to be a form of motion sickness. Motion sickness is a general term for the constellation of symptoms which result from exposure to motion or certain aspects of a moving environment (Casali, 1986), although changing visual motions (Crampton and Young, 1953; Teixeira and Lackner, 1979) may induce the malady. Pathognomonic signs are vomiting and retching; overt signs are pallor, sweating, and salivation; symptoms are drowsiness and nausea (Kennedy and Frank, 1986). Postural changes occur during and after exposure. Other signs (cf., Colehour and Graybiel, 1966; McClure and Fregly, 1972; Money, 1970; Stern, Koch, Stewart, and Lindblad, 1987) include changes in cardiovascular, respiratory, gastrointestinal, biomedical, and temperature regulation functions. Other symptoms include general discomfort, apathy, dejection, headache, stomach awareness, disorientation, lack of appetite, desire for fresh air, weakness, fatigue, confusion, and incapacitation. Other behavioral manifestations influencing operational efficiency include carelessness and incoordination, particularly in manual control. Differences between the symptoms of simulator sickness and more common forms of motion sickness are that in simulator sickness visual symptoms tend to predominate and vomiting is rare.

Previous simulator sickness research

The studies by Havron and Butler (1957) and Miller and Goodson (1958) appear to be the first published reports of simulator sickness. They found a substantial incidence of symptoms among users of the Navy's 2-FH-2 helicopter simulator. (Instructor pilots were found to be more susceptible than students.) One of the first attempts to document the problem in the Air Force was reported by Kellogg, Castore, and Coward (1980). They surveyed 48 pilots using the Air Force simulator for air-to-air combat (SAAC) and found a majority (88 percent) had experienced some symptoms of simulator sickness (primarily nausea) during SAAC training. Of particular interest were the F-4 pilots who reported delayed perceptual aftereffects including sensations of climbing and turning while watching TV, or they experienced an 180-degree inversion of the visual field while lying down. The Air Force authors suggested "the users of such (wide field-of-view) simulators should be aware that some adjustment may be required by pilots when stepping back into the real world from the computer-generated world ..."

U.S. Navy studies

An investigation of simulator sickness in the Navy's 2E6 air combat maneuvering simulator (ACMS) found that 27 percent of the aircrews using the ACMS reported varying degrees of symptoms (McGuinness, Bouwman, and Forbes, 1981). The more experienced aircrews (over 1500 flight hours) had a higher incidence of symptoms than the less experienced flight crews. Dizziness was the most frequent symptom, followed by vertigo, disorientation, "leans," and nausea. The incidence of symptomatology was greater in pilots than in radar intercept officers (RIOs). The authors suggested one reason for the reduced levels of simulator sickness found in the 2E6 pilots, relative to the Air Force SAAC, may have been the less intensive schedule of simulator time. Exposure duration and frequency appear to be potentially important variables, as has been found in other environments that produce motion sickness (McCauley and Kennedy, 1976).

Frank (1981) has reported almost 1 out of every 10 individuals using the 2F112 simulator (F-14) experienced symptoms of simulator sickness, and that close to 48 percent of the 21 aircrews sampled using the 2F110 simulator (E-2C) reported symptoms. Crosby and Kennedy (1982) have documented cases of simulator sickness in the 2F87F (P-3C), particularly at the flight engineer's position. There also have been reported occurrences in the 2F117A simulator (CH-46E) (Frank and Crosby, 1982).

For the past 5 years, the U.S. Navy has conducted a systematic program of research on simulator sickness. This program was initiated to (1) provide problem definition using field survey data (Crosby and Kennedy, 1982; Kennedy, Dutton, Ricard, and Frank, 1984; Kennedy, Lilienthal, Dutton, and Ricard, 1984; Kennedy, Merkle, and Lilienthal, 1985), (2) conduct a review of the literature (Casali, 1986; Casali and Wierwille, 1986a, b; Kennedy and Frank, 1986), and (3) convene two workshops (McCauley, 1984; Kennedy, Berbaum, Dunlap, Lilienthal, and Hettinger, 1987, in preparation).

Subsequently, a conference of experts (Kennedy, Berbaum, Lilienthal, Dunlap, Mulligan, and Funaro, 1987), and a more comprehensive analysis of field data (Kennedy, Merkle, and Lilienthal, 1985; Lilienthal and Merkle, 1986; Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley, 1987, in preparation; Lane, Kennedy, and Lilienthal, 1987, in preparation) resulted in the development of a field manual and guidelines for the alleviation of simulator sickness (Kennedy, Berbaum, Lilienthal, Dunlap, Mulligan, and Funaro, 1987). These documents were issued as an interim measure until experimental work could be conducted to identify and measure the extent to which specific simulator equipment features promote simulator sickness. Some experimental studies have been conducted. Uliano, Kennedy, and Lambert (1986) conducted a study at the Navy's visual technology research simulator (VTRS) in Orlando in which helicopter pilots flew simulated air taxi and slalom maneuvers in the vertical takeoff and landing (VTOL) simulator. The results indicated the occurrence of symptoms was most prevalent in the first of three sessions (conducted on separate days), dropping off dramatically following the initial exposure. These experimental studies are continuing at VTRS, with physiological measures of sickness and relationships to vection (Hettinger, Nolan, Kennedy, Berbaum, Schnitzius, and Edinger, 1987) as the main emphasis.

The U.S. Navy also has conducted a survey in 10 flight trainers where motion sickness experience questionnaires and performance tests were administered to pilots before and after some 1200 separate exposures. From these measures on pilots, several findings emerged: (a) specific histories of motion sickness were predictive of simulator sickness symptomatology; (b) postural equilibrium was degraded after flights in some simulators; (c) self-reports of motion sickness symptomatology revealed three major symptom clusters: gastrointestinal, visual, and vestibular; (d) certain pilot experiences in simulators and aircraft were related to severity of symptoms experienced; (e) simulator sickness incidence varied from 10 to 60 percent; (f) substantial perceptual adaptation occurs over a series of flights and (g) the'e was almost no vomiting or retching, but some severe nausea and drowsiness.

In addition, a recent study examined the effects on sickness rates of differing energy spectra in moving base simulators (Allgood, Kennedy, Van Hoy, Lilienthal, and Hooper, 1987). The results showed the incidence of sickness was greater in a simulator with energy spectra in the region described as nauseogenic by the 1981 Military Standard 1472C (MILSTD-1472C) and high sickness rates were experienced as a function of time exceeding these very low frequency (VLF) limits. Therefore, the U.S. Navy has recommended, for any moving-base simulator which is reported to have high incidences of sickness, frequency times acceleration recordings of pilot/simulator interactions should be made and compared with VLF guidelines from MILSTD-1472C. However, in those cases where illness has occurred in a fixed-base simulator, other explanations and fixes are being sought.

The Navy has recommended when simulator sickness symptoms, including disequilibrium are of sufficient magnitude, such individuals may be considered to be at risk to themselves and to others if they drive themselves home or return to demanding work activities. While simulator exposure in general did not produce gross changes in a person's cognitive or simple motor abilities, some simulators induced unsteadiness afterwards. The Navy has recommended pilots should be indoctrinated early to identify whatever postural and symptom changes are occasioned by their simulator exposures and those pilots exhibiting identifiable unsteadiness and severe symptoms should remain in the simulator building until symptoms dissipate and perhaps restrict their flying for 1 day.

These data suggest areas of future research. The results of the Navy survey have been used to provide suggestions and criteria for future simulator design, and recommendations are offered for simulator usage regimen. Incidence of simulator distress for the separate indicants (nausea, dizziness, eye strain, ataxia) were indexed by simulator and equipment configuration. This approach appears to hold promise to diagnose the problem (e.g. alignment, inertial motion profile, cue asynchrony) since different symptom clusters may follow from different equipment features. Methodological considerations of surveys into simulator sickness (e.g., statistical power, effects of adaptation, individual differences, etc.) also are under investigation.

U.S. Coast Guard study

Ungs (1987) evaluated simulator sickness in four simulators. Three were rotary-wing aircraft and one was a fixed-wing aircraft. Two of the simulators had computer-generated imagery. Only 4.3 percent of the pilots reported the occurrence of delayed simulator sickness; the interval between simulator flights and recurrence ranged from 1 day to several weeks. Symptoms ranged from disorientation and dizziness to visual flashbacks, illusions, or distortions.

U.S. Army's involvement with simulator sickness

Prior to the actual fielding of the newest rotary-wing simulator, the AH-64 Apache combat mission simulator (CMS), at U.S. Army installations, training of Apache pilots was conducted at the Singer Link facility in Binghamton, New York. At this time, anecdotal information indicated some of the pilots and instructor operators (IO) were experiencing symptoms of simulator sickness resembling those reported in U.S. Navy and U.S. Coast Guard systems. The training flights were 2 hours in duration and most of the students completed the course of instruction in a week's time. This included 15 hours of instruction alternating between the pilot and copilot-gunner stations. Instructor operators were complaining of the onset of a "spinning room" sensation while lying in bed by the middle of a training week. Indeed, some students took Dramamine to alleviate the effects of their symptoms. In May 1986, documentation of the problem reached the U.S. Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, Alabama. In July 1986, the Aviation Training Brigade at Fort Rucker formed a study group to examine the Apache training program. One of the issues was that of simulator sickness.

A brief survey of existing records and a literature search were conducted in August 1986. Training records of 115 students from the CMS showed that 7 percent of the students had sufficient symptoms to warrant a comment on their grade slips. While this incidence is low compared with Navy simulator sites (Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley, 1987, in preparation), rates were derived from training records not designed to document simulator sickness, recording only those cases severe enough to interfere with training or to cancel a flight. The Navy has reported an incidence rate of 12 to 60 percent from the same simulator (Kennedy, Frank, McCauley, Bittner, Root, and Binks, 1984), depending on whether the data were collected by the squadron, the squadron flight surgeon, or by an independent source with guarantee of anonymity. Comparatively, the 7 percent incidence rate appeared to underestimate the magnitude of the Army's problem. The literature search led USAARL investigators to visit the Naval Training Systems Center (NTSC) in Orlando, Florida. From that association has grown a working relationship geared to capitalize on lessons learned from past research and expand the database of simulator sickness studies. As part of that search, it also was discovered that an independent survey in Europe by a U.S. Army flight surgeon had employed the NTSC methodologies to survey the incidence of simulator sickness in the AH-1 Cobra flight weapons simulator (Crowley, 1987).

In the report to the Army study group, it was recommended a problem definition study be conducted to ascertain more accurately the scope and nature of the problem of simulator sickness in the CMS. The request for that study was received in February 1987. The protocol for the study was approved by the USAARL Scientific Review Committee on 4 May 1987, and data collection began on 8 May 1987. This report documents the results of that study.

METHODS

Description of the Army system

The newest generation of U.S. Army attack helicopters is the AH-64 advanced attack helicopter, commonly known as the Apache. This attack helicopter is the replacement for the AH-1 attack helicopter, known as the Cobra. The Apache helicopter provides the commander with a means of rapidly concentrating antitank and suppressive firepower on targets during all environmental conditions: day, night, and adverse weather.

The Apache, built by McDonnell Douglas Helicopter Company, is a twin-engine, four-bladed attack helicopter operated by a tandem-seated crew of two (Figure 1). Planned operations are below 15,000 ft, and generally at tree-top level. The rear seat is occupied by the pilot who is responsible for flying the aircraft. The front seat is occupied by the copilot-gunner (CPG) who is responsible for detecting, engaging, and destroying enemy targets. Both stations have controls for flying the aircraft and instrumentation for flying in instrument meteorological conditions (IMC). However, the CPG often will fly the entire flight and never touch the controls. In general, the CPG will spend the majority (more than 80 percent) of his time looking at the video display unit (VDU) or through his helmet mounted display unit (HDU) for target acquisition, designation, and engagement. The remainder of the time is spent programming his navigation and weapons systems' computers in the cockpit. On the other hand, the pilot's task is to guide the aircraft's flight path and most of his time is spent controlling the aircraft and looking outside the cockpit inspecting for obstacles and enemy aircraft.

Armament for the Apache is of three types (Figure 2). The primary weapon on the Apache is the Hellfire antitank missile, a laser-guided missile capable of defeating all currently known armored vehicles at a significant standoff range. The 30 mm chain gun automatic cannon is the primary area weapon subsystem, providing suppressive firepower and the capability to destroy lightly armored vehicles. Another option is the 70 mm folding fin aerial rockets which have been a standard U.S. Army and NATO munition for many years.

The pilot night vision sensor (PNVS) developed by the Martin Marietta Orlando Aerospace Corporation enables pilots to fly at night and in periods of reduced visibility. Coupled with this system is the target acquisition and designation sight (TADS) which combines high-power direct view optics, a forward looking infrared (FLIR) sensor for night operations, and a high-resolution day TV system with a laser designator and a laser spot tracker. The PNVS FLIR sensor provides real-time imagery of the terrain for nap-of-the-earth (NOE) flight and penetration of obscurants such as rain, fog, dust, and smoke. Sensors for these systems are located on the nose of the aircraft in a rotating turret which is slaved to the pilot's and copilot's head movements.

The TADS is operated by the CPG; however, both pilots may view the video. Normally, the PNVS is operated by the pilot, but it also can be used as a backup for the CPG as well. The wide field-of-view of the TADS FLIR optics also is used as a backup for the PNVS. The pilots view the imagery produced by these systems in one of two ways. The first is by selecting the desired system and viewing it on the video display unit (VDU) mounted on the instrument panel of the pilot's console or through the displays of the optical relay tube assembly (ORT) and its associated VDU mounted at the copilot-gunner's console. The second mode is to select the display and view it through the HDU attached to the integrated helmet unit (IHU) of the Integrated Helmet and Display Sighting System (IHADSS).

Each pilot can observe what his turret is looking at through the HDU. The HDU is an electro-optical monocular display device designed to provide the pilot with a selected video signal magnified to a 30-degree by 40-degree field-of-view (FOV), collimated to infinity, and projected at unity-magnification; that is, a one-to-one size relationship between the FLIR image of an object and the actual object. The HDU consists of a cathode ray tube (CRT) and combiner glass mounted on a barrel-type assembly with adjustments for focus and image orientation. The CRT uses a coarse-grained phosphor known as P43 which, when excited, emits visible light in the blue, green, and red wavelengths. (The red and blue wavelengths are filtered out in this application.) The P43 was chosen because its rapid decay rate allows the pilots to slew their heads at normal rates of movement and not have the problem of image smearing (afterimage).

Superimposed on the FLIR image is flight symbology to enhance the pilot's NOE flying capabilities. This provides the pilot with needed aircraft and flight performance information independent of his viewing direction. This symbology includes a magnetic heading tape, power readings in percentage of power available, sensor location, Doppler steering information, radar altimeter information, thrust vector and cyclic input information, as well as weapon system status and selection information.

Description of simulation system

The CMS faithfully reproduces all aircraft systems with great fidelity and realism using 29 high speed 32-bit microprocessors arranged to provide parallel processing. Virtually the only difference is that all of the images are produced by a digital image generator. Trees look like cones, the terrain is not textured, and the houses and manmade structures appear to be "cartoonish." Considerable and compelling realism is present in the simulator and pilots report becoming so engrossed in the unfolding battle scenario that the exercise takes on the sights, sounds, and intensity of a real conflict. The CMS produced by the Singer Link Company is a full motion-based simulator with 6 degrees of freedom, with 60 inches of travel. One unique feature is each of the pilots is located on an individual motion platform with a colocated instructor-operator (Figure 3). The two motion platforms are linked by the computer so visual and motion information are the same for each. One pilot at a time is designated to "have the controls." Each cockpit has three windows for out-the-window (OTW) viewing in addition to VDU and HDU visuals of the actual aircraft. The CMS incorporates whole cockpit vibration supplemented by a seat shaker for each pilot. (When the aircraft fires its chain gun, the pilots' seat shakers add increased vibration to simulate that activity. However, the added vibration is not felt by the IO.) CMS now does not have G-suit, G-seat, or lap and shoulder belt tightening features. When air-to-air combat features are added to the database, these features are felt to be needed to accurately simulate the envisioned flight scenarios. Even at its present stage of development, the CMS is on the cutting edge of technology and has yet to reach its full potential.

The database now covers a 16-by-16 km area of generic European terrain. Efforts are underway to expand the database to a 32-by-40 km area. Almost all of the flight scenarios are NOE and therefore, require detail of terrain, vegetation, and trees, etc., not required by other simulators. As a result, only 20 percent of the database is provided with the detail in which to conduct NOE flight.

The CMS is an interactive simulator in the sense it shoots back. The IO can set the hostility level from a low of 1 to a maximum of 10 depending on the crew's skill and proficiency level. The IO also can set the lethality level from a low of 1 to a maximum of 10. Basically, these levels initially determine how rapidly the Apache can be acquired on radar by the enemy, and secondly, how deadly will be the resultant fire he receives. Each of the enemy armor and antiaircraft systems in the database are capable of acquiring, tracking, and engaging the Apache aircraft with the same capabilities as the real pieces of equipment. The pilots also receive information in the form of radar warning and lock-on data in the same manner they would in the aircraft. Should the crew expose themselves to detection and not seek cover, the enemy can and effectively will engage them and the result is a very violent engagement. Noise, impact, and system malfunctions are simulated with alarming accuracy.

Method

The Army's initial study into simulator sickness was a field study designed to complement and expand the Navy's database of 10 simulators (Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley, 1987, in preparation; Van Hoy, Allgood, Lilienthal, Kennedy, and Hooper, 1987), and the Coast Guard data (Ungs, 1987). As employed in previous surveys, this study consisted of an on-site survey of pilots and IOs using a motion history questionnaire (MHQ), a motion sickness questionnaire (MSQ), and a postural equilibrium test (PET).

The MHQ is a self-report form designed to evaluate the subject's past experience with different modes of motion and the subject's history of susceptibility to motion sickness. The MHQ is administered once. The MSQ is designed to assess the symptomatology experienced from the simulator. It has a pre- and postflight component. Additional information about this instrument are in Kennedy, Lilienthal, Berbaum and Fowlkes (1987).

The MSQ is divided into four sections. The first section is preflight background information which gives a better description of the pilot subject and allows placing that subject in the proper category according to flight position, duties, total flight time in the aircraft and in the simulator, and a history of recent flight time in both the aircraft and the simulator. Additional descriptive information concerning scoring methods and validity data are in Lenel, Berbaum, Kennedy, and Fowlkes (1987).

The second section is the preflight physiological status section. This section is administered at the simulator site, and gathers benchmark data as to the subject's recent exposure to prescription medications, illness, and use of alcohol or tobacco products. The second part of this section is the preflight symptom checklist which documents how the subject felt before entering the simulator.

The third section is the postflight symptom checklist and is exactly the same as the preflight symptom checklist. This section is administered immediately after the simulator flight, and provides data regarding any increase or decrease in severity of the symptoms that the subject is experiencing. Should the subject be experiencing an increase in any of the symptoms, an attempt was made to monitor him or to interview him the following day in order to provide some information regarding recovery from the experienced symptoms. This was easier at the Fort Rucker site than at the Fort Hood site.

The fourth section is the postflight information section which provides data on the flight conditions the pilot experienced while in the simulator and information concerning the status of the various systems within the simulator.

Postural equilibrium tests (Thomley, Kennedy, and Bittner, 1986) were administered concurrently with the MHQ and MSQ. These tests consist of three subtests, each designed to measure an aspect of postural equilibrium, as follows:

a. Walk-on-floor-with-eyes-closed (WOFEC). The subject is instructed to walk 12 heel-to-toe steps with his eyes closed and arms folded across his chest. The subject is given a score (0-12) based on the number of steps he is able to complete without sidestepping or falling. The subject is tested five times, both pre- and postflight. Subjects are scored on the average number of steps taken using the best three of the five tests.

b. Standing-on-preferred-leg-with-eyes-closed (SOPLEC). The subject designates his preferred leg (the leg he'd use to kick a football) and this is annotated on the form. The subject then is asked to stand on his preferred leg for 30 seconds with his eyes closed and arms folded across his chest. The experimenter records the number of seconds the subject is able to stand without losing balance. The subject is scored on the number of seconds he is able to stand. The test is administered five times with the best three of the five being used for analysis.

c. Standing-on-nonpreferred-leg-with-eyes-closed (SONLEC). The SONLEC is administered and scored in the same manner as the SOPLEC. The SONLEC will use the opposite leg from the SOPLEC and is administered five times. The subject's score is the average number of seconds he is able to stand using the best three of the five tests.

In order to gather the most comprehensive data in the least intrusive manner, the surveys were administered to all aviators who presented themselves at the simulator sites for flight periods. No attempt was made to randomize the population, but rather to study the problem in the operational setting in which it is found and using flight scenarios normally found during training.

Participants

Three candidate populations comprised the survey sample. The first were student aviators. These individuals are rated Army aviators who were at Fort Rucker for the AH-64 transition course. They were either recent initial entry rotary-wing graduates with 150 hours, or more senior aviators with several thousand hours of flight time. Of importance for this survey was that they were essentially naive with respect to both the simulator and the AH-64 helicopter prior to this course. During the final 2 weeks of their course, after all of their time allocated in the actual aircraft has been accomplished (normally 40 hours of flight time), they spend 15 hours of flight time in the simulator. This consisted of five flights in each crew station, each flight consisting of 1.5 flight hours. Because Uliano, Kennedy, and Lambert (1986) reported illnesses associated with simulator sickness quickly dissipate with time when a pilot who is unfamiliar with a simulator is exposed repeatedly, it was expected similar adaptations would occur here. The opportunity to monitor the students in the transition course afforded the Army an opportunity to compare its experience with adaptation to these findings. Approximately 40 students were surveyed over an average of 9 flights each.

The second target population was the rated Army AH-64 pilots who return to the simulator site at their duty station for continuation and mission training on an irregular basis. All these individuals currently are located at Fort Hood, Texas, which is the Army's single station for the fielding of the Apache helicopter and its advanced attack helicopter battalions. It also is the only other operational CMS facility now used by the Army.

The third and final population was the IOs or instructor pilots (IPs) for the CMS. At Fort Rucker, they all are members of the Aviation Training Brigade and are warrant officer aviators charged with training the students attending the AH-64 transition course. Conversely, at Fort Hood, the IOs are Department of the Army civilians who work at the simulator site as IPs. However, each is a retired Army aviator and most are former AH-1 Cobra pilots with combat experience in Vietnam. They are restricted from flying in the aircraft by regulation and job description. Unit IPs from the units which are located at Fort Hood provide very limited duty as IOs. It should be noted due to the scheduling of IOs at the Fort Rucker site and the resulting small number of subjects available, and the fact that all of the Fort Hood IOs do not fly the aircraft, most of the data concerning the IOs was considered invalid. Consequently, no data of any substance for this population is available for this report.

In order to capture the data necessary from the mentioned populations, the sites used were Fort Rucker and Fort Hood. A target population of 200-250 was the objective, but due to time constraints and the nuances of operational usage of the simulator, only 127 subjects were obtained. Due to suspense dates placed on the study by the Assistant

Secretary of the Army/Research, Development and Acquisition, only the CMS could be surveyed. There are three other Army simulators that must still be surveyed (AH-1, CH-47, and UH-60). They performed the normal program of instruction at the Fort Rucker site and one of several operations orders (OPORD) designed to maintain proficiency at the Fort Hood site. As a matter of explanation, each flight in the CMS at both sites is based upon a tactical situation as presented in an OPORD and proceeds as rapidly or as slowly from target to target as the crew's skill permits. Hostility levels and lethality levels are set by the IO depending on skill level of the crew and the desired teaching goal for that particular flight. The investigator did not perform any intervention or exercise any control over the flights in the conduct of this survey.

All aviators scheduled for flight were surveyed. Each was guaranteed anonymity and they were permitted nonparticipation. Data obtained from the questionnaires and the PET were entered into a generic database using the programs in use at the NTSC, and data reduction and analyses were performed as in previous studies. The data in this report now are incorporated into the Navy's simulator sickness database, which also includes Coast Guard data in order to determine commonality of symptoms and simulator usage and design. Unique to the present study is that the student population was evaluated over a 2-week period and 9-10 flights. An initial look at adaptation to the simulator and postsimulator symptoms recovery time is presented.

The 127 Army aviators surveyed ranged in age from 20 to 47 years (mean 30.6, SD 5.77). Their ranks ranged from warrant officer 1 to chief warrant officer 4 and first lieutenant to colonel. Flight experience was in the range 150 to 8400 flight hours (mean 1583.48).

RESULTS

Overall incidence

Based on our previous experiences in monitoring motion sickness in Navy simulators, we have adopted as our index of discomfort the percent of persons who were sick enough upon exiting to report at least one minor symptom which is ordinarily associated with motion sickness. These overall incidence data, based on 434 separate simulator pilot exposures, appear as Table 1. Presented in the table is the overall incidence as well as the grand incidence for two symptom categories --- those related to asthenopia and those related to motion sickness.

In Table 2, the information presented in Table 1 is presented separately for student and rated aviators. Student aviators were surveyed over nine to ten flights during the transition course. The data for rated aviators represents only the first observation for each subject even though some were surveyed two or three times during the course of the study. In addition, for each pilot group, the data are presented by seat (whether the pilot occupied the pilot or copilot-gunner position). For rated aviators, the data indicate that pilots generally are more likely than copilots to experience symptoms of greater severity. Previous studies (Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley, 1987, in preparation; McGuinness, Bouwman, and Forbes, 1981; Havron and Butler, 1957) have found aviators with greater experiences in the actual aircraft reported more difficulties with simulators, particularly when they have 'recent high time.' In the present survey, it is our understanding individuals selected to fly in the pilot seat from the "rated aviator" category would be expected to have considerably higher Apache flight times than those selected for the copilot seats and it is our speculation this is the probable genesis for this difference in incidence.

Table 1

Incidence of postflight (15-30 minutes) symptoms recorded following 434 simulator flights (127 subjects)

Overall incidence*: 44%

Asthenopia	Percentage	Motion sickness	Percentage
Eye strain	29%	Drowsiness/fatigue	43%
Blurred vision	3%	Sweating	30%
Difficulty focusing	9%	Nausea	7%
Difficulty concentrating	11%	Dizziness/vertigo	5%
Headache	20%	Stomach awareness	6%
		Fullness of head	7%

* At least one minor symptom checked off on the postflight symptom checklist

Table 2

Comparative incidence of key postflight (15-30 minutes) symptoms* for student aviators and rated aviators by seat where N = number of observations for students and N[1] = number of subjects for rated aviators

	Student aviators Copilot	Student aviators Pilot	Rated aviators Copilot	Rated aviators Pilot
	(N=171)	(N=168)	(N^1=44)	(N^1=42)
Overall incidence	41%	44%	44%	57%
Symptoms of asthenopia:				
Eye strain	29%	30%	18%	36%
Blurred vision	1%	4%	2%	5%
Difficulty focusing	9%	8%	9%	17%
Difficulty concentrating	6%	13%	14%	17%
Headache	21%	24%	9%	14%
Symptoms of motion sickness:				
Drowsiness/fatigue	39%	47%	43%	38%
Sweating	29%	35%	16%	36%
Nausea	7%	7%	0%	10%
Dizziness/vertigo	1%	2%	2%	7%
Stomach awareness	4%	7%	2%	19%
Fullness of head	4%	8%	16%	7%

* At least one minor symptom checked off on the postflight symptom checklist

Ataxia

The postural equilibrium test (PET) means and standard deviations, along with minimum and maximum scores, are reported in Table 3. Paired t-tests were used to assess changes from prescores to postscores for each of the three PET dependent variables, where pre- and postscores were based on the average of the best three out of five pre- and posttrials, respectively. Comparison of pre- and post-WOFEC scores (t = 4.74, df = 408, p < .001), pre- and post-SONLEC scores (t = 5.20, df = 405, p < .001), and pre- and post-SOPLEC scores (t = 6.19, df = 406, p < .001) revealed statistically significant decrements in postural stability occurred for each measure.

In Table 4, the PET data are presented according to pilot group and seat occupied. For the student aviators, only the SOPLEC measure revealed a significant decrement for both pilots and copilots from the pre- to posttesting. Analysis of WOFEC and SONLEC measures revealed statistically significant decrements for the pilots only. Analyses for the rated aviators revealed statistically significant decrements for both pilots and copilots on the WOFEC and SOPLEC measures. However, on the SONLEC measure, a significant decrement was found only for the pilots.

Table 3

Means, standard deviations, minimum/maximum scores and Ns* for pre- and post-WOLFEC, SONLEC, and SOPLEC measures

	WOFEC Pre	WOFEC Post	SONLEC Pre	SONLEC Post	SOPLEC Pre	SOPLEC Post
Mean	11.38	11.02	23.17	21.81	23.06	21.54
SD	1.42	1.79	7.89	8.07	7.81	8.16
Min-max	3.3-12.0	3.3-12.0	5.0-30.0	2.3-30.0	5.6-30.0	3.3-30.0
N	410	409	410	406	410	407

* N = Number of observations

Table 4

Pre- and postexposure PET scores for student aviators and rated aviators by seat

	N*	Premean	Postmean	Difference mean	t	p
Test: WOFEC:						
Student aviators:						
Copilot	163	11.29	11.29	0.00	0.03	.980
Pilot	158	11.35	11.07	0.28	2.70	.008
Rated aviators:						
Copilot	43	11.65	10.70	0.95	3.61	.001
Pilot	41	11.73	10.46	1.27	3.97	.000
Test: SONLEC:						
Student aviators:						
Copilot	163	22.70	22.33	0.37	0.91	.370
Pilot	158	23.83	21.81	2.02	5.56	.000
Rated aviators:						
Copilot	41	23.68	22.76	0.92	1.13	.270
Pilot	40	22.57	20.48	2.09	2.43	.020
Test: SOPLEC:						
Student aviators:						
Copilot	163	22.99	22.27	0.73	2.06	.041
Pilot	158	23.45	22.00	1.45	4.14	.000
Rated aviators:						
Copilot	41	23.21	20.81	2.39	2.29	.030
Pilot	41	22.03	18.79	3.23	3.63	.001

* N = Number of observations

Simulator sickness symptoms

Table 5 shows overall preexposure and postexposure mean scores for the MSQ. The MSQ is a composite score summarizing many symptoms. A paired t-test, used to assess changes across pre- and postmeasures of symptomatology, revealed a statistically significant increase in symptomatology ($t = 11.29$, $df = 432$, $p < .001$). The results show that aviators training in the CMS experience a marked change in motion sickness symptomatology over the course of a training session. These data are presented according to aviator group and seat in Table 6. For both aviator groups, there was a statistically significant increase in symptomatology from the pre- to postsimulator training.

Table 5

MSQ mean, minimum/maximum scores, and Ns*

	Pre	Post
Mean	0.85	1.66
SD	1.30	1.59
Min-max	0.0-4.0	0.0-6.0
N	434	433

* N = Number of observations

Table 6

Pre- and postexposure diagnostic MSQ means for student aviators and rated aviators by seat

	N*	Premean	Postmean	Difference mean	t	p
Student aviators:						
Copilot	171	.73	1.54	.81	7.45	.000
Pilot	168	.98	1.74	.76	6.74	.000
Rated aviators:						
Copilot	43	.58	1.58	1.00	3.91	.000
Pilot	42	.93	1.95	1.02	3.86	.000

* N = Total number of observations for student aviators and number of cases for rated aviators

Characteristic symptoms of sickness and asthenopia

Table 7 shows the self-reported incidence of four characteristic symptoms of motion sickness (dizziness with eyes open, vertigo, stomach awareness, and nausea) and for three characteristic symptoms of asthenopia (headache, eye strain, and difficulty focusing). The samples for each symptom exclude individuals reporting the symptoms prior to simulator exposure so that the proportions and frequencies are limited to those individuals who did not have the symptoms upon entering the simulator, but did have them when exiting. This particular method of presenting the data may underestimate the extent of the problem because different aviators may experience different symptoms, and others may experience an increase in a preexisting symptom--it is suggested this is one reason why the incidence rates in Table 1 generally are higher than those in Table 7. In addition, for our survey, measures of characteristic motion sickness symptoms generally result in conservative values that may underestimate the magnitude of the problem. Aviators train in the simulator from 1 to 10 times during the qualification course and some individuals seemingly adapted or habituated to the simulator. It was not possible to correct these data by using an aviator's report of syllabus number because of the multiplicity of other variables which occur during regular training (e.g., there were different time intervals between flights and different kinematics are known to occur in the same syllabus number). We propose this is an additional reason why the data reported here may be expected to be conservative estimates of the incidence.

The data in Table 7 are separated in Table 8 according to aviator group and seat. Data for student aviators suggest the severity of symptoms experienced largely is independent of seat occupied. However, for rated aviators, there is a general tendency for pilots to experience symptoms of greater severity than those experienced by the copilot-gunners.

Table 7

Characteristic symptoms of motion sickness and asthenopia*

Primary motion sickness symptoms**

Dizziness (eyes open)	Vertigo	Stomach awareness	Nausea
1.4% (6/434)	1.2% (5/434)	5.2% (22/424)	5.8% (25/429)

Eye strain related symptoms**

Headache	Eye strain	Difficulty focusing
14.0% (53/388)	24.3% (98/403)	9.3% (40/431)

* Percentages of those not reporting a symptom before exposure that report the symptom after exposure
** Total possible observations = 434

Table 8

Characteristic symptoms* of motion sickness and asthenopia for student aviators** and rated aviators*** by seat

Primary motion sickness symptoms	Student aviators Copilot		Student aviators Pilot		Rated aviators Copilot		Rated aviators Pilot	
Dizziness (eyes open)	1.2%	(2/171)	1.2%	(2/168)	2.3%	(1/44)	2.4%	(1/42)
Vertigo	0.0%	(0/171)	1.8%	(3/168)	0.0%	(0/44)	4.8%	(2/42)
Stomach awareness	3.0%	(5/166)	6.0%	(10/166)	2.3%	(1/43)	19.5%	(8/41)
Nausea	5.8%	(10/170)	6.0%	(10/166)	0.0%	(0/44)	9.5%	(4/42)
Eye strain related symptoms:								
Headache	13.7%	(21/153)	17.7%	(26/147)	9.1%	(4/44)	7.7%	(3/39)
Eye strain	26.0%	(42/162)	24.2%	(37/153)	14.3%	(6/42)	31.6%	(12/38)
Difficulty focusing	8.8%	(15/170)	7.7%	(13/168)	9.1%	(4/44)	15.0%	(6/40)

* Percentage of those not reporting symptoms before exposure that report the symptom after the exposure
** Total possible observations = 171 for copilots; 168 for pilots
*** Total possible cases = 44 for copilots; 42 for pilots

Table 9

Correlational analysis of symptomology and flight characteristics

Flight characteristic	Post-MSQ diagnostic criteria r	Post- minus pre-MSQ r
Mission	-.06	.04
Flight hours	-.05	-.04
Flight hours last 2 months	-.08	-.07
Night vs. day	.08	.12
Duration of exposure	.15	.30*

N = 76
$p < .01$

Correlation analysis of the level of motion sickness severity and the post- minus pre-MSQ scores indicated a significant correlation for only one variable, duration of exposure. This correlation was based on the first recorded session in which symptoms were noted. Contrary to previous studies, the Army data do not indicate flight experience level to be a prediction of simulator sickness. (Although consistent with findings from other studies, because 10 correlations were calculated for this comparison, such a finding might be expected to occur by chance 50 percent of the time when no other true correlations were present.)

Figure 4 presents the postflight MSQ severity scores for aviators who completed their qualification course phase in the CMS according to the training syllabus. As might be expected the figure indicates during the 10 flights, there is adaptation as the aviators gain simulator experience in the CMS. Aviators generally report fewer symptoms as they fly the simulator more often. There is a general trend downward even though there are slight deviations from a decreasing function. It was expected this downward trend might be sharper than actually experienced.

Figures 5, 6, and 7 present the postflight ataxia test difference scores for the same student aviators. This preflight score minus the postflight score for the three tests, WOFEC, SOPLEC, and SONLEC, is used as an indicator of gain and loss of function, in this case, equilibrium. It should be noted that there is an apparent loss of equilibrium that progresses over the course of flights. Following session four, the three tests indicate a general trend of a sustained level of a loss of equilibrium. In the earlier flights it would be expected that whatever effect was present would be masked by the learning that would be taking place, as seen in Thomley, K. E., Kennedy, R. S., and Bittner, A. C. (1986). This appears to be what has happened in these cases.

DISCUSSION

The results of this Army study are clear. Simulator sickness symptomatology in the AH-64 CMS has shown an overall incidence from 434 observations of 44 percent, a value which is comparable to those reported by the U.S. Navy in their report of 10 different simulators (range ~ 10-60 percent). We have compared the AH-64 CMS to the 10 simulators of the Navy's database in a series of fine-grained analyses of the individual symptomatology according to a series of dichotomies: fixed-wing versus rotary-wing - Table 10; moving base versus fixed base - Table 11; CRT/calligraphic display versus dome projection - Table 12. It would appear the results obtained in our study are in line with expectations, that is, the symptoms which more commonly are associated with motion sickness also are present to a considerable extent. Eye strain and fatigue are prevalent symptoms in the CMS. However, those flying the Apache consistently complain of eye strain from flights in the aircraft and the workload inherent in the mission of the aircraft also is considered task saturated and fatiguing. These data from the Army survey are very much in line with the Navy's findings from their larger survey.

Table 10

Overall percentages of key symptomatology for Navy fixed wing versus rotary wing and the Army CMS (total number of observations >1630)

Asthenopia:	Headache	Eye strain	Difficulty focusing	
FW	15.9	14.8	6.2	
RW	8.9	22.5	10.2	
CMS	20.0	29.0	9.0	
Motion sickness:	**Dizziness**	**Vertigo**	**Stomach awareness**	**Nausea**
FW	4.0	6.2	7.0	3.6
RW	3.3	3.9	8.8	9.9
CMS	5.0	5.0	6.0	7.0

Table 11

Overall percentages of key symptomatology for Navy motion base versus fixed base and the Army CMS (total number of observations >1630)

Asthenopia:	Headache	Eye strain	Difficulty focusing	
MB	16.1	22.6	10.1	
FB	4.7	10.6	4.7	
CMS	20.0	29.0	9.8	
Motion sickness:	**Dizziness**	**Vertigo**	**Stomach awareness**	**Nausea**
MB	3.7	3.9	8.0	9.2
FB	2.6	7.3	9.1	3.4
CMS	5.0	5.0	6.0	7.0

Table 12

Overall percentages of key symptomatology for Navy dome versus CRT/calligraphic visual systems and the Army CMS (total number of observations >1630)

Asthenopia:	Headache	Eye strain		Difficulty focusing
Dome	5.5	9.3		4.6
CRT	15.5	22.5		9.9
CMS	20.0	29.0		9.0
Motion sickness:	**Dizziness**	**Vertigo**	**Stomach awareness**	**Nausea**
Dome	3.1	8.5	10.6	4.0
CRT	3.6	3.7	7.7	8.9
CMS	5.0	5.0	6.0	9.0

* At least one minor symptom checked off on the postflight symptom checklist

The comparative percentages of symptomatology and eye strain in the two differing aviator populations reveal an almost equal amount of simulator sickness symptomatology in the "student" aviators versus the "rated" aviators when flying in the copilot-gunner seats, but there appears to be considerably greater incidence of sickness symptoms in "rated" aviators when flying in the pilot's seat. However, the pre- versus post-motion sickness symptomatology scores obtained in the present study are comparable with those of the Navy studies. These differences statistically were significant in the present study, and as indicated above, persons who flew in the pilot's seat appeared to be more affected than those with copilot-gunner exposures. Although these differences are small, it would appear they are real.

The postural equilibrium scores generally reveal a significant change from before to after flying in the simulator. These differences support the findings from the Navy study and imply that aviators may be at some risk in activities which require balance and manual control after their flights. The individual findings for the different groups reveal that flying in the pilot seat may entail more visual/vestibular recalibration than after equal times in the copilot-gunner seat. Whether this is related to the increased amount of time spent in out-the-window activities is problematic, and should be studied further.

The comparison of the postural and symptomatology data in the student aviators who were followed over 10 flights is revealing in this regard. It appears that while reported symptoms lessen with continued practice in the simulator, the amount of post-adaptation phenomena evident through the ataxia performance implies that aviators may be at greater risk in later sessions than earlier ones. The data suggest that the price that is paid for this adaptation is decreased equilibrium. As the aviators' symptoms would appear to be lessening, perhaps his confidence in his own adaptability would be leading him to be less poised to attend to such aftereffects. In our opinion such a relation could result in compromises to safety, both on the ground and in flight. We believe this should be examined in a larger population of aviators observed longer than the present 15-30 minutes postflight. It must be determined whether or not the duration of these postadaptation effects outlasts the stimulus for a period greater than the aviators remained in the simulator building for this study.

The results of this study and the continuing dialogue among users of flight simulators will be an ever-expanding database of simulator sickness experiences. Better design criteria and operational guidelines designed to alleviate the effects of simulator sickness also will be forthcoming. In the meantime, it is apparent that the problem of simulator sickness still exists with new and yet only partially understood ramifications. Managers and aviators alike should become aware of these and take appropriate action to insulate those at risk.

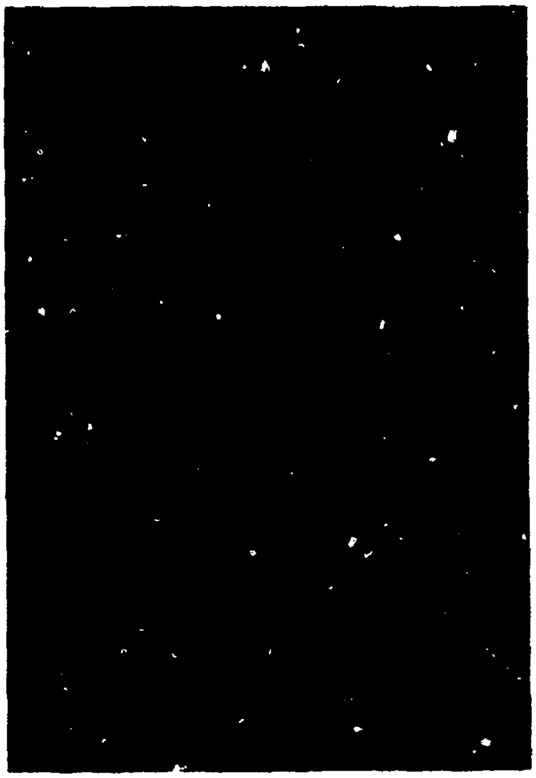

Figure 1. The AH-64 advanced attack helicopter

Figure 2. AH-64 armament

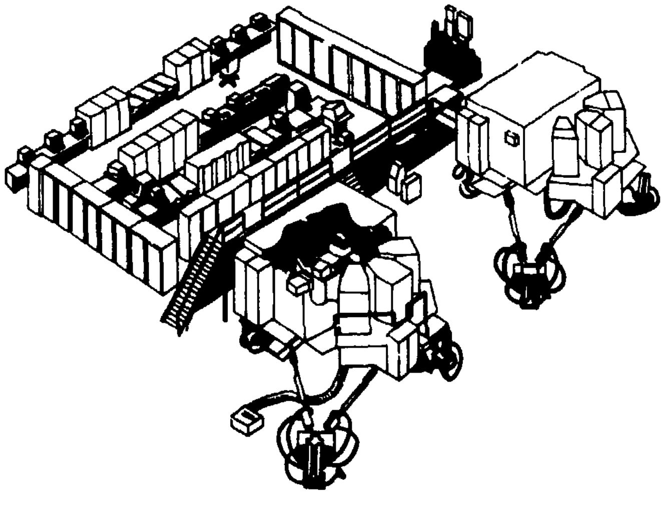

Figure 3. The AH-64 combat mission simulator (CMS)

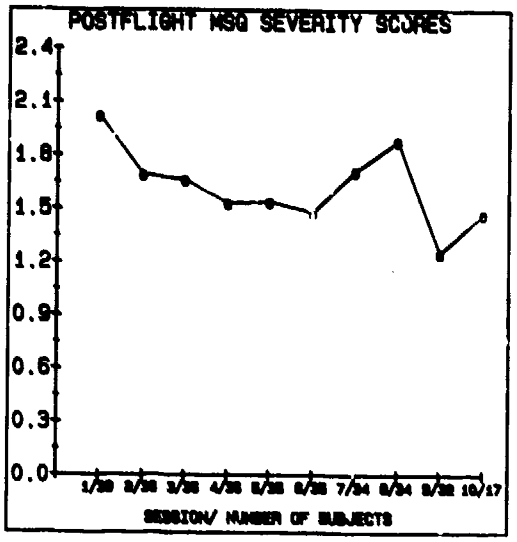

Figure 4. Postflight-MSQ severity scores for student aviators over 10 sessions in the CMS

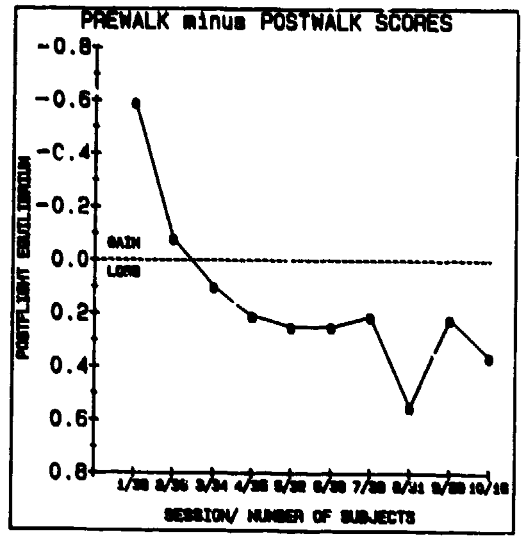

Figure 5. Preflight minus postscores (WOFEC) for student aviators over 10 sessions in the CMS

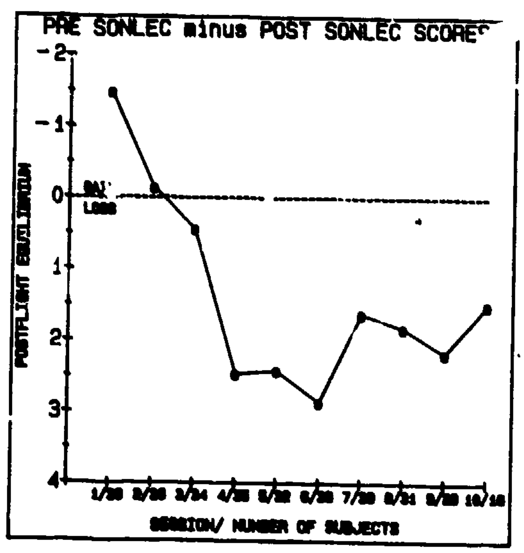

Figure 6. Preflight minus postflight scores (SONLEC) for student aviators over 10 sessions the CMS

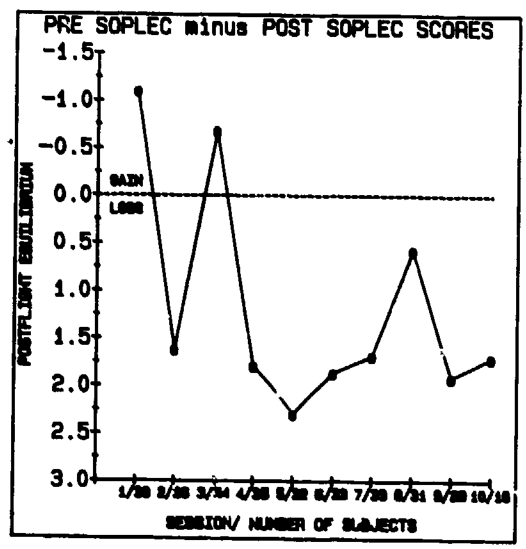

Figure 7. Preflight minus postflight scores (SOPLEC) for student aviators over 10 sessions in the CMS

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DISCUSSION

GUEDRY: I had the impression that you showed a difference in experienced pilots versus students early in your series of slides and then later on I thought you said there was no difference. Could you clear that up for me?

GOWER: We have the same kind of problem as that of my Canadian colleague who talked earlier. We had a mixed group of aviators going through training; they had flight experience ranging from 150 hours to 8400 hours but were still listed as students.

BENSON: Can I ask you the same question that I asked our Canadian friend this morning? Have you any idea of the nature of the postural disturbances and impairment of equilibrium following a real flight?

GOWER: We have not done a study that provides an answer to your question. I would agree that if a simulator produces something that the aircraft does not, then potentially we have poor simulation. On the other hand, if it produces effects like those produced by the aircraft, then maybe we should leave it alone.

BENSON: My question relates to the possibility that any exposure to vibration and motion may cause impairment of postural equilibrium. We are placing a lot of emphasis on changes in postural stability that may be less than those produced by real flight. I remember talking to one colleague who indicated quite severe disturbances of postural equilibrium after having been on a Greyhound bus for 2 hours.

GOWER: Having flown the simulator and being rated myself, I would say that the simulator produces stronger effects because of the altered environment.

WOLFE: I wonder if these pilots were there for TDY training, and if they were, did you look at the history of their drinking prior to their training?

GOWER: Yes, sir. Was that all of your question?

WOLFE: We know that even moderate alcohol consumption has an effect on the vestibular system that may persist up to 72 hours. Because you're doing a form of vestibular test, I wonder whether or not some of your results may be influenced by earlier alcohol intake. The other question is, how many of the pilots have refractive errors and wear glasses? Is there any correlation between the symptoms of eye strain and whether or not they wear glasses?

GOWER: In answer to your first question, sir, as part of the motion history questionnaire administered pre-flight, subjects were asked two questions: Do you smoke? If so, in the last 24 to 48 hours? Have you had any alcoholic beverages in the last 24 to 48 hours? There was no correlation. I can tell you that the training for the Apache transition course is probably one of the toughest for these pilots to undergo. They are home studying on Friday nights, and not at the Club. I was there to take these surveys myself - there were no hangovers to mention.

WOLFE: I'm not speaking about hangover. Equilibrium tests are obviously affected by moderate drinking. I think there have been some recent papers indicating there is effect on performance in the simulator up to 18 hours after moderate drinking.

GOWER: There was no correlation between the walking or the standing component of the postural equilibrium test with use of alcohol or cigarette smoking.

WOLFE: In other words, the equilibrium test was not very sensitive. Sensitive effects, e.g., positional alcohol nystagmus, have been recorded after a couple of beers, up to 3 or 4 days later.

GOWER: That may be a measure to look at but it is more sophisticated, more costly, and more time-consuming than our measures. This was a field study, an initial look; and as a result of that, we did not look at it any more deeply than to ask the question on the questionnaire as to whether or not they had been drinking and then take a look at it statistically.

KENNEDY: These were pre/post simulator-exposure measures, so you would expect subjects to have disequilibrium before as well as after if effects were due to alcohol.

GOWER: In terms of how many subjects wore glasses, we did not gather those data.

PRICE: Seventeen percent of Apache pilots wear glasses.

GOWER: Seventeen percent of the over-all population wear glasses. I don't know how many in our sample had corrected vision. Seventeen percent may be very accurate for the sample.

WOLFE: I was interested in whether there would be a high correlation between those with visual symptoms flying the simulator and those who wore glasses.

GOWER: I can tell you, sir that it hurt my eyes and I don't wear glasses.

PRICE: I have a comment pertaining to the question. You suggest that you would expect a high correlation. I would disagree; unless there was some prismatic distortion, or someone with presbyopia, with multifocal correction, which we didn't have, corrective glasses would not contribute much increase in eye strain symptomatology.

UNIDENTIFIED SPEAKER: Were they flying with integrated helmet and display sighting systems (IHADSS) in the simulator?

GOWER: Absolutely.

UNIDENTIFIED SPEAKER: I think that's where your peak eye strain came from.

GOWER: The IHADSS comes in depending on the way particular flight scenarios in the training were done. For those in the student group, it depended upon what they were doing that day, whether or not they were flying a day mission, or an all-night mission; some pilots use the HDU without regard to day or night. Some use it a lot and some don't use it, except at night.

UNIDENTIFIED SPEAKER: Significant eye strain has been reported with the IHADSS after about 20 minutes of flying.

GOWER: The green phosphor when cranked up to high intensity produces a glare and a "flashbulb" after-effect. Many, I think, referred to that as eye strain with the IHADSS. Also the CRT depiction caused some eye strain as well.

PRICE: The transition students had prolonged periods in simulator training uninterrupted by actual flight?

GOWER: That's correct. The student aviators only flew the simulator.

PRICE: So there we have a group who flew a number of consecutive simulator flights. I would be curious about whether they showed any additional delayed symptoms in comparison with the other group.

GOWER: I don't have that one worked out as yet. We've looked at those data with Dr. Kennedy's people in a separate paper. We did not do a detailed gathering of information post-flight. It was more of a structured interview. "Did you have any problem?" If they said nothing, that was all that was done. Those who did make mention of it were noted in the book. I think we could best look at that with the MSQ severity scores. They complained of fewer and fewer symptoms as they progressed through the training periods. As I remember it, in general, those who complained of after-effects did so in the first, second, or third session, and then they did not mention after-effects after that.

CHAIRMAN: Is there anyone who cares to make a remark at this time?

VIOLETTE: (In French) Note: Due to technical recording difficulties, translation from French to English is not available.

CHAIRMAN: Thank you for your opinion. Any further remarks?

PARKER: We've been talking about simulator sickness in this last session and attributing effects to simulator exposure. The previous speaker, the previous commenter, and Alan Benson have alluded to a need for adequate control studies. Many of the problems we have been seeing may also be associated with the actual flight environment. It seems that a series of control studies should be undertaken prior to pursuing what could be very expensive fixes for simulator sickness. Secondly, there has been emphasis on postural equilibrium disturbance after simulator exposure. There is a society of posturography, and there are a number of laboratories both in Europe and in the United States and Japan pursuing posturography studies. There are some very nice techniques for separating out postural disturbances, techniques that provide the opportunity to manipulate the visual surround and a moving platform. I think if we're going to put emphasis on postural disturbance as a function of being in a simulator, perhaps better techniques should be employed.

LANDOLT: I would like to ask a question of both Dr. Benson and Dr. Kennedy. This morning, Dr. Benson, you gave an extensive list of factors that you associate with simulator sickness. Where should we put our dollars in looking at these simulator sickness factors insofar as research goes? Where should we do research?

BENSON: If we knew the answer, if we knew what was important, then I think that work would already be done. I think the work that Dr. Kennedy is doing in trying to relate symptoms in different simulators to specific characteristics of those simulators may reveal some of the critical factors. I personally think it's the nature and quality of the visual imagery that's the most important. In my limited experience, optical distortions, lack of optical alignment, the fact that the images are collimated, are factors that often seem to be most provocative. I think when you come on to motion bases, then we're in a difficult area. My feeling is that in combat simulation, then the motion bases are only giving a weak caricature of an adequate stimulus, and you may just as well do without a motion base.

KENNEDY: It's perhaps not appropriate to start by saying motion sickness, or simulator sickness in this case, is polygenic and polysymptomatic. But I believe that that is a correct characterization of the answer to the question. I believe that there are some instances where individuals become sick in a simulator because the simulator is behaving like a ship. That is, the simulator has substantial energy at 0.2 Hz and people become sick for whatever reason people become sick at sea. Alternatively, there are conditions where pilots have built up a conditioned compensatory response so that they no longer are bothered by the sensory feedback they receive from the aircraft maneuvers they initiate. These pilots, placed in simulators for maintenance training or refresher training (which may be fixed-base or moving-base), now receive unexpected sensory feedback based on their adaptation. I don't believe the people who in the first case got sick at 0.2 Hz are getting sick for the same reason as the people who are getting sick in the second case as a result of adaptation and conditioned compensatory responses. Also, distortions in the visual scenery create cue conflict problems, e.g., lack of corroboration of depth cueing, distortion due to lack of collimation, things out of alignment, etc. I don't think that the sickness that occurs in the third case is the same as the other two cases. Therefore, the sickness - the genesis of the problem - is markedly different in the three cases. Also, I think that there are examples that could be offered where the stimulus, if you will, is not the same for all of these people. I think the same thing is true for the response mechanisms. Sometimes we measure eye strain and we use this as a sign of sickness; sometimes we measure gastric upset and use this as a sign of sickness. I would say we should spend more effort on how we will characterize the stimulus and how we will characterize the responses.

McCAULEY: I'm part of a research team looking at the fiber-optic helmet-mounted display that was built by CAD, which has been mentioned earlier. This simulator is about to go operational at NASA Ames. Therefore, I was very interested to see what the Air Force had to say in the paper that we didn't hear. I wondered if we have Air Force people with information about that same helmet-mounted display which is in use at Williams Air Force Base.

DOPPELT: The author of the paper is not available and the data that we have with us are not of sufficient character to provide a complete answer at the present time. With the fiber-optic display as used in the Human Resources Laboratory, there have been some concerns related to the things that have been discussed, namely, collimation, optical alignment, and so forth. There have been some symptoms of fatigue or eye fatigue and so forth, but that is part of the display development program. I feel that the study does not have a population large enough to present. Dr. Kellogg is not available so the small data pool that we had initially commented upon is difficult to describe in a read paper.

THE USE OF VESTIBULAR MODELS FOR DESIGN AND EVALUATION OF FLIGHT SIMULATOR MOTION

Steven R. Bussolari, Ph.D and Laurence R. Young, Sc.D.
Man-Vehicle Laboratory
Room 37-219
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

Alfred T. Lee, Ph.D
MS 239-1
NASA Ames Research Center
Moffett Field, California, USA

SUMMARY

Quantitative models for the dynamics of the human vestibular system have been applied to the design and evaluation of flight simulator platform motion. An optimal simulator motion control algorithm has been generated to minimize the vector difference between perceived spatial orientation estimated in flight and in simulation. The motion controller has been implemented on the motion system of the Vertical Motion Simulator at NASA Ames Research Center and evaluated experimentally through measurement of pilot performance and subjective rating during VTOL aircraft simulation. In general pilot performance in a longitudinal tracking task (formation flight) did not appear to be sensitive to variations in platform motion condition as long as motion was present. However, pilot compensation required to perform the flight tasks, as reflected in Cooper-Harper ratings of vehicle handling qualities and the direct assessment of motion fidelity by means of a rating scale designed for this purpose, were sensitive to motion controller design. Platform motion generated with the optimal motion controller was found to be generally equivalent to that generated by conventional linear crossfeed washout.

The vestibular models have been used to evaluate the motion fidelity of transport category aircraft (Boeing 727) simulation in a pilot performance and simulator acceptability study at the Man-Vehicle Systems Research Facility at NASA Ames Research Center. Eighteen airline pilots, currently flying the B-727, were given a series of flight scenarios in the simulator under various conditions of simulator motion. The scenarios were chosen to reflect the flight maneuvers that these pilots might expect to be given during a routine pilot proficiency check. Pilot performance and subjective rating of simulator fidelity was relatively insensitive to the motion condition, despite large differences in the amplitude of motion provided. This lack of sensitivity may be explained by means of the vestibular models, which predict little difference in the modeled motion sensations of the pilots when different motion conditions are imposed.

INTRODUCTION

The use of flight simulation as a tool for pilot training, certification, and flight control system development has increased dramatically in recent years as the associated technology has become more sophisticated. To the extent that the pilot makes use of visual, aural, tactile, and motion cues in aircraft control it is necessary to reproduce those cues accurately in the simulator. A fundamental question concerns how much engineering and psychological fidelity is necessary to produce the same piloting behavior in the simulator as that observed or expected in the actual aircraft. It is recognized that the fidelity requirements of simulators used for flight training will, in general, differ from those used for research. Once those requirements have been established, however, the simulator designer must decide how best to generate the cues that enhance fidelity.

Under current regulations of the Federal Aviation Administration, all simulators used for civil aircrew training within the U.S. are required to provide at least three degrees of freedom (DOF) of platform motion. Simulators used for initial, transition, and upgrade training and checking are required to have full six DOF platform motion systems. The requirement for platform motion is ostensibly based on the assumption that physical fidelity is highly correlated with training effectiveness. Since aircraft are capable of motion in all six axes (three translational, three angular), it is believed that the absence of motion in the simulator would significantly reduce its training effectiveness. Although no data exist to confirm or disconfirm this hypothesis for civil transport operations, training transfer studies conducted on general aviation and military training simulators do not support this assertion (Waag, 1981). While it is arguable that the motion systems in these studies were of the highest quality, the absence of motion effects across such diverse training environments and simulator equipment considerably weakens the case for requiring elaborate motion platform systems in flight simulators used for training pilots in fixed wing aircraft operations. Simulator motion requirements for hovering aircraft have yet to be firmly established.

The purpose of this paper is to describe work in progress directed towards understanding the influence of motion platform systems on pilot behavior. First, the development of a quantitative model of human spatial orientation is outlined. The model provides the system designer with a tool by which motion platforms and their associated drive logic can be developed. An optimal simulator motion control algorithm that uses the spatial orientation model is presented along with the results of an experimental evaluation of the design technique in a VTOL aircraft simulation. Finally, the results of a recent study which evaluated the influence of platform motion variations on pilot performance and ratings of simulator fidelity in a transport category aircraft (Boeing 727) simulation are presented. This study represents the first attempt to evaluate the influence of platform motion on a simulator certificated under the FAA's advanced simulation plan.

THE VESTIBULAR MODEL

A substantial effort extending over many years in the Man-Vehicle Laboratory at MIT has been devoted to the development of quantitative models for human spatial orientation based primarily upon physiological models of the human vestibular system. These models relate linear acceleration to perception of tilt and linear motion, and angular acceleration to perception of angular velocity (Young and Meiry, 1968; Young and Oman, 1969; Ormsby and Young, 1976). Early in this process, we recognized the relationship between spatial orientation models and the influence of flight simulator and aircraft motion on pilot orientation perception and performance. Our earlier work tying semicircular canal and otolith models to fixed base versus motion base simulation (Shirley and Young, 1968; Curry et al., 1976; Zacharias and Young, 1981) indicated the relationship of motion cues to the development of pilot lead, particularly in the task of flying aircraft with marginal stability. Although these efforts helped to explain the influence of motion cues, they were not explicitly directed toward the generation of motion base washout algorithms.

Simulator motion fidelity can be expressed quantitatively by comparing the modeled perceptions of the simulator pilot with those of the pilot of the actual aircraft in flight (see Figure 1). The physical motion of the aircraft and that of the simulator are used as inputs to identical human spatial orientation models: one of the aircraft pilot and one of the simulator pilot. The outputs of these models are taken as the motion perceptions, respectively, of the aircraft pilot and the simulator pilot. The physical limitations of motion base flight simulators are such that the input to the simulator pilot spatial orientation model will, in general, be significantly different from the input to the model of the aircraft pilot. The degree to which the simulator effectively reproduces, in the simulator pilot, the perception of actual aircraft motion is expressed as the difference of the outputs: the spatial orientation error. The use of a linear model to produce spatial orientation error as a quantitative fidelity metric is applicable to all types of motion drivers, including non-linear, adaptive washout systems.

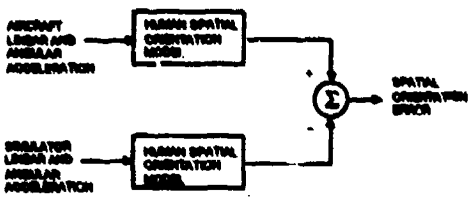

FIGURE 1 The comparison of simulator platform motion to aircraft motion through the use of spatial orientation models.

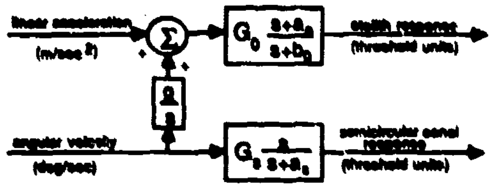

FIGURE 2 Block Diagram of spatial orientation model in pitch-surge direction. Otolith model parameters: $G_o = 5.32$ sec^2/m; $a_o = .076$ rad/sec; $b_o = .190$ rad/sec. Semicircular canal model parameters: $G_s = .659$ sec/deg; $a_s = .169$ rad/sec. (g is gravitational constant).

Rather than use models based solely upon the mechanics of the vestibular end organ mechanics (e.g. Steinhausen, 1931; van Egmond et al., 1949); or upon the transfer function to perception of spatial orientation (e.g. Young and Oman, 1969; Young, 1974); we choose to employ models whose output reflects the typical firing rate of the vestibular afferent neuron. The rationale for this approach is that vestibular afferent firing rate is a more relevant indication of the perception of spatial orientation because the dynamics of the transduction of mechanical events to electrical impulses in the peripheral nervous system are included. There is, of course, additional signal processing (with associate dynamics) that takes place at higher levels of the central nervous system to produce the human's perception of motion, but validated models for this have yet to be formulated. The model parameters were chosen, based upon the squirrel monkey experiments of Fernandez and Goldberg (1971, 1976), and are assumed to be a reasonable approximation of those of the human. A block diagram of the spatial orientation model is depicted in Figure 2 for linear acceleration on the longitudinal axis (surge) and angular velocity in pitch. Similar models are constructed for motion in the other two linear and two angular axes. Angular motion in pitch is sensed by the semicircular canal as angular acceleration and by the otolith as an apparent change in body force due to the angular displacement of the gravity vector. Actually, the coupling of pitch attitude to the otolith varies as the sine of pitch angle; therefore, we make the small pitch angle approximation to preserve the linearity of our model. The coupling between the perceived linear acceleration and pitch angle as sensed by the otolith organ is exploited in flight simulator motion design by tilting the simulator cab (g-tilt) to create the illusion of sustained linear acceleration.

The gain of each model was adjusted so that its output is an average normalized firing rate of the vestibular afferent neuron expressed in threshold units. The normalizing factor (one threshold unit) corresponds to the level of angular velocity or linear acceleration that is just perceptible to a pilot performing flight tasks in a simulator (Hosman and van der Vaart, 1978). Simplification of the model was achieved by eliminating dynamics that were well outside the capabilities of existing flight simulator motion systems (e.g. the .003 sec. short lag time constant of the semicircular canals).

OPTIMAL WASHOUT SYSTEM

Given the linear vestibular model as a tool, we are able to address the design of flight simulator motion drive logic as an optimal control problem (Sivan et al. 1982). The structure of the optimal washout system is shown in Figure 3. The basis of the design technique is the assumption that the utility and acceptability of flight simulator motion is optimized by minimizing the expected value of the mean-square spatial orientation error as computed by the model given the physical constraints of the simulator motion base. A weighted quadratic optimization cost functional is formed by combining the state vector of the spatial orientation model with the state vectors of the aircraft model and the simulator dynamics. The elements of the weighting matrix are assigned a priori based upon the desired maximum values of spatial orientation error and simulator motion platform acceleration and travel. Aircraft motions resulting from pilot inputs and external disturbances are modeled as a random process with a rational spectral density that can be adjusted by means of a shaping filter to match the particular aircraft and range of expected flight tasks (Zarchan, 1979). The motion controller is then synthesized off-line using standard linear-quadratic-Gaussian optimal control methods (Kwakernaak and Sivan, 1972).

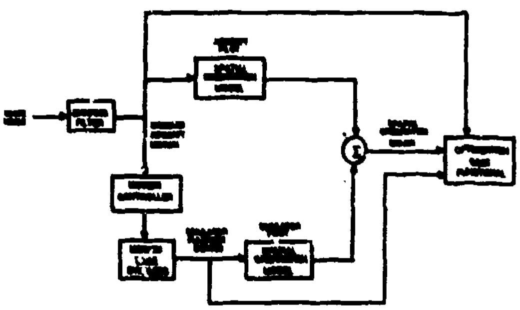

FIGURE 3 Optimal washout system structure.

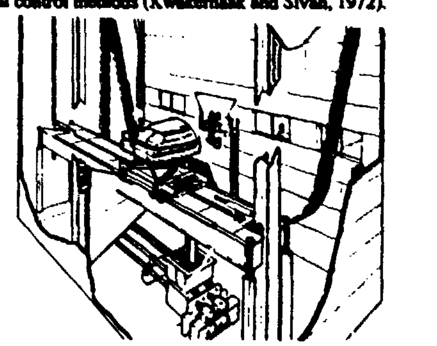

FIGURE 4 NASA Ames Research Center Vertical Motion Simulator.

VALIDATION OF OPTIMAL WASHOUT SYSTEM IN VTOL SIMULATION

In an attempt to validate our model, we have used the optimal control design technique to produce a motion washout system for two of the six degrees of freedom (pitch and surge) of the Vertical Motion Simulator (VMS) at NASA Ames Research Center (Figure 4). This facility, designed primarily for VTOL simulations, has a total vertical travel capability of 14m and a total horizontal travel of 9m. For the purpose of the validation study, the simulator cab was rotated 90 degrees so that the longitudinal axis of the cockpit was aligned with the horizontal track providing a full 9m of travel in the surge direction. The aircraft mathematical model selected for the experimental evaluation was that of a vectored-thrust VTOL vehicle. The vehicle's transfer function in the pitch-surge direction is depicted in Figure 5. It includes parameters that model aerodynamic drag (t1), damping in pitch (t2), and control system delay (t3).

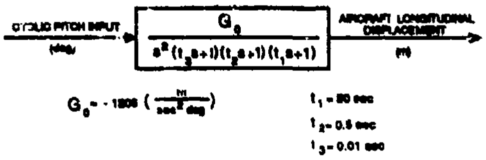

Figure 5 VTOL aircraft transfer function used in VMS motion study.

In order to assess the sensitivity of our motion drive logic to its design parameters and compare the experimental system with established washouts, six different washout systems were developed. Three versions of the optimal washout system (OWS) were synthesized by choosing different values for the weights in the quadratic cost functional. The first, OWS Nominal, was designed to make maximum use of the simulator motion base travel and placed equal weight on the modeled otolith and semicircular canal errors, relative to their thresholds. The second, OWS Decreased Gain, was generated by placing large weights on platform motion states as compared to the computed orientation error. This washout was designed to make use of approximately half of the VMS platform horizontal travel. The third, OWS High Otolith Weighting, was synthesized by placing twice the weight on the orientation error contribution of the modeled otolith response as that placed on the orientation error contributed by the semicircular canals. In addition to the three motion drive systems synthesized by the optimization technique, three versions of the motion controller currently used with the VMS were implemented in the pitch-surge axes. All three were of the crossfeed type as designed by R. Bray at NASA Ames Research Center and described by Sinacori (1977). The first, Ames Nominal, was tuned by the designer to make maximum use of the simulator motion travel given the types of flight maneuvers anticipated in the study. The second, Ames Decreased Gain, was modified to reduce the horizontal travel of the simulator cab by a factor of two by reducing the gain of the linear washout filter. The third, Ames Increased Omega, was generated by increasing the break frequency (omega) of the high-pass washout filter in order to decrease the low-frequency content of the simulator motion. This has the effect of decreasing the travel requirements of the simulator without attenuating the amplitude of the high frequency motion.

The response of each of the six motion washout systems as implemented on the VMS are compared in Figure 6 for a single dash quick-stop maneuver. In this maneuver, the aircraft is pitched nose-down to accelerate forward to a given velocity and then pitched nose-up to decelerate rapidly to a stationary hover. Identical pilot inputs were given to the aircraft mathematical model for each of the six washout systems. For each motion drive system, the measured simulator displacement, computed otolith error, and computed semicircular canal error are plotted vs time. The time responses of the Ames washouts are characterized by extremely low otolith error due to the fact that this washout system placed emphasis on the coordination of tilt of the simulator cab with longitudinal acceleration. The reduction of washout filter gain in the Ames Decreased Gain case produces the predicted effect of a lower simulator horizontal displacement. This is achieved at the expense of a slight increase in the computed semicircular canal error. A similar effect can be seen for the Ames Increased Omega washout. The OWS Nominal washout was generated with equal weighting on otolith and semicircular canal error in the cost functional and this is reflected in the balance between the two errors for the dash-quick-stop maneuver. The OWS Decreased Gain washout commands a smaller simulator displacement with very little change in the modeled otolith and semicircular canal error. The OWS High Otolith Weighting washout, designed by placing high weights on the computed otolith error, generates otolith error that is only slightly less than that produced by the OWS Nominal washout. This, combined with the observation that the computed otolith and semicircular canal errors do not change significantly when the simulator platform travel is reduced by the OWS Decreased Gain washout, indicates the existence of an apparent insensitivity of the optimization equations with respect to the orientation error. The insensitivity of optimal controller performance to changes in the weights of certain components of its cost functional is commonly encountered in optimal controller design (Kwakernaak and Sivan, 1972) and may be compensated for by placing larger weights on those components and their time derivatives.

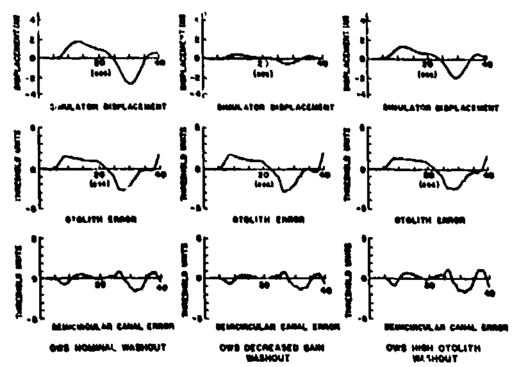

FIGURE 6a. Response of Ames crossfeed washout system to a single dash-quick-stop maneuver.

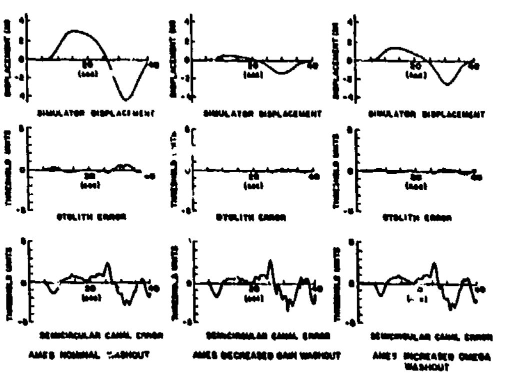

FIGURE 6b. Response of optimal washout system (OWS) to a single dash-quick-stop maneuver.

VTOL SIMULATION METHODS

In order to determine the effect of each of the six motion washout systems upon pilot performance and simulator acceptability, a series of evaluation experiments were performed using the VMS. Four NASA test pilots participated in the study, all of whom were current in VTOL aircraft (three had extensive experience in the VMS). Each pilot subject was given a simulator familiarization and practice session followed by two experimental sessions of approximately 6 minutes each. During each experimental session, the pilot subject experienced four motion conditions: fixed base and three of the six washouts described above. The order of presentation of the motion conditions was adjusted for each subject so that the effect of learning could be assessed. The small number of subjects tested precluded a complete counterbalancing of all motion condition to compensate for learning effects; however, learning proved not to be a significant factor in this study. In each case that the motion base was active, all six degrees of motion freedom were used; however, only motion control in the pitch and surge axes were manipulated. The other four motion axes were controlled by the Ames Nominal washout throughout the experiment. After a period of warm-up flight, each pilot performed a formation flight task in which a lead VTOL aircraft was placed in the visual scene 33 meters in front and slightly to the left of the simulator. The pilot was instructed to maintain his aircraft in formation at a fixed distance from the lead aircraft. During each 75 second trial, the lead aircraft (with flight characteristics identical to the simulated VTOL aircraft piloted by the subject) was subjected to a pseudo-random pitch disturbance produced by a sum of five sinusoids of equal amplitude at frequencies of 0.257, 0.513, 0.770, 1.15, and 1.54 radians/second. During the formation flying task, the relative positions of the lead aircraft and the simulator were recorded, as were the pilot control inputs. At the end of each trial, the pilot subjects were asked to give a rating of the aircraft handling qualities, as presented in the simulator, according to the Cooper-Harper rating scale (Cooper and Harper, 1969). After four trials of the formation flight, the simulator was re-initialized at an altitude of 10 meters above a simulated canyon scene. The pilots then performed a series of dash-quick-stop maneuvers and sinusoidal pitch oscillation maneuvers. At the end of these flight tasks, they were asked specifically to rate the motion of the simulator using a seven component rating system designed for this purpose (see Table 1). The motion rating scale used numerical ratings of smoothness, sense, amplitude, phase lag, discomfort, and disorientation as well as an overall rating of the motion relative to fixed base operation.

RESULTS OF VTOL SIMULATION

The instructions given to the pilot subjects were to maintain relative position during the formation flight. However, due to the difficulty of judging distance, given the limitations of the visual scene and the 33m separation between the lead aircraft and the simulator, the relative velocity proved to be a more appropriate measure of performance. The velocity difference between the lead aircraft and the simulator was computed as a velocity error. The performance of each pilot was scored by computing the variance of the velocity error and recording this as a Velocity Error Score (VES). The variance of the velocity error was used for the VES instead of the root-mean-square velocity error to eliminate the effect of a steady state velocity error. For this reason, the VES is a more appropriate measure of the correlation of the velocity of the simulated VTOL aircraft and the target aircraft. Despite the fact that the pilots were highly trained in VTOL aircraft, their performance varied widely, eliminating the possibility of combining measurements across subjects. For illustration in this discussion, data taken from a single pilot (Pilot #3) is presented. The observations and conclusions drawn from this data are generally applicable to all four pilot subjects.

ATTRIBUTE	RATING 1	5
SMOOTHNESS	EXTREMELY SMOOTH - COMPARABLE WITH FIXED BASE	EXTREMELY JERKY LIMIT OF TOLERANCE
SENSE	DEFINITELY CORRECT AS IN AIRCRAFT	TOTALLY REVERSED
AMPLITUDE	NO MOTION EXPERIENCED	AT LEAST TWICE THAT EXPECTED
PHASE LAG	NONE EXPERIENCED	AT LEAST 180°
DISCOMFORT	NONE EXPERIENCED	CANNOT CONTINUE MANEUVER
DISORIENTATION	NONE EXPERIENCED	CANNOT PERFORM MANEUVER
OVERALL	EXCELLENT	EXTREMELY POOR

TABLE 1. Multi-attribute motion rating scale.

The velocity error scores for Pilot #3 given in Figure 7a indicate that the greatest differences in tracking performance occur between fixed base and and one of the motion conditions. The differences in tracking performance when motion cues were present were relatively small. The effect of learning on tracking performance is also quite small as indicated in Figure 7b where performance is plotted against the order of presentation of the individual motion conditions. The fact that pilot performance appears to be robust in the presence of significantly different motion conditions is a limitation inherent in the use of performance alone as an indicator of motion fidelity, particularly when highly skilled pilots are used as test subjects.

In order to examine the effects of motion conditions on pilot control behavior a pilot describing function analysis was performed. Using the disturbance input to the lead aircraft, the pilot cyclic pitch inputs, and the model aircraft dynamics, the linear portion of the pilot control response was reconstructed. A typical frequency response plot of the open-loop pilot/aircraft dynamics is presented in Figure 8. The characteristics of this plot are representative of all pilots and all conditions. The decrease in system gain (20 to 30 dB/decade) in the vicinity of the crossover frequency (approximately 1.3 radians/second) is consistent with previous observations of human control behavior (McRuer and Krendel, 1974); however, the computed phase angle remains in the region of -180 degrees, indicating the presence of strong closed-loop instability. The fact that the performance data show that the pilots were able to stabilize the aircraft during the formation flying task appears to counter the notion of instability implied by the linear pilot describing function. The reason for this discrepancy may be that a linear control model is not applicable to the piloting of a vehicle with high-order dynamics (Young and Meiry, 1965). The presence of non-linear control behavior is consistent with low signal-to-noise ratio (1/remnant) of the pilot describing function generated from the data. Overall, there were no reliable differences in the pilot describing function among the motion conditions, including fixed base.

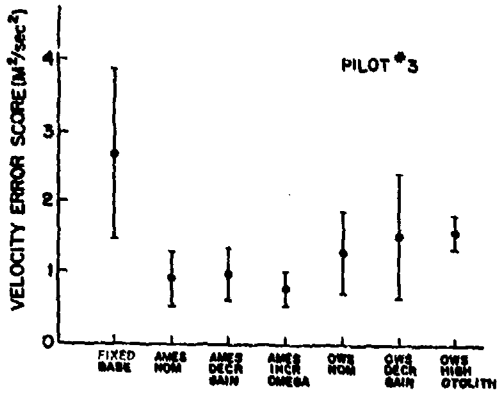

FIGURE 7a Pilot performance in longitudinal tracking task (formation flight) vs motion condition.

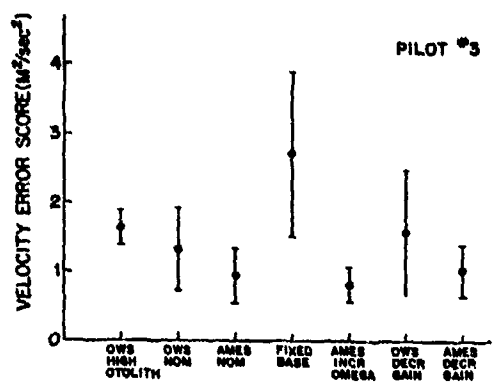

FIGURE 7b Pilot performance in longitudinal tracking task (formation flight) vs motion condition in order of presentation

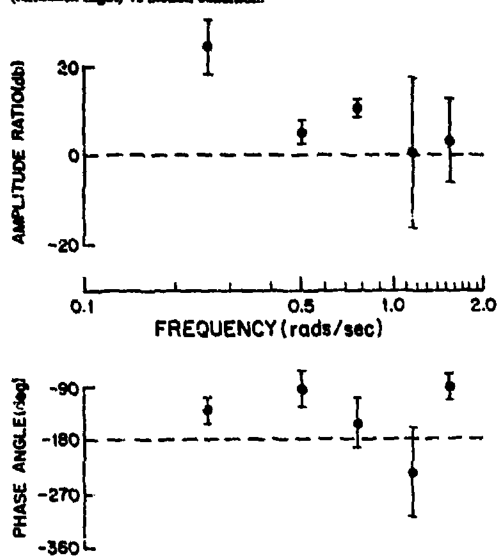

FIGURE 8. Frequency response of open-loop pilot/aircraft dynamics measured during longitudinal tracking task (formation flight).

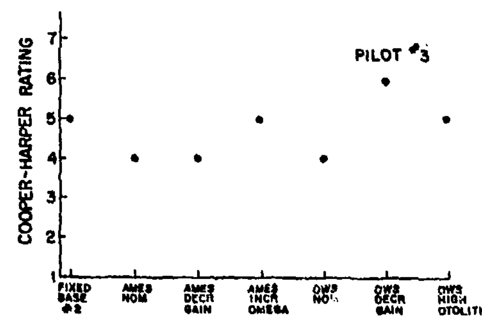

FIGURE 9 Pilot ratings of vehicle handling qualities vs motion condition during longitudinal tracking task (formation flight).

The level of pilot compensation required to perform the formation flying task for each of the motion conditions is reflected in the Cooper-Harper ratings presented in Figure 9 (a high Cooper-Harper rating reflects poor handling qualities). The relatively high (4 to 6) Cooper-Harper ratings given for the handling qualities of the simulator in the formation flying task indicate that considerable pilot compensation was required to achieve adequate task performance. Differences in required pilot compensation among motion conditions appear to be more significant than differences in task performance. The slight correlation ($R = 0.61$) between performance and the Cooper-Harper rating assigned indicates that pilot compensation may be a more sensitive measure of the role of motion cues in the formation flying task. The Ames Nominal, Ames Decreased Gain, and OWS Nominal received equal ratings (CH-4), indicating that the simulator required less pilot compensation to fly with these washout systems than it did under Fixed Base (CH-5) The Ames Increased Omega and OWS High Otolith Weighting (CH-5) were judged equivalent to Fixed Base and the OWS Decreased Gain (CH-6) was judged poorer than Fixed Base.

The ratings given by Pilot #3 of the motion conditions by means of the scale given in Table 1 are presented in Table 2. In general, there was some correlation ($R = 0.72$ to 0.91) for all pilots between the Cooper-Harper handling quality rating assigned to the formation flying task under each motion condition and the overall rating of simulator motion. Pilot #3 rated all washout system equally on the overall scale with the exception of the poor rating of the OWS Decreased Gain washout. The OWS Decreased Gain washout condition also received the poorest Cooper-Harper rating from Pilot #3. The deficiencies in motion amplitude and phase lag (the phase difference between the motion of the visual scene and that of the motion platform) as reflected in the poor ratings assigned to those components appear to be the major contributors to the formulation of an overall motion rating by Pilot #3. On the other hand, the motion component ratings given to Ames Nominal, Ames Decreased Gain, and the OWS Nominal were significantly different, yet the overall motion ratings and the Cooper-Harper ratings given to those same conditions did not differ from each other. It would appear, therefore, that the direct assessment of the platform motion by means of a multi-component scale is more sensitive to changes in motion conditions than the estimation of vehicle handling qualities by means of the Cooper-Harper scale or an overall subjective rating of the simulator motion. In general, each pilot exhibited a different correlation between components of the motion rating scale and the overall motion rating, indicating considerable between-subject variation in the assessment of each component of simulator motion. This difference among individuals makes comparison of ratings across a pool of pilot subjects quite difficult. A similar effect has been observed for the subjective rating of mental workload and techniques exist to reduce the between-subject variation in workload ratings (Hart and Staveland, 1986). These same techniques could be applied to the motion rating scales described here.

TABLE 2. Motion ratings assigned to each washout system by Pilot #5.

WASHOUT	SMOOTHNESS	SENSE	AMPLITUDE	PHASE LAG	DISCOMFORT	DISORIENTATION	OVERALL
AMES NOMINAL	2	1	3	2	1	1	2
AMES DECREASED GAIN	2	1	3	4	1	1	2
AMES INCREASED OMEGA	2	1	3	3	1	1	2
OWS NOMINAL	2	1	4	3	2	1	2
OWS DECREASED GAIN	2	1	2	4	1	1	4
OWS HIGH OTOLITH WEIGHTING	2	1	4	2	1	2	2

EVALUATION OF MOTION PLATFORM ALTERNATIVES

A second study in this research program was recently conducted to provide an additional opportunity to evaluate the motion model and to investigate the impact of alternative limited motion design options for air transport flight simulators. Assessing motion platform effects on pilot performance in tasks representative of those which are required during training and checking is a first step in identifying candidate systems which could be evaluated in a training environment.

Eighteen air transport pilots, currently flying Boeing 727 aircraft, participated as paid volunteers in the study. Of the eighteen pilots, three served in the Captain and fifteen in the First Officer crewmember position. Experience in the 727 ranged from 3 months to 7.5 years with an average of 2.4 years. A Boeing 727-200 flight simulator certificated under Phase II of the Federal Aviation Regulations simulator requirements section (Part 121, Appendix H) was used for the study. The simulator, which is located at NASA Ames Research Center provides a full six DOF motion utilizing a nonlinear, adaptive motion drive logic scheme. A dusk/night visual system provides a computer generated image of the out-of-the-cockpit scene to both the Captain and First Officer positions. For this study, only night scenes were presented.

Three motion platform conditions were compared in this study: the full six DOF motion required for Phase II simulators and two limited motion conditions. The latter platform motion conditions were provided by restricting the software logic driving the platform. For one of the limited motion conditions, the six DOF system was reduced to two DOF: vertical and lateral translational motion. Inclusion of this condition in the study was to allow an evaluation of a system limited to providing largely disturbance information about the state of the aircraft. Amplitude of normal platform motion excursion in these two axes was not limited. In the second limited motion condition, small amplitude vertical translation motion commonly called "special effects" were the only motion cues provided. These special effects included the following: runway touchdown bump, vibrations induced by runway roughness, buffets associated with flap, landing gear, and spoiler extension, and Mach and stall buffet. Maximum leg extension with these effects was .63 cm. These special effects were provided in the full motion and two axes motion conditions as well.

Six of the eighteen pilots were randomly assigned to each of three test scenarios. The three test scenarios were constructed to allow the evaluation of pilot performance in task conditions representative of those they would receive in the operational training environment. An additional criterion for task selection was the desire that significant pilot control activity be involved. This criterion was included to increase the probability of detecting motion platform effects if they did, in fact, exist. Each pilot was tested individually with the pilot-not-flying duties performed by a research pilot. The three test scenarios were as follows: (1) engine flameout on takeoff subsequent to rotation; (2) an airwork scenario consisting of steep turns, approach to stall, and standard rate turns with yaw dampers failed; and (3) an ILS approach and landing flown through a low-level, horizontal windshear. All scenarios were conducted in and around the simulated San Francisco International Airport (SFO) environment. With the exception of the ILS approach and landing, all maneuvers were conducted in standard day, no wind, visual meteorological conditions. The simulated aircraft had a takeoff weight of 67,300 kg. In order to standardize testing, fuel quantities were held constant throughout the flights.

Prior to testing, pilots were provided with the opportunity to fly VFR approaches and landings with full platform motion in order to become familiar with the simulation environment. Pilots were not informed that motion platform conditions would be altered, only that the study's intent was to assess simulator fidelity issues. In all motion test conditions, all normal procedures involving full motion operations were conducted so that pilots would not be made aware of any changes in platform functioning prior to testing. Those tested in the engine-out on takeoff scenario were required to perform two successive takeoffs from a standing start under each of the three motion conditions. Engine flameout onset time varied, but always occurred within 5 seconds following rotation. Engines 1 and 3 were failed randomly on successive takeoffs to reduce anticipatory control responses by the pilots. Pilots were instructed to maintain runway heading and level out at 610 m altitude (2000 ft). The order in which the three motion conditions were tested was counterbalanced across the six pilots who flew the scenario.

In the airwork scenario, the simulated aircraft was initialized at 250 KIAS and 4570 m (15,000 ft) MSL. The pilot was required to execute two successive steep turns followed by two successive approach to stall maneuvers with the aircraft in the clean configuration. Two standard rate turns with failed yaw dampers were then flown at an altitude of 10,000 m (33,000 ft) and 300 KIAS. Each pilot flew the airwork scenario once under each of the three motion conditions. The order of testing for motion conditions was counterbalanced across pilots. Pilots assigned to fly the ILS approach and landing scenario began the approach at an altitude of 1200 m (4000 ft) and an airspeed of 220 KIAS. The pilots were initialized with an intercept course 30 degrees off the localizer course to runway 28R at SFO. The ILS approach was flown manually by use of flight directors. Ceiling for the approach was 183 m (600 ft) with unlimited visibility at and below 152 m (500 ft). At this altitude, a windshear was introduced which altered wind speed and direction from a 15 knot headwind to a 10 knot tailwind at the runway surface. Wind was changed at a rate of -1 knot per 30 m (100 ft) in speed and 36 degrees per 30 m in direction.

Both subjective pilot ratings and objective simulator measurements were taken during the course of the study. The pilot ratings were taken after the completion of testing on a given motion condition within each scenario. The rating instrument consisted of six items, each requiring a response on a 5-point scale. A rating of 3 on this scale indicated that the pilot felt the simulator to be very similar to the aircraft. For example, a rating of 1 on control workload was given if the simulator control effort was much less than that of the aircraft, a 5 if the effort was much more than that of the aircraft. The six items addressed the following: total control workload in the scenario, control workload during configuration changes, general responsiveness of the simulator to control inputs, the utility of the simulator for training and checking, and an assessment of overall realism of the simulation. For all items, pilots were asked to base their ratings to the extent possible on experience with the aircraft. Objective measures of pilot and simulator performance were collected in real time at a rate of 15 samples per second. Aircraft state parameters such as airspeed, attitude, and altitude were sampled as were measures of simulator motion, the output of the spatial orientation models, and pilot control inputs.

RESULTS OF TRANSPORT AIRCRAFT SIMULATION

The results of the subjective ratings of the simulator are depicted graphically in Figure 10. This figure shows the rating for each of the six categories averaged across the eighteen pilots and three test scenarios. In all categories and in all motion platform conditions, the pilots rated the simulation to be very similar to the aircraft. No reliable differences in pilot ratings were found for the three motion conditions, either within or across test scenarios for the six rating categories.

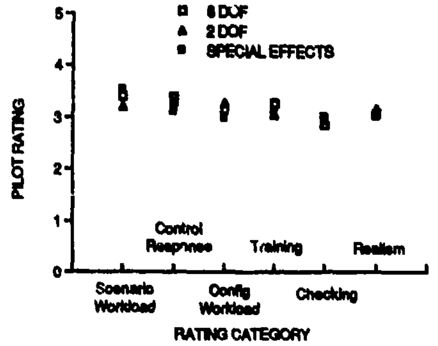

FIGURE 10 Pilot rating of simulator fidelity as a function of motion condition.

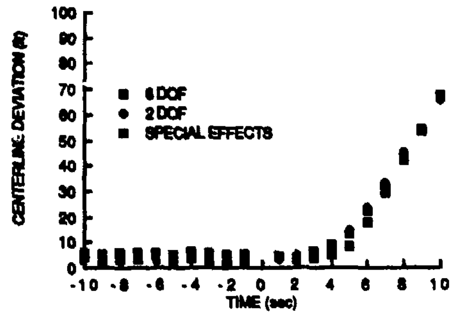

FIGURE 11 Aircraft centerline deviation prior to and following engine flameout (at time = 0) as a function of motion condition.

Aircraft state parameters and pilot control activity were analyzed to determine the effects of platform motion variations on pilot performance. Where successive trials of the same maneuver were executed, data from these trials were averaged. Statistical analyses for a repeated measures design were conducted to determine whether differences among platform motion conditions were reliable.

Engine Flameout Scenario - For the engine flameout scenario, most of the data of interest occur shortly before and after the loss of power. Figure 11 shows the simulated aircraft mean absolute deviation from runway centerline as a function of motion platform condition from 10 seconds prior to 10 seconds following engine flameout. No reliable differences were found. In order to evaluate motion effects on pilot control behavior, the mean variance of the combined rudder positions was calculated for this period. In general, greater amounts of control activity will be reflected as an increased variance of control position over time. An analysis of pilot rudder control activity for the three motion conditions did not reveal any reliable differences. An analysis of the time to climb to a safe altitude was also conducted for this scenario because of the operational significance of achieving altitude in optimal time under these flight conditions. Time to climb to an altitude of 120 m (400 ft.) from a speed of 120 KIAS was calculated for each pilot for each trial under each of the three motion conditions. Figure 12 shows the average time as a function of motion condition. Less than 10% difference (approximately 3 seconds out of 35 seconds total) in mean climbout time was evident among the three motion conditions and that difference was not statistically significant.

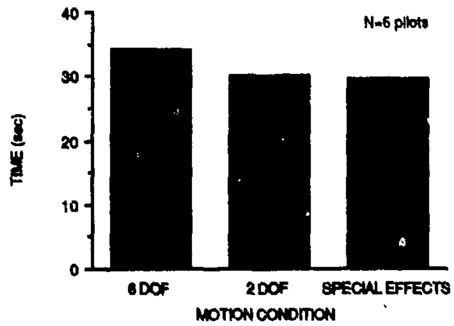

FIGURE 12 Time to climb to altitude following engine flameout (N = 6)

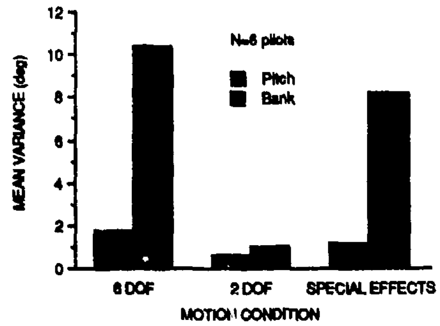

FIGURE 13 Mean variance of aircraft pitch and bank angle during approach to stall

Airwork Scenario - Of the three maneuvers executed, data only on the last two maneuvers performed during the airwork scenario (stalls and turns with yaw dampers failed) will be presented here. These two maneuvers provided an opportunity to examine pilots' ability to control the simulated aircraft at high angles of attack and when the aircraft was operating with significantly reduced control stability. The data analysis window for the stall maneuver was defined as the period 10 seconds prior, to 10 seconds following the lowest airspeed attained. Figure 13 shows the mean variance in aircraft attitude during this period. analyses of both aircraft pitch and roll angle variation was conducted for the three motion conditions. No reliable differences were found among motion conditions for either of these measures. Pilot performance measures during the stall maneuver were also unaffected by platform motion condition, as reflected in analyses of control column and control wheel position variation during the analysis window. Analyses of aircraft attitude and pilot control response during the standard rate turns with yaw dampers failed yielded results similar to the stall maneuver. No reliable differences were found in either pitch or roll variance for the three motion conditions. Although there was significant control activity during this maneuver, analyses of pilot control column and wheel inputs did not reveal reliable differences as a function of motion condition.

Approach and Landing Scenario - The instrument approach scenario was divided into two segments for the analyses. The first segment was the period during the approach starting at the time windshear was initiated (150 m, 500 ft.) and ending 20 seconds later. This period will be identified as the approach maneuver segment in the subsequent discussion. The mean absolute deviations of the aircraft from the glideslope and localizer are depicted in Figure 14. [As a reference in interpreting this data, note that the fuselage of the 727 is approximately 4 m wide.] although there appeared to be small differences in mean glideslope and localizer deviation as a function of motion platform condition, none of these differences proved statistically reliable.

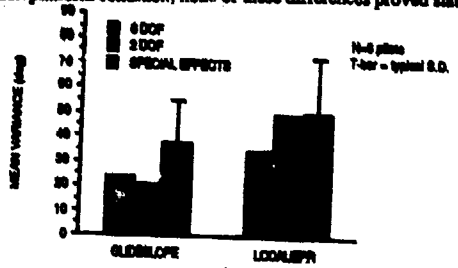

FIGURE 14 Mean glideslope and localizer deviation during the instrument approach maneuver

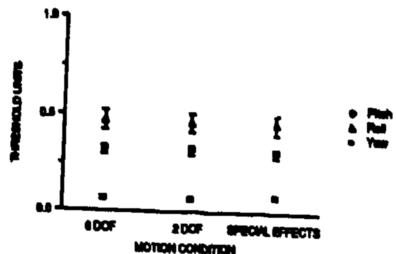

FIGURE 15 Mean RMS vestibular error in pitch, roll, and yaw computed for the instrument approach scenario.

The analysis window for the landing segment was defined as the last 10 seconds of flight. Aircraft sink rate and lateral deviation from the runway centerline at touchdown were analyzed for each of the three motion conditions. As with the approach segment, the observed differences fell well within those expected due to sampling variation alone. Analyses of pilot control activity measured during the last 20 seconds of flight revealed no reliable differences for control column or control wheel activity as a function of motion condition.

Spatial Orientation Error - The dynamic models of the vestibular system described above were used to estimate the mean root-mean-square (RMS) difference (vestibular error) between motion sensed by the pilot of the simulator and a pilot in an actual aircraft performing the same maneuver. The results of these computations are depicted in Figures 15, 16, and 17 for the instrument landing scenario and are typical of all scenarios. In general, the vestibular error in roll, pitch, and yaw was sub-threshold for all three motion conditions. Vestibular error computed in the vertical axis (heave) was several times the threshold value but was sub-threshold in the longitudinal axis (surge). Due to difficulties encountered with the simulation software, values for lateral acceleration (sway) were not recorded and could not be analyzed. In general, no reliable differences in mean RMS vestibular error were found among motion conditions.

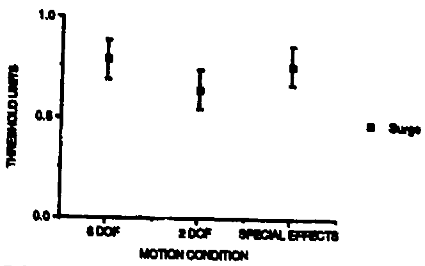

FIGURE 9. Mean RMS vestibular error in the longitudinal axis (surge) for the instrument approach scenario.

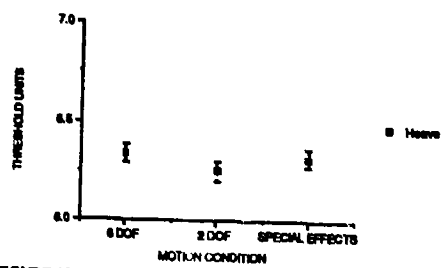

FIGURE 10. Mean RMS vestibular error in the vertical axis (heave) for the instrument approach scenario.

The absence of any reliable effects of platform motion on either subjective assessments of simulator fidelity or performance of the pilots is of particular interest since the absolute accelerations provided by the full motion conditions were, in general, well above threshold for the perception of whole body motion. However, when the vestibular model is used to estimate the difference between sensed motion in the simulator and the actual aircraft, the differences between full six DOF simulator platform motion and limited special effects motion alone are not significant. Whether whole-body motion affects pilot behavior is dependent on a number of factors. The more important of these are the dynamics of the vehicle being simulated, the nature and extent of pilot experience in aircraft and simulator operations, the task environment including the availability of information redundant to that provided by motion alone (e.g. a wide field-of-view visual scene), and pilot attitudes and beliefs. In the VTOL study described above, the pilots were aware that platform motion was being manipulated and were sensitive to differences in motion condition. In this study, the pilots were unaware that motion was being manipulated and this, combined with the overall realism of the simulation and the dynamics of the aircraft (a transport category fixed-wing aircraft as opposed to a hovering vehicle) may have overwhelmed the small differences in motion sensed as computed by the vestibular model.

CONCLUSION

A model for the perception of human spatial orientation based on physiological models of the vestibular organs has been successfully applied to the problem of flight simulator motion fidelity design and evaluation. The optimal control approach to the design of platform motion controllers is capable of producing motion drive logic that has been demonstrated to be comparable to an existing empirically optimized washout system in terms of pilot performance and simulator acceptability. The advantage of the model-based optimal design technique in that it permits the manipulation of the motion controller performance not only in terms of the motion platform displacement and accelerations, but directly at the level of the pilot's modeled motion perception. The motion controller synthesized with the optimization technique may be generated off-line by assuming that the pilot inputs and aircraft disturbances are a stochastic process. It is theoretically possible to improve the performance of an optimal washout system by measuring pilot inputs during the simulation and optimizing platform motion on-line, given the instantaneous state of the motion system; however, the computation time required to perform this is currently prohibitive. The emerging technology of high-speed parallel processors may provide a solution to this problem.

The validation of any simulator motion drive system in a human factors study presents a considerable challenge to the researcher. The relative insensitivity of the performance of highly-trained pilots to motion conditions restricts the use of such performance measures to assess simulator motion fidelity. Pilot compensation as reflected in Cooper-Harper handling qualities ratings appears to be a more sensitive indication of the degree to which motion cues affect the difficulty of a particular piloting task. The direct assessment of motion fidelity by means of a multi-component rating scale similar to that employed in this study shows promise as a measurement technique, particularly if normalizing corrections are made for the emphasis placed by each evaluator on individual components of the rating scale.

The tasks selected for inclusion in the transport simulator study are representative of the types of tasks that a pilot would be required to perform during transition and recurrent training in this aircraft. No attempt was made to alter the normal operating characteristics of the aircraft simulated. The presence of visual, auditory, and tactile cues which would normally occur in the simulator training or checking environment were provided. This study does not address the issue of whether motion platform cues affect pilot behavior under all conceivable conditions but only a sample of those conditions to which the pilot is normally exposed in the simulator. From the standpoint of normal training operations, the subjective and objective data collected in this study suggest that large, complex motion platform systems may not be necessary for either reasons of pilot acceptance or performance, given the presence of a wide field-of-view visual scene and sufficient "special effects" motion to enhance the realism of the simulation. For this type of aircraft (the Boeing 727), simulators with very limited motion capability may be adequate for training purposes. Further research on this issue is in progress. Caution should be exercised in any attempt to generalize from these data to other transport aircraft simulations. For example, substantial asymmetric thrust effects in aircraft with wing-mounted engines may produce lateral accelerations that differ markedly from those produced in the 727. Finally, the study evaluated the behavior of experienced 727 pilots. It remains to be determined whether motion plays a significant role in the acquisition of flying skills in the simulator and if the transfer of these skills to the aircraft is affected by the absence of large amplitude platform motion.

Finally, the effect of wide field-of-view visual scenes upon the pilot must be incorporated in future models of spatial orientation perception used in flight simulation. As new models are created for the interaction between visual and vestibular cues in the human pilot's perception of spatial orientation, they may be used in a manner similar to that described above as engineering tools for the flight simulator designer.

ACKNOWLEDGEMENT

We would like to extend our appreciation to John Stewart and Richard Bray of NASA Ames Research Center for their assistance during the design and performance of the VMS experiments. This research was performed with the support of the National Aeronautics and Space Administration under grant NAG 2-12.

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DISCUSSION

ELLIS: I would guess that there are two possibilities as to why the particular type of motion you used didn't seem to matter. One would be that you don't have a sensitive enough test to differentiate different types, and the other would be that perhaps you haven't found an extensive enough task to be able to separate the different types. I wondered what you thought the answer might be.

YOUNG: There is, Dr. Ellis, of course, a third possibility and that is that there really is no difference. I think that the question of the task is very important. Take the two extremes where in one situation (you might consider air-to-air combat as an example), the task is such that no motion will be adequate. Consequently, it doesn't matter very much what you use. The other extreme is a task like a well-behaved transport in which any motion is adequate. I think that the two cases I discussed were near those two extremes. That may be why we did not find vast differences. You will recall that in research situations in which one deals with aircraft that are close to the margin of stability, the motion is very important and the particular motion (especially motion delay) is critical in the stability of the pilot-vehicle system. So I think that the issue of the appropriate task is a very important one. As far as the appropriate measure, if we knew of a more sensitive one, we would have used it.

NAGEL: I wonder if any of your subjects became disoriented or had any of the other symptoms associated with the simulator sickness syndrome.

YOUNG: We were conscious of the simulator sickness situation and had no reports of it either in the VTOL or in the 727. Typical exposures were not very long, on the order of 30 to 40 minutes. Dr. Bussolari who conducted the tests at Ames was alert to this, queried his subjects, and did not receive reports indicating simulator sickness. There were reasonably good visual systems in both cases.

VAN HOLTEN: In aircraft combat, g-force is a very important impact on performance. Did you have any measurement of g-force?

YOUNG: No. g-force, of course, is the most difficult to reproduce in conventional simulators of the kind that we used here. Obviously you have to go to a centrifuge in order to produce the sustained g-forces that can be present in flight. We found that it was pointless for us to concentrate on g_x - on longitudinal acceleration in the optimization because in all cases we would have enormous errors. You may have noticed in my plot of the surge errors that the vestibular errors in longitudinal acceleration were six or seven times threshold. There we're in a situation similar to what I described to Dr. Ellis. Any motion system is so inadequate for reproducing g_x that it doesn't matter too much which motion is being used unless we were using a centrifuge. I would say that the specific examples I have discussed this morning are not applicable to the case of centrifuges for training.

UNIDENTIFIED SPEAKER: On a rotating platform it is possible to produce changes in apparent attitude.

YOUNG: Well, a rotating platform in which the center of the pilot's head is well off-axis is by my definition of centrifuge.

VIOLETTE: Due to technical recording difficulties, translation of Dr. Violette's comments (in French) are not available. However, Dr. Young's reply follows.

YOUNG: I'm in complete agreement with your generalization about the differences between transport category simulators and combat aircraft simulators. I have two comments about the motion requirements in combat aircraft simulation. One has to do with the flying qualities and handling qualities, and the other has to do with the safety-related aspects of, in particular, the problem of G-LOC, the sudden loss of consciousness due to high g. For the first problem, air-to-air combat simulation with wide field of view - there have been many people who have offered the opinion that with a sufficiently wide field-of-view, high-resolution visual system, motion is no longer a requirement, and here in Brussels in 1979 we discussed the problem of the continuing need for motion in wide field-of-view simulators. The accumulating evidence, I believe, states that motion remains an important requirement for air-to-air combat, even with wide field-of-view simulation. However, the magnitude of the motion can be drastically reduced because the only remaining requirement for motion is the onset cueing, the initial acceleration to hurry the onset of vection (visually induced motion). The other part of the question has to do with g-training to ensure that the pilot of a combat aircraft is aware of the danger of sudden high-g onset and also sustained g in relation to the dangers of not only traditional gray-out, but also the sudden loss of consciousness. For that purpose, we're really not talking about closed-loop simulation as much as g-training, for which I believe personally, the centrifuge is an extraordinarily important device - in fact, an irreplaceable one. I think that it is necessary that the pilot be given a task during centrifuge training that is related to his aircraft flying task. In fact, Professor Kenyon and I have taken some steps with the people at Brooks Air Force Base (Dr. Gillingham in particular) to implement a visual flying task on the centrifuge. There have been attempts to produce alternate g-cueing devices in flight simulators, including the g-seat, but in my opinion, none of them is, as yet, an adequate substitute for centrifuge training.

MOTION CUES IN EVERY DAY LIFE

J. Kriebel, A. Kornhuber and H. Lange*

Abt. Neurologie und Psychiatrie, Bundeswehrkrankenhaus Ulm
Oberer Eselsberg 40, D-7900 Ulm
*Abt. Neurologie, Universität, Oberer Eselsberg, D-7900 Ulm

SUMMARY:
Motion cues are perceived via different sensory modalities. Convergence of teleceptive and proprioceptive sensory information is a prerequisite of task-related senseful motor reaction. Research with event-related brain potentials (ERP) delivers important functional and topographical information of these complex interaction. From ERP data the function of the frontomesial supplementary motor area (SMA) could be analyzed. Their important role in timing sequential tasks and connecting the sensory and motor system is demonstrated. Sensory dysfunctions might irritate the onset and sequence of taskrelated motor reactions.
Vestibular evoked cerebral potentials are chosen to demonstrate the restrictions of the interpretion of the ERP results. From steady state evoked and transient evoked potentials further knowledge can be expected.

INTRODUCTION.

Event related brain potentials (ERP) play an important role as indices of mental work load, of flight performance, air crew selection etc. Therefore the whole problem has been limited as follows:

a. Motion cues as measurable by electrophysiological techniques, and
b. not only referring to every day life, but with some reference to simulator problems, and
c. not only focusing at one sensory modality but preferring the multisensory convergence and trying to give a link to the performing motor system. The pilot's hands are the link to the stick and throttle. Here the transmission between sensory perception and motor action i.e. to the aircraft takes place. Perception and reaction - motor (re)action of a pilot - , multimodal sensory analyses and task related senseful motoric (re)action and the thereby additionally produced sensory feedback (proprioceptive and teleceptive) are a continuously interwoven sequential process (Fig 1).

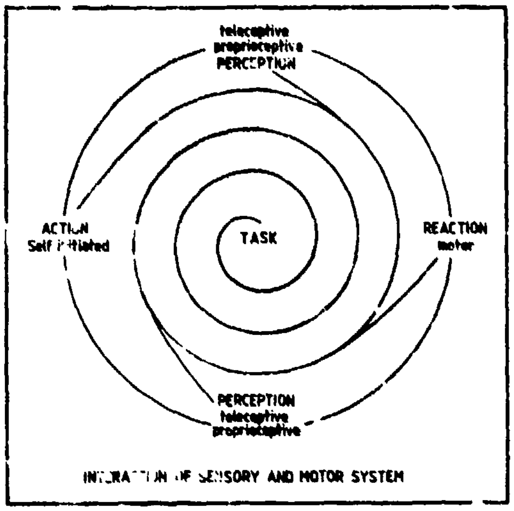

Fig. 1. After the self-initiated start of a real flight or a simulator flight the motor reactions and sensory perceptions are continuously interwoven through out the task.

At any level -especially under high workload - psychic influences may be supporting or complicating occurences. Individual skills and experience (i.e. learning, memory) will influence the outcome of the mission.
Research focusing on one sensory modality is highly needed and very important. But it should not be overemphasized with respect to the immensely complicated topic of similutor sickness. This is true even for the very important vestibular system in this context.

VESTIBULAR SYSTEM.

Despite the aforementioned limitation, we start to look at the vestibular system only. Before the interpretation of results we should very carefully proof what we are measuring (16). Are we really able to record mere vestibular evoked responses? Only an electric excitation of the vestibular nerve could result in a certainly vestibular evoked cortical potential (37). The arguments of some authors (18, 31, 36) are convincing in so far as they are measuring cortical evoked responses and as they reject or control artifact contaminations. But for us they are not that convincing as far as the exclusion of influences of the somatosensory system is concerned. There is evidence that we are dealing with a primary bimodal cortical projection field - a vestibular and somatosensory representation area - in the (ASSG) anterior suprasylvian gyrus (1, 2, 4, 10, 11, 21, 28, 32).
The vestibular cortex belongs to the somatosensory area (10) and of course there is close bimodal convergence and interaction. With scalp recordings of event related potentials (ERP) an interference of both modalities might be assumed. In rotary evoked potentials in normal and labyrinthectomised rabbits (17) relatively constant ocurrance in latencies and amplitudes of the early peaks (P 1 and P 2) was found. This suggests their somatosensory origin and does not underline the vestibular influence. But it seems likely that the later peaks (P 3 and P 4), which are much less commonly seen in labyrinthectomized animals, represent a cortical potential of the afferent vestibular fibres. Perhaps a suitable animal model may distinguish between the vestibular and the somatosensory part of the evoked potentials whereas the test situations with human subjects probably might not.

We had the opportunity to study evoked brain potentials with a 19-year-old patient with bilateral complete failure (agenisia) of the vestibular apparatus. So we could differentiate between the reaction of the vestibular and the somatosensory system by comparing the patient's data with those obtained from four healthy subjects of the same age.
In this study steady state vestibular evoked brain potentials were recorded (23).

Technique of Registration:

The patient and the healthy control subjects (aged between 19 and 21 years) were seated on a swivel chair and fastened to it with the heads bent forward by 30 degrees. Continuous sinusoidal rotations around the body axis were performed. In order to preclude any influence of eyemovements (vestibuloocular reflex) the subjects had to fixate a small lighted spot. This spot moved in phase with the swivel chair motion and therefore remained at the same place for the subjects eyes. The complete darkening of the experimental room, the masking of the subjects audition by white noise , the use of special spectacles permitting foveal vision only served to exclude conceivable visual, acoustic or somatosensory influences to the maximum extent possible.

With reference to the international 10/20-System Ag/AgCl electrodes were placed parietally on both sides 1 cm anterior to the positions P 3 (P 3') and P 4 (P 4'). For the unipolar EEG-registrations linked ears were used as reference electrodes. The registration of the electrooculogram (EOG) was used to avoid influences by eye movements, eyelid blinking and vestibulo-ocular reflex. Any possible sources of electromagnetic interferences in the experimental room could be excluded before the actual experiment by a pretest with a highly sensitive antenna mounted at the swivel chair. The transition resistance between the skull surface and the electrodes was less than one kOhm, the time constant was five seconds, the upper limiting frequency was at 70 cps. During the experiment the EEG, EOG and the technical data (including angular acceleration, angular velocity, position of the swivel chair) were recorded and stored on a magnetic tape for off-line analyses with artifact rejection. Averages of 400 EEG-epochs covering full sinusoidal patterns of the patient and the healthy subjects were obtained. All subjects were familiarized with the tasks to be accomplished and the behaviour required during the experiment in a standardized way. Above all, the subjects were instructed to especially concentrate on the conscious perception of the rotary motion. The first part of the experiment was designed to determine the threshold of sensation by means of psychophysical tests without registration of cortical potentials. Then, in a second step, we registrated cortical potentials below and above the threshold of perception.

FINDINGS.

Fig. 2 summarizes the results. The threshold values of the conscious rotary movement perception of the healthy subjects was different from that found for the patient. The patient could not perceive a rotary movement with a maximum angular velocity (Vmax) of 3.8 degree/sec (frequency: 0.4 cps; amplitude between two turning points: 3 degrees), whereas the healthy subjects showed a clear perception of the rotary movement. A maximum angular velocity (Vmax) of 5.8 degree/sec caused in the patient inconstantly and unreproducibly a sensation of a movement. Only when stimulated with a Vmax of 6.8 degree/sec or higher and an amplitude of 6 degrees between turning points, he was able to clearly perceive and describe the rotary movement and the position of the chair in the room.
The potentials registrated from healthy subjects showed - with only minor inter-individual differences (Fig. 2, diagram a & b) - a typical pattern of cerebro-electric negativity and positivity. When stimulated with a Vmax of 3.8 degree/sec, the registrated cerebral potential amplitude showed a frequency twice as high as the rotation frequency of the swivel chair. The measured value of the maximum amplitude between the negative and the positive maximum was 2 microvolt.
The recorded pattern can be considered typical because an inter-individual comparison revealed no significant differences. At the same time, the comparison showed a close phase correlation between the negative maximum over the cortex and the varying values of the rotation velocity. The latency difference between the maximum negativity and the maximum angular velocity amounted to values from 10 to 20 degrees only.
The literature tells us that fluctuations of cortical negativity are to be taken as an indication of cortical activities (3, 24, 25); in this case as an indication of the activity associated with the rotation stimulus. Psychophysical experiments support this assumption, since under other but similar experimental conditions a phase correlation between conscious perception of a rotation movement and the rota-

tion velocity has already been found (27).

Our results (23) allow the conclusion that the potentials registrated with healthy subjects with normal vestibular systems are of vestibular origin mainly. In this connection, the fluctuations of cortical potentials, which could be excited in the patient by stimuli of considerably higher intensity only, must be evaluated as an answer to multiple somatosensorial afferences, which - as to the time factor - are not firmly phase related to the steady state rotation stimulus (Fig. 2, diagram d). The experiments show that a normal vestibular apparatus certainly is a necessary prerequisite for the potentials registrated. But when interpreting the results, also the additional influence of a higher cortical processing must be considered (directed attention pot. DAP (24); contingent neg. variations, CNV (26, 35). The more so as the cerebral area, the potentials of which were registrated over the skull, is a location of converging vestibular and multiple somatosensorial and, particularly, kinaesthetic afferences (6, 20, 22, 32).

Another interesting aspect of the case presented in this study should be noted. It is certainly surprising how small the rotation stimuli are the patient is able to perceive by his normal somatosensorial afferents. But during nighttime, on rough ground, this information is not sufficient to enable the patient to counterpoise any disturbances of his balance immediately by a posture correction of his body. With the balance maintained, such corrections of the body posture are possible by vestibularly mediated labyrinthine reflexes (22, 23).

Whether transient evoked vestibular potentials or steady state evoked vestibular potentials or the combination of both will give better information needs further investigations. The interference of somatosensory system, however, has to be taken into account (23).

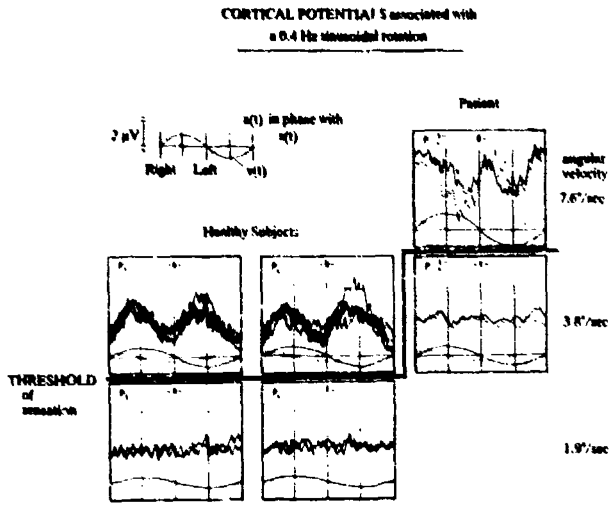

Fig. 2.
Slow cerebral potential shifts accompanying a steady state sinusoidal rotation. Comparison of the cortical evoked potentials of healthy subjects (diagram a-f) with those of a patient with completely lacking vestibular excitability (diagram d&c). The horizontal line indicates the threshold of conscious perception of the rotary motion. P_3 and P_4: bilateral parietal electrode positions. Angular acceleration: a(t); angular velocity: v(t); position of the swivel chair: s(t).

VESTIBULAR - (NECK)PROPRIOCEPTIVE INTERACTION.

The vestibular system measures linear and angular acceleration of the head in space (20, 21, 22, 27, 28). Proprioception signals position and movements of the parts of the body in relation to each other (22). Both systems are needed for postural stabilization, kinesthesia and spatial orientation. The labyrinths in the skull record movements of the head, regardless of what happens with the trunk. The CNS has also to take into account the proprioceptive signals of the neck about the excursions of the head relative to the trunk. The vestibulo-spinal and cervicospinal reflexes are used for the stabilization of the trunk (22). Neck input also reaches the cortical vestibular field in the anterior suprasylvian gyrus (ASSG) All canal-neck interaction appears to be quite consistently either the result of an additive or of a subtractive interaction of canal and neck induced effects. (4, 6, 11, 22).

Fig. 3 left side shows vestibular-neck interactions. Movements of the head relative to the trunk are also movements of the head in space. A convergence of labyrinthine, somatosensory and neck-proprioception is necessary. There exist some differences between the perception of active and passive movements (27).

PASSIVE MOVEMENTS AND PROPRIOCEPTIVE ILLUSIONS.

Fig. 3 right side concentrates on the results of passive horizontal rotations (f = 0.2 cps) of sitting healthy subjects (27). Pure labyrinthine stimulation was obtained by whole body rotation (H + T). The subject estimated the angle (Phi) from the individual turning sensation. Pure neck proprioceptive stimulation (Gamma) was obtained by rotations of the trunk relative to the stationary head. This led to a trunk turning sensation (TS). The direction was that of the actual trunk movement with respect to the stationary head. Surprisingly the subjects experienced also sensation of their head being rotated in the direction of the relative head-to-trunk deflection. This turning sensation represents a perceptive illusion (27) because no head movement took place. This illusion did not arise during active head movements. Perhaps this kind of passive trunk movements may happen during a simulated helicopter flight with the pilots head (and eyes) staying fixed on a target. Perhaps this kind of proprioceptive illusionary movements may contribute to a sensory dysfunction resulting in vegetative symptoms.

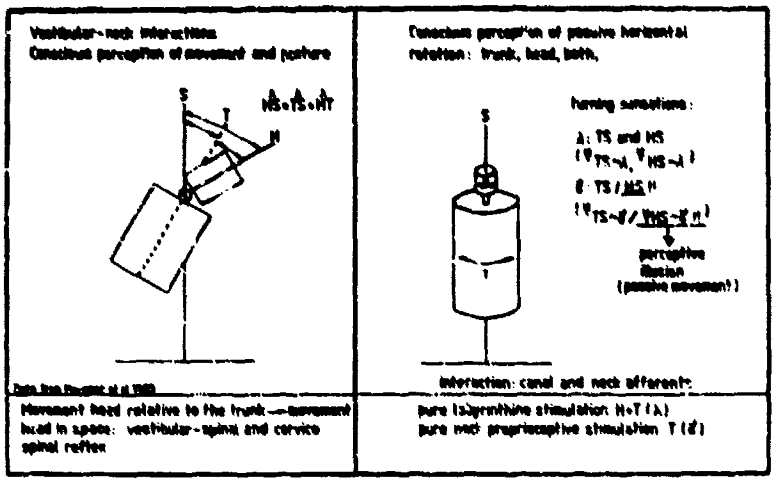

Fig. 3.
Left side. Schematic diagram of the head on the trunk defining reference direction. S: space: T: trunk: H: head: HS, TS, HT: angles between the vertical axis (S) an the axis of the trunk and head (29).
Right side. Subjective estimation of trunk-in-space and head-in-space rotation during combined horizontal canal and neck stimulation (H+T). The subjects registrate turning sensations TS and HS. Pure neck proprioceptive stimulation (T) by rotation of the trunk relative to the stationary head provoked perceptive illusions of head rotation (27).

CONTRAST SENSITIVITY FUNCTION AND VISUAL PERFORMANCE.

Even mere visual stimuli might cause nausea under certain conditions. This might happen, for example, if the visual input does not fit to expectancy, memory and experience. The recordings of transient visual evoked potentials added important information to our knowledge of the visual system. Even more information of this kind can be expected by the stationary visual evoked potentials now coming in use (12, 1, 29, 30, 34). This method enables us to determine the contrast sensitivity objectively by using sinusoidal grating patterns. The contrast function can be more important in target detection and identification than visual acuity (12, 13, 30, 34). Sinusoidal gratings varied in frequency, contrast and phase will deliver a visual equivalent (visuogram) of an audiogram. Visual acuity measures sensitivity at high spatial frequencies while contrast sensitivity functions cover a wide range of spatial frequencies. Individual differences in contrast sensitivity functions are the basis of differences in performance of complex tasks.Comparing research done so far indicated that contrast sensitivity and not visual acuity predicted simulated target detection (12, 13). Further studies related to size and distance perception occuring with artificial display systems probably will add some information to the understanding of simulator induced problems.
Of course vision plays also a role in spatial orientation, body posture, perception of self motion and locomotion. The ambient mode of visual processing interacts with the vestibular, somatosensory and auditory system to subserve spatial orientation, posture and gaze stability (20, 22).

MULTISENSORY CONVERGENCE.

The presumed function of converging information via multimodal sensory input is conscious perception of position in space and of movements (22). Thus information from any peripheral sensory organ is seldom transferred and analyzed separately on the cortical level. Integrated perception takes place already in subcortical levels (2, 6, 11). Multisensory convergence and selective data reduction occur at any time in every day life. They are of special interest in complex tasks like simulator work. Relative prepo derence of one sensory modality with respect to specific stimuli due to various tasks with reference to experience and memory may happen. No wonder that highly sophisticated and elaborate studies concentrated on one sensory modality do not exhibit reliable and useful information for these complex intermodal coordination (19).

MOTOR SYSTEM.

Multimodal sensory convergence is necessary for motor mechanisms (8, 20, 21, 22). The motor cortex is juxtaposed to the sensory cortex. From the sensory point of view, the motor cortex is mainly a somatosensory and vestibular association area (22). Within the motor cortex only those movements are represented which need sophisticated tactile and proprioceptive regulation: e.g. finger-, hand-, tongue-, lip- and toe movements (7, 22). However articulatory movements for speaking are guided by Wernicke's perisylvian speech area (8, 14, 15, 16, 22). Eye movements are localized in the pre-occipital, posterior, parietal and frontal cortex (8, 22). They are not represented in the motor cortex at all. The motor system is rather decentralized.

TIMING FUNCTION OF THE SMA.

Despite the decentralisation of the motor system temporal coordination between teleceptive and proprioceptive systems is necessary. This function is subserved by the frontomedial paralimbic supplementary motor area (SMA). Motivation and planning are channeled into the motor system via the SMA (8, 9, 14, 15, 16, 22). This area also has a real timing function in deciding on the start of a movement. The decision for the right moment for action must take into account the external and internal situation. This is the explanation for the extraordinary multitude of efferent and afferent connections of the SMA. This area has a convergence of teleceptive inputs via sensory projection and association areas (posterior cortex) and from motivational impulses from the limbic system (8, 22). We have a longitudinal functional division of the brain, known as hemispheric specialisation. Furthermore we have a transverse functional division of the brain. The retrorolandic posterior part with the sensory association area deals with the external features of a situation. The frontal lobes are mainly concerned with internal aspects of action. This includes coordination, planning, anticipation and temporal sequence (5, 22). We may speak of an anterior motivational brain and a posterior attentional brain (8). The necessary coordination is subserved by the SMA. The priming function of the fronto-mesial cortex (SMA) for voluntary self-paced movements is very well documented by studies of the surface negative Bereitschaftspotentials (BP) or readiness potentials (7, 8, 9, 14, 15).

VISUOMOTOR TRACKING AND MOTOR LEARNING.

Visuomotor tracking tasks include voluntary self-paced and stimulus-dependent movements in response to time-locked events (7, 24, 25).

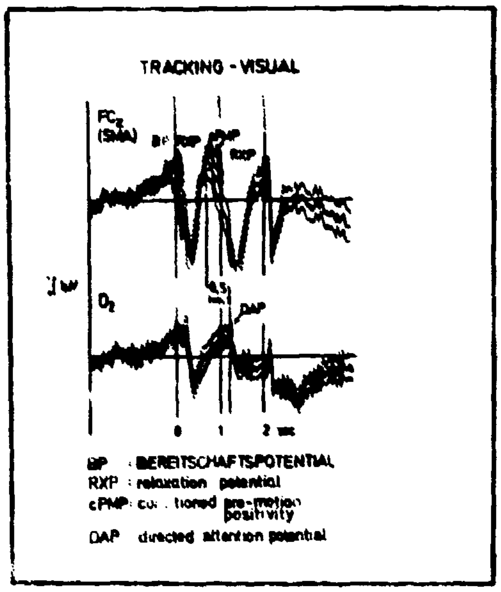

Fig. 4.

Grand averages of cerebral potentials across 16 subjects. Monopolar recordings vs linked ears. Dotted lines indicate double standard error. Time scale 6 sec. Vertical lines: voluntarily initiated stimulus onset (t=0): change in direction of the stimulus (t=1): fast reset of the stimulus (t=2). The different cortical areas show different patterns of negativity and positivity. FC_z (SMA): fronto-med., O_2: right occipital EEG-electrode positions. O_2 is exemplary for the visual projection area.

Fig. 4 shows hand tracking with a fixed time program. Between second 0 and 1 the visual stimulus constantly goes in a random direction. In sec 1 a sudden change in stimulus direction occurs. Between sec 1 and 2 the stimulus moves in another constant random direction. The motivation system is able to anticipate the time fixed changes of stimulus direction. Therefore the preceding negative Bereitschaftspotential (BP) declines already about 300 msec before the change of stimulus direction over the SHA (FCz). Over the teleceptive sensory association area (O_z), however, a high negative potential (DAP, directed attention potential) is maintained until 200 msec after the change of stimulus direction. This 200 msec-epoch represents the time of the sensory information processing for the new tracking direction (7, 24, 25).

CONCLUSIONS.

The few chosen examples of ERP show that complex functional and topographical information of the sensory and the motor system can be obtained. Motion cues in every day life or in sequential sensorimotor tasks like in simulator work can be studied. However, only a small part of the complex interwoven sequential sensorimotor process can be extracted for experimental analysis. Therefore the interpretation of the results is restricted and an explanation of such a complicated topic like simulator sickness is not possible. To this restriction we can add some other well known facts.
More experienced air crews are more likely to experience simulator sickness. Simulator sickness seems to depend on computer generated simulator situations and their multisensory perception by the pilot. The greater the fidelity of simulation the more likely simulator sickness will occur (19, 33).

The best simulation of flight situations is not (yet ?) equivalent to real flight experience (33). Pilots being able to realize these differences even under great work load can be assumed to be experienced ones. The simulator situation does not exactly fit to the real in-flight experience and causes a memory conflict. The psycho-physiological conflict related to simulator induced syndromes may occeur uncousciously. The problem might be psychologically aggravated because they are "flying" and not doing just some simulator work which might become helpful lateron during real flight maneuvers. Putting all these informations together we would assume that simulator sickness could be reduced if

a. the technical development could eliminate the differences between sensory perception in simulator and real flight situations, or if
b. less sophisticated simulators producing less similarity between training situations and real flight environment would be used. Does skill acquisition always require a highly sophisticated reproduction of flight enviroment (19,33) ?

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DISCUSSION

VIOLETTE: The comments (in French) by Dr. Violette could not be translated due to the quality of the tape recording. The following is an estimate of the intended content of a small part of his commentary:

I congratulate the speaker on his outstanding presentation. The review of neurophysiological systems was most enlightening. In my opinion, this talk should have been included in the opening session of this meeting. I feel that conditioned reflexes have not been sufficiently addressed. The highly experienced pilot is conditioned to expect particular patterns of sensory feedback when he initiates control actions in his aircraft. When he initiates the same control action in a simulator, the sensory information he has been conditioned to expect is not forthcoming. This explains the simulator sickness of experienced pilots.

Dr. Violette then commented on terminology.

KRIEBEL: I think that we have had too much talk on one point. Every point should be discussed in detail with reference to what we know from physiological experiments. However, this would take the rest of the session, and I think the chairman would not permit me to answer in such detail. I would like to make a very short comment on the terms we are using, for example, the term, motion cues. English is not my mother language - in everyday language and in scientific language also - we have quite a lot of terms. When you try to interpret them, you'll find that they are sometimes senseless, yet they are still used because everybody knows what we are speaking about even if it is not defined in great detail.

VIOLETTE: Not translated.

CHAIRMAN: Gentlemen, we must stop this discussion to allow time for the other papers. We will accept one more question. Larry, do you have one quick question?

YOUNG: Yes, it's a brief question to the author. Briefly, you stated that the cortical-evoked potentials were uniquely vestibular, and I would like to know what is the evidence that they are not an artifact of the auditory cues or a representation of other somatosensory inputs?

KRIEBEL: First, I didn't say that they were only of vestibular origin. I said, "mainly of vestibular origin." In reproducing the test situation, and in comparing it with the patient's data, it seems that these potentials might be caused by the vestibular system. I am not very certain of this because as I indicated, only excitation of the vestibular nerve would give us more confidence that we are recording only vestibular-evoked responses. If you examine the way we collected the data, our analysis and registration techniques, you'll see that most of the influence of artifacts of other origins were excluded insofar as is possible. We are very careful about artifacts. I've worked for about 3 years, focusing on artifact problems. I did not indicate that we have only vestibular-evoked responses; but some other authors do, and that's the reason I stressed this point.

MANIFESTATION OF VISUAL/VESTIBULAR DISRUPTION IN SIMULATORS: SEVERITY AND EMPIRICAL MEASUREMENT OF SYMPTOMATOLOGY

by

John G. Casali, Ph.D.
Department of Industrial Engineering and Operations Research
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24060
U.S.A.

and

LCDR Lawrence H. Frank, MSC, USN, Ph.D
Human Factors and Operational Analysis Branch
Pacific Missile Test Center
Point Mugu, California 93042-5000
U.S.A.

SUMMARY

Reported incidence rates of vehicular simulator-induced sickness in operators is highly variable both within and between devices. Recent review of the literature indicates that documented incidence rates range from 0 to nearly 90% in flight devices and even higher in some driving devices. However, the severity of the simulator sickness problem is not adequately gauged by a simple count of those operators experiencing one or more physiologic symptoms. Instead, a battery of metrics is useful in identifying and properly assessing an induced state of simulator sickness. This is of particular importance with the recent thrust in empirical research toward determination of the effects of simulator design parameters, such as control loop delays, on operator sickness and performance. This paper reviews the symptomatology experienced by operators of flight and driving simulators. Drawing upon this review, dependent measures are recommended for use in simulator-sickness research, including self-report forms, specific physiologic indices, postural equilibrium tests, performance tests, and susceptibility prediction instruments. A tabular documentation of published research studies concerning simulator sickness is also provided, as is a discussion of the ramifications of the problem.

INTRODUCTION

Background

Simulator-induced syndrome, more commonly termed "simulator sickness," has received considerable notoriety in recent years. There are cases in which specific vehicle simulators have developed a reputation for inducing infirmity symptoms in operators and as a result, have been severely hindered in application. Not only do operators often become leary of these devices because of the discomfort they may produce, training instructors and researchers may become skeptical about their ability to provide a realistic vehicular control experience (Casali and Frank, 1986). Though the severity of the simulator-induced syndrome is highly variable among devices, and a few devices have no reported problems, it is clear that a serious and ill-defined problem does exist. Unfortunately, human factors research aimed at determining the simulator-based causes of the syndrome has lagged considerably behind the rapid advances made in simulator technology, which have greatly expanded performance capabilities and application potential of the devices. In fact, since the first documentation of simulator sickness by Havron and Butler in 1957, there has been a paucity of empirical studies to determine either the symptomatology or the etiology of the problem. Most of the existing work is summarized in tabular form in this paper.

Simulators have been employed to mimic several full-scale vehicular systems, including fixed- and rotary-wing aircraft, automobiles, heavy trucks, tracked military vehicles, surface excavation equipment, underground mining devices, railway locomotives, space vehicles, ship bridges, and submarines. Of these, automobile and aircraft devices have most often been reported to have simulator sickness problems. Usually, the display perspective in devices which are reported to elicit sickness is "inside-out" rather than "outside-in." That is, the operator views an out-the-window scene through the windscreen and performs as an in-the-loop controller. Reports of sickness with "outside-in" devices are rare, though sickness has occurred in some simulators in which certain crew members do not view an out-the-window scene (e.g., Casali and Wierwille, 1986), and in teleoperated systems (Pepper, 1986). Symptomatology of the simulator sickness syndrome varies widely among individuals who experience it and among simulators that induce it. Acute effects may include headache, dizziness, disorientation, eyestrain, cold sweating, pallor, burping, nausea, and even full emesis. Degraded vehicular control and task performance may also result, which certainly inhibits the learning experience and/or influences the research process (e.g., Casali, 1981). And particularly disturbing are the residual post-simulator symptoms, including prolonged nausea and malaise, fatigue, motor dyskinesia, visual dysfunctioning, ataxia, and in rare instances, illusory visual flashbacks to the simulator experience for up to 10 hours afterward (Kellogg, Castore, and Coward, 1980). In certain military simulators, the "aftereffects" have been deemed severe enough to warrant prohibiting actual aircraft flight for a predetermined post-simulator period (e.g., Fitron 124, 1981).

Ramifications of the Problem

Simulators represent a useful resource for research and design, training, screening, and proficiency maintenance. Reliance on aircraft and ship bridge simulators for instructional purposes is particularly high in the military and maritime industry, respectively. Driving and flight devices are also heavily employed in research and system design. Sickness which accompanies simulator use in these applications poses several problems which may inhibit simulator effectiveness (e.g., Casali, 1981; Frank, Kellogg, Kennedy, and McCauley, 1983). Though the state of sickness in operators may not always be particularly overt or severe, the ramifications of the occurrence are quite serious, albeit in many cases, subtle. A few of these ramifications warrant mention.

1.) Compromised training. Trainee sickness may interfere with training syllabus objectives due to distraction, disruption, and reduced trainee confidence. Trainees may adopt certain strategies to reduce the inducement of sickness in the simulator, such as judiciously using certain control movements which result in innocuous simulator motion response. Obviously, such strategies may be totally inappropriate in the full-scale vehicle for the same set of circumstances. As a result, there is potential for negative transfer and habit interference when the full-scale vehicle is undertaken, particularly for novice trainees. The need to "unlearn" such responses results in inefficient utilization of the simulator and transfer vehicle as well as wasting trainee and instructor time.

2.) Safety risks. Though post-simulator driving or flying incidents and or accidents are not well-documented, simulator sickness does pose a potential safety hazard. While there appears to exist no firm evidence that post-simulator accidents are correlated with simulator-induced aftereffects (McCauley, 1984), measures have been taken to restrict same day flight in U.S. Navy aircraft following simulator exposure (OPNAVINST, 1984). Ataxia, visual dysfunction, and visual flashbacks are symptoms which are of particular concern to the post-simulator safety of operators.

3.) Inappropriate behavioral response. Simulator-induced sickness constitutes an inappropriate by-product of the simulator experience. If it were the case that simulator subjects became ill under precisely the same set of conditions for which they became motion-sick in the actual vehicle, then theoretically the sickness would be appropriate. However, this is not usually the case. For instance, drivers of automobiles rarely get sick but passengers often do. However, certain driving simulators are notorious for inducing sickness in the driver. Because such a simulator, but not the full-scale vehicle it attempts to replicate, induces operator illness, it can be argued that the simulator is inadequate.

4.) Validity problems. Related to the issue of artificial behaviors is the influence of simulator sickness on device validity. The presence of sickness constitutes an extraneous source of variance in the operator's data, because it does not correspond to responses observed in the actual system. Therefore, it poses a threat to the validity of the simulation and acquired data may not be readily generalizable to the actual system.

5.) Reduced utilization. Simulator utilization, and the development and realization of simulator application potential in general, is inhibited by the problem of operator sickness. As a result of the discomfort, instructors and trainees alike may lose confidence in simulator-based training and consequently may not use the simulator in a serious or consistent manner. Trainee motivation and attention are essential to an efficient, effective training program but these needs are somewhat opposed by the problem of trainee sickness. From a research standpoint, the performance data obtained from a sickness-inducing simulator are suspect and diminished use, and well as decreased funding, may result.

6.) Ethics. Particularly in military training devices, the problems caused by simulator sickness may be outweighed by the necessity and benefit of the training effort. A moderate degree of sickness may be acceptable (and furthermore lessen with exposure) as long as training objectives are not overly compromised. It is difficult, however, to apprise trainees or subjects of the potential of sickness beforehand without biasing their behavior in the simulator. Accepted ethical principles of informed consent in research (e.g., American Psychological Asso., 1982) dictate that such disclosure be made to subjects who are undertaking a decision to participate in a simulator-based experiment.

EXPERIMENTAL INVESTIGATION OF SIMULATOR-INDUCED SICKNESS

The aforementioned implications of simulator-induced sickness give rise to the need for research attention to alleviate the problem via simulator redesign and the application of countermeasures. Although the literature is somewhat limited in this regard, several studies have been performed to determine the scope and severity of the sickness problem in specific simulators. A very few studies have also investigated, in limited fashion, several simulator design features which are thought to contribute to sickness. However, the etiology remains ill-defined and further work is required before the underlying causes are fully understood.

Prior Research - Tabular Overview

The research studies and incidence accounts of simulator-induced sickness exist in a variety of the psychological, physiological, aerospace, military, and human factors literature. In an attempt to reduce this literature base to a concise, easily-referenced form, Tables 1 through 5 were devised. These tables are intended to provide the reader with a quick background reference on simulator sickness research, including information about the symptomatology, severity, and independent variables investigated. The tables are not exhaustive nor all-inclusive; as such, the reader should refer to the original references for specifics concerning experimental protocol and data analyses. An attempt was made to obtain and include all available references that have direct mention of simulator sickness occurrences among flight trainees or flight/driving research subjects. (A very recent study performed by the Naval Training Systems Center is not included in the review.) References are divided into those of an "experimental" nature, in which simulator-induced sickness was the primary focus of an investigation (see Tables 1 and 3), and those of an "anecdotal" nature, in which the incidence of operator sickness was simply reported as it occurred in conjunction with an applied effort (see Table 5). The latter group of reports include mention of simulator sickness in the context of its hindrance to a training, research, or evaluation effort and not as the intent of an experimental investigation. The experimentation reports vary considerably in the level of detail provided, though in all cases, the reports are catalogued to the fullest extent possible with respect to those aspects germane to simulator sickness. Blanks in the tables indicate that either the information was not evaluated or not reported in the study. Significant effects designate only those findings which were statistically-significant.

It is difficult to draw conclusions about a study on simulator sickness without first knowing the characteristics of the device on which it was performed. For this reason, provided in Tables 2 and 4 is an overview of specific simulators used in the studies. Brief information on the simulator visual display, motion system, operator cockpit, auditory system, operating procedures, intended applications, and corresponding actual vehicle is provided.

Information in the tabular overview is further subdivided into studies performed on an automobile simulator and those performed on an aircraft simulator. Most research has been conducted using aircraft devices, the majority of which are fixed-wing military devices (Table 1). Table 2, which is intended to be paired with Table 1, provides information on the aircraft simulators used in the studies. Though fewer experiments have been conducted on driving simulators, more emphasis has been placed on the manipulation of simulator independent variables in the driving studies. This research is documented in Table 3 which corresponds to the driving simulators' features in Table 4. Finally, Table 5 consists of simulator-induced sickness incidence reports in both flight and driving devices.

The tables are, for the most part, self-explanatory. However, in Table 1, it should be noted that the Hartman and Hatsell (1976) study which used the simulator for air-to-air combat (SAAC) was conducted with the motion system, whereas the Kellogg, Castore, and Coward (1980) study was performed on the SAAC without motion. (Currently, the SAAC is operated for training without the motion system.) A spectral analysis of heave motion in the SAAC was conducted by Hartman and Hatsell, indicating that a majority of spectral energy fell between 0.2 and 0.4 Hz, with a peak at approximately 0.25 Hz. As established by O'Hanlon and McCauley (1974), a provocative stimulus for inducing motion sickness is vertical oscillation of approximately 0.2 Hz. Consequently, the inherent motion energy spectrum of a simulator would be a critical factor in the inducement of simulator sickness.

Etiology

Though the intent of this paper is not to address the etiology of simulator-induced sickness, the independent variables noted in Tables 1 and 3 and the simulator descriptions in Tables 2 and 4 may provide limited guidance in targeting simulator design characteristics with potential for influencing sickness. In general, however, because so few of the studies have defined the stimulus conditions under which the inducement occurred, it is difficult to draw firm conclusions regarding the salient variables. It appears that sickness is provoked by a stimulus array emanating from certain design and usage characteristics of simulators, and that this array may differ between devices. Indeed, the causes of sickness may be simulator-specific, especially in that relatively subtle characteristics of a given simulator, such as geometric display distortion due to lack of alignment maintenance, may influence subject discomfort. Identification of critical stimuli in one device may not be generalizable to other devices. This problem, coupled with the likely interactive nature of some stimuli (such as display field-of-view and scene detail), makes the causes of simulator sickness somewhat difficult to investigate and isolate.

There has been limited progress in identifying certain simulator characteristics in need of research attention with regard to their influence on operator discomfort (e.g., McCauley, 1984; Casali and Wierwille, 1986). Some of these characteristics are not simulator-specific in that they occur in many simulators and research results concerning them may be generalizable Examples include control loop lags and delays, control loading and response, motion system axes and position/acceleration envelope, motion spectrum, display medium and optics, display field-of-view and scene detail, display update rates, dynamic imaging problems, and cockpit environment (e.g., temperature, humidity)

Table 1. Summary of Published Studies on Aircraft Simulator-Induced Sickness.

Reference Report	Hevron and Butler 1957	Miller and Goodson (1958, 1960)	Ryan, Scott, and Browning (1978)	Crosby and Kennedy (1982)	Kellogg, Castore, and Coward (1980)
Sim. Desig./Aircraft	2-FH-3/HTL4	2-FH-2/HTL4	2F87F-1/P-3C	2F87F-11/P-3C	SAAC/F-4
Type of Study	field study	field study	field study	field study	field observation
Intent	training effectiveness evaluation	simulator sickness	transfer of training	simulator sickness	simulator sickness
Simulator Tasks					
Scenario	footnote e	footnote e	landing	patrol mission	air combat maneuvering
Duration	30 min	30 min	4 hr	4 hr	about 60 min
Subjects					
Type	instructor/student pilots	instructor/student pilots	instructor/student pilots	flight engineers	pilot
Number	36	10	47	20 plus	48
Active/passive	active	active	active	passive	active
Independent variables			motion/no motion	field-of-view	
Dependent measures[a]	Q	Q, I	Q	D, Q, I	I
% incidence sickness	78[f]	60 instructor, 12 student	11	50	88
% Leaving simulator					
Signs/symptoms[b]					
Queasiness					
Sweating	x				54
Nausea	x				79
Emesis					
Eyestrain					
Headache	x		6		
Pallor					
Respiration changes					
Skin resistance changes					
Heart rate changes					
Fatigue/drowsiness					
Disorientation					
Visual dysfunction					
Ataxia			11	50	60
Dizziness					
Vertigo		x			
Aftereffects	x	x		x	
Other					Spinning sensation-54%, maneuvering sensations-25% headache, leans, dizziness-23%, flashbacks-35% dreams-35%, inverted visual field-10%
Habituation Effects[c]	x	x			x
Experience Effects[d]	x	x			
Instructor/Student Effects	x	x			
Significant Effects					

[a]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.
[b]A number indicates % occurrence; x indicates occurrence reported, but not by %.
[c]Symptoms lessen with exposure to simulator.
[d]More experienced real-world vehicle operators more susceptible.
[e]Two scenarios: low level (55 ft) or high level (500 ft) maneuvers.
[f]7 of 11 instructors also had to quit due to sickness.
[g]Also had a maximum maneuvering scenario.
[h]Slight discomfort to mild nausea.
[i]Both F-4 and F-14 cockpits evaluated.
[j]Transport delay, 3 levels in msec: 126 ± 70 (standard), 177 ± 23 (CH-53E), 215 ± 70 (SH-3).
[k]Stand-on-one leg test for ataxia.

characteristics. These are but a few examples, as over 60 independent variables have been identified in McCauley (1984).

As can be surmised from Tables 1 and 2, a few independent variables have already been investigated and their isolated influence on operator discomfort determined. Briefly, these include the following findings: (1) visual system transport delay is more disquieting than motion system delay, visual cue should lead (temporally) motion cue

Table 1. Summary of Published Studies on Aircraft Simulator-Induced Sickness. (Continued)

Reference Report	Hartman and Hatsell (1976)	Money (1980)	McGuinness, Bouman, and Forbes (1981)	Lilienthal and Merkle (1986)	Uliano, Lambert, Kennedy, and Sheppard (1986)
Sim. Design/Aircraft	SAAC/F-4	OP140 FDS/P-3C	2E6[i]/F-4,F-14	2F120/CH53E	VTOL/SH-60B
Type of Study	field study	field study	field survey	field study	laboratory
Intent	simulator sickness	simulator sickness	simulator sickness	simulator sickness	simulator sickness and flight performance
Simulator Tasks					
Scenario	air combat maneuvering[g]		air combat maneuvering	full mission	air taxi and slalom
Duration	about 60 min		30-45 min	90 min	40/80 min
Subjects					
Type	pilot	pilot	pilot/navigators	pilot/copilot/instructor	experienced pilots
Number	100-114	14	66	42	25
Active/passive	active	active	active/passive	active	active
Independent variables					visual lag[j], days of exposure (1,2, or 3), pilot experience
Dependent measures[a]	Q,I	Q	Q	Q	O[k], Q
% Incidence sickness	52	43	27	62	46 on 1st day, reduced thereafter
% Leaving simulator					(exact symptoms unspecified, "almost all" had symptoms of motion sickness)
Signs/symptoms[b]					
Queasiness				6	
Sweating				8	
Nausea	14	x[h]	9	13	
Emesis	2				
Eyestrain	50			38	
Headache			7	30	
Pallor					
Respiration changes					
Skin resistance changes					
Heart rate changes					
Fatigue/drowsiness	38		11	38	
Disorientation	52				
Visual dysfunction			8	20	
Ataxia					x
Dizziness			17	13	
Vertigo			11	8	
Aftereffects			x	2	
Other			Leans-9%, discomfort-8%, other-9%	Changes in appetite-3%, discomfort-34%, boredom-13%, change in salivation-8%, difficulty concentrating-13%, depression-5%, fullness of head-11%, faintness-2%	No effect of lag on illness, longer hops did not increase illness, wind increased illness, increased lag degraded performance
Habituation Effects[c]		x			x
Experience Effects[d]			x		x
Instructor/Student Effects					
Significant Effects					(see above)

[a]How obtained: Q=Questionnaire, I=Interview, R=Instrumentation, O=Direct observation, S=Subject comment.
[b]A number indicates % occurrence; x indicates occurrence reported, but not by %.
[c]Symptoms lessen with exposure to simulator.
[d]More experienced real-world vehicle operators more susceptible.
[e]Two scenarios: low level (55 ft) or high level (500 ft) maneuvers.
[f]7 of 11 instructors also had to quit due to sickness.
[g]Also had a maximum maneuvering scenario.
[h]Slight discomfort to mild nausea.
[i]Both F-4 and F-14 cockpits evaluated.
[j]Transport delay, 3 levels in msec: 126 ± 70 (standard), 177 ± 23 (CH-53E), 215 ± 70 (SH-3).
[k]Stand-on-one leg test for ataxia.

Table 2. Flight Simulator Characteristics.[a]

Sim. Designation	2-FH-2	V/STOL	2F87F I	2F87F II
Actual Vehicle	Bell HTL-4	General V/STOL	P-3C turboprop	P-3C turboprop
Type Vehicle	helicopter	jet-lift	patrol	patrol
Application	hover training	research	training	training
Visual System				
Type	point-light proj.	point-light proj.	CCTV monitor Redifusion Duoview	CGI MDEC[e] Vital IV
Image Source	transparency	transparency	model board	digital CGI
Medium	curved screen	spherical screen	CRTs	calligraphic CRTs
Infinity ∞ scaling	refraction, 6-12 ft. viewing distance	reflection, viewing distance	reflective ∞ optics	reflective ∞ optics
Lighting Cond.	sim. daylight	daylight	day, dusk, night	dusk, night
H/V FOV (deg)[b]	200/75	100/30	48/36[d]	48/36[d]
Scene Content	sky, earth	sky, earth, objects	sky, earth	sky, earth
Motion System				
Type	fixed-base	unk.	synergistic	synergistic
Deg of Freedom[c]	-	P, R, Y	all 6	all 6
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	yes	unk.	-	-
Cockpit Environ.				
Cab type	open	unk.	enclosed, A/C cab	enclosed, A/C cab
No. Crew	2	1	3	3
Audio	engine	unk.	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	unk.	takeoff & land	takeoff & land
Typ. Task Length	30 min.	unk.	4 hr.	4 hr.
Freeze Capa.	yes	yes	unk.	unk.
Slew/Reset Capa.	yes	-	unk.	unk.
Ext. View Allowed	unk.	unk.	unk.	unk.
Other Characteristics	control lag noted	orig. fixed-base, motion added		flight engr. had off-axis display view--induced sickness

[a]As existing in studies referenced in Table 1.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[d]One window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. II).
[e]McDonnell-Douglas Electronics Corporation.
[f]CCTV camera model target projectors.
[g]CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.
[h]Crew instructed not to view display during reset.
[i]Motion seat disabled during Uliano et al. study.

(Frank et al., 1987); (2) no effect of visual delay on sickness (Uliano et al., 1986); (3) experienced pilots (or drivers) more susceptible, discomfort subsides with increased simulator exposure (Kellogg et al., 1980; McGuinness et al., 1981; Money, 1980; Reason and Diaz, 1971; Uliano et al., 1986); (4) tilt cueing of lateral acceleration, delayed dynamics, and subject enclosure heighten operator uneasiness (Casali and Wierwille, 1980); (5) pilot (controller) more susceptible than passive crew (McGuinness et al., 1981); (6) no differences between motion/no motion with respect to dependent measures (Crosby and Kennedy, 1982; Hartman and Hatsell, 1976; Ryan et al., 1978); (7) reduction in sickness symptoms with addition of motion in V/STOL (Sinacori, 1967); (8) off-axis viewing of displays produces discomfort and ataxia (Crosby and Kennedy, 1982); and (9) field-independent subjects more susceptible than field-dependents (Barrett and Thornton, 1968). Caution against interpreting these findings in the global sense is advised. Due to the polygenic nature of simulator sickness, may factors may contribute, singly or in concert, to induce a state of discomfort.

SYMPTOMATOLOGY MEASUREMENT

From the preceding tabular overview, it is clear that the effects of simulator-induced sickness may be manifested via a variety of signs and symptoms. To properly study the problem, the selection of valid and reliable dependent variables for identifying degrees of operator sickness and for assessing the effects of manipulated simulator variables must be done with care. The importance of recognizing the polysymptomatic nature of the state of simulator-induced sickness has been well-demonstrated (e.g., Kennedy et al., 1984; Testa, 1969).

Table 2. Flight Simulator Characteristics.[a] (Continued)

Sim. Designation	(2 cockpits) SAAC	CP 140 FBS	2E6 ACM (2 cockpits)	2F112
Actual Vehicle	F-4 jet	Aurora turboprop (P-3C)	F-14/F-4 jet	F-14 jet
Type Vehicle	fighter	patrol	fighter	fighter
Application	air-air combat training	training, limited research	air-air combat training	air-air combat & misc. training
Visual System				
Type	CGI mosaic[f]	CGI	point-light proj.[f] MDEC	point-light proj.[g]
Image Source	digital CGI	digital CGI	2 transparency spheres	2 transparency spheres
Medium	8 monochrome raster CRTs	2 CRTs	40 ft. dia. dome	40 ft. dia. dome
Infinity ∞ optics	reflective ∞ optics	unk.	20 ft. viewing distance	20 ft. viewing distance
Lighting Cond.	unk.	dusk, night	day, dusk, night	day, dusk, night
H/V FOV (deg)[b]	~ 296/180	unk.	~ 330/200	~ 330/200
Scene Content	sky, earth, A/C	sky, earth, objects	sky, earth, A/C	sky, earth, objects, carrier
Motion System				
Type	synergistic	synergistic	fixed-base	fixed-base
Deg of Freedom[c]	all 6	all 6	-	-
g-seat/g-suit	both	-	both	both
g-display dim	yes	-	yes	yes
Vibration	-	-	control stick vib.	control stick vib.
Cockpit Environ.				
Cab type	actual cockpits w/ canopies	enclosed	actual cockpit w/ canopies	actual cockpit w/ canopy
No. Crew	1 ea. cockpit	3	2 ea. cockpit	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	in-air combat	whole flight	in-air combat	whole flight
Typ. Task Length	45-60 min.	30 min.-2 hr.	45 min.-1 hr.	1-1.5 hr.
Freeze Caps.	yes	yes	yes	yes
Slew/Reset Caps.	yes	yes	yes	yes
Ext. View Allowed	unk.	unk.	no	no
Other Characteristics	0.2-0.4 Hz motion spectrum component apparent		gentry handrails in view of cockpit	

[a]As existing in studies referenced in Table 1.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[d]One window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. 11).
[e]McDonnell-Douglas Electronics Corporation.
[f]CCTV camera model target projectors.
[g]CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.
[h]Crew instructed not to view display during reset.
[i]Motion seat disabled during Uliano et al. study.

The purpose of this section is to review the measures which have been applied in studies of simulator sickness to date, assess the sensitivity of those measures, and provide guidance for the researcher as to which measures are the most promising for future studies. It is stressed at the outset that the scope of this review is limited to published research specific to simulator-induced sickness or closely-related problems. Though many physiological symptoms of simulator sickness appear akin to those of motion sickness, the intent herein is to stress those metrics which have existing data sets from simulators. As such, an exhaustive review of the motion sickness literature and motion sickness symptomatology is not included in this brief paper. The interested reader is advised to consult Money (1970) and Reason and Brand (1975) for complete treatises on motion sickness symptomatology.

Self-Report Measures

Probably the most popular and easily-administered data collection technique for simulator use is that of self-report. Post-simulator subject self-evaluation has been obtained successfully in several studies with a variety of different questionnaires (e.g., Barrett and Thornton, 1968; Frank et al., 1987; Hartman and Hatsell, 1976; Testa, 1969; Uliano et al., 1986). Post-simulator verbal interviews using structured questions, have also proven useful for discovering symptoms and identifying their frequency and severity of occurrence (Kellogg et al., 1980).

Table 2. Flight Simulator Characteristics.[a] (Continued)

Sim. Designation	2F120	2F64C	2F110	2F117
Actual Vehicle	CH-53E	SH-3	E-2C turboprop	CH-46E
Type Vehicle	helicopter	helicopter	AEW/tactical	helicopter
Application	training	training	training	training
Visual System				
Type	CGI MDEC Vital III	CGI MDEC Vital IV	CGI Redifusion Marevlew SP1	CPI Redifusion CTS
Image Source	digital CGI	digital CGI	digital CGI	digital CGI
Medium	calligraphic CRTs	calligraphic CRTs	calligraphic CRTs	raster CRTs
Infinity optics	reflective = optics	reflective = optics	reflective = optics	reflective = optics
Lighting Cond.	night	dusk, night	dusk, night	day, dusk, night
H/V FOV (deg)[b]	~144/32	130/30 & chin window	~130/38	200/90 & chin window
Scene Content	sky, earth, ships, objects	sky, earth, ships, objects	sky, earth, carrier, objects	sky, earth, ships, objects
Motion System				
Type	synergistic	synergistic	synergistic	synergistic
Deg of Freedom[c]	all 6	all 6	all 6	all 6
g-seat/g-suit	-	-	-	-
g-dimming dim	-	-	-	-
Vibration	yes, multiple	yes	yes	yes
Cockpit Environ.				
Cab type	enclosed helo. cab	enclosed helo. cab	enclosed A/C cab	enclosed helo. cab
No. Crew	2	3	2	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	whole flight	whole flight	whole flight
Typ. Task Length	1.5 hrs.	unk.	2-2.5 hrs.	1.5-2 hrs.
Freeze Capa.	yes	yes	yes	yes
Slew/Reset Capa.	-	yes	yes	yes[h]
Ext. View Allowed	yes	unk.	yes	yes
Other Characteristics				

[a]As existing in studies referenced in Table 1.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[d]One window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. 11).
[e]McDonnell-Douglas Electronics Corporation.
[f]CCTV camera model target projectors.
[g]CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.
[h]Crew instructed not to view display during reset.
[i]Motion seat disabled during Uliano et al. study.

Particularly in the case of a written questionnaire, it is important that the selected instrument is easily understood, concise enough to complete quickly, face valid from the subjects' point-of-view, quantifiable for analysis purposes, reliable over time and trials, and correlated with objective measures which are known to be valid.

Motion sickness questionnaire (MSQ). The MSQ, developed by Wiker, Kennedy, McCauley, and Pepper (1979), meets the above criteria and has been demonstrated to be sensitive to simulator-induced effects in several studies (e.g., Frank et al., 1987; Lilienthal and Merkle, 1986; Uliano et al., 1986). The MSQ is a 27-item checklist of physiological symptoms, sensations, and visual/vestibular effects, some of which are subject-rated on a four-point scale as to their severity. The form is usually administered before and after the simulator experience. A primary feature of the MSQ is that subjects' responses may be rated post-hoc according to a validated diagnostic categorization scheme to achieve a seven-point sickness severity score (Kennedy, Dutton, Lilienthal, Ricard, and Frank, 1984). This composite score is then applicable to statistical analyses. Wiker et al., have demonstrated that MSQ scores have a significant point-biserial correlation of mean r = 0.63 with the dichotomous criterion of emesis/no emesis. Because of its demonstrated validity and sensitivity, the MSQ must be considered as a measure of choice in simulator-induced sickness research.

Direct Observation

The motion-sick individual may experience a subset of approximately 40 physiological symptoms which have been identified in the literature (e.g., Reason and Brand, 1975). Certain of these symptoms are overt and may allow direct observation and identification

Table 2. Flight Simulator Characteristics.[a] (Continued)

Sim. Designation	2F121/2F120	2E7 ACTT (2 cockpits)	2F132	VTRS
Actual Vehicle	CH-53D/E	F-18 jet	F-18 jet	SH-60B
Type Vehicle	helicopter	fighter	fighter	helicopter
Application	training	air-air combat & tactics	training	research
Visual System				
Type	CGI Rediffusion [illegible]	CGI [illegible] generator	CGI MDEC Vital IV	CGI (GE Compuscene)
Image Source	digital CGI	CGI	digital CGI	digital CGI
Medium	raster CRTs	raster TV proj. on 30 ft. dia. dome	calligraphic CRTs	light-valve projection onto 24 ft dia. dome
Infinity Optics	reflective optics	viewing distance	viewing distance	viewing distance
Lighting Cond.	day, dusk, night	day, dusk, night	dusk, night	day, dusk
H/V FOV (deg)[b]	200/50 & chin window	~ 300/150	~ 48/32	~ 160/70
Scene Content	sky, earth, ships, objects	sky, earth, A/C	sky, earth, carrier objects	sky, earth, objects
Motion System				
Type	synergistic	fixed-base	fixed-base	fixed-base
Deg of Freedom[c]	all 6	-	-	
G-seat/G-suit	-	both	both	motion seat[i]
G-display dim	-	yes	unk.	
Vibration	yes	yes	-	
Cockpit Environ.				
Cab type	enclosed helo. cab	actual cockpits w/canopies	actual cockpit w/canopy	helicopter cockpit
No. Crew	3	1	1	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	in-air combat	takeoff & land	whole flight
Typ. Task Length	1.5-2 hr.	unk.	unk.	variable
Freeze Capa.	yes	yes	yes	unk.
Slew/Reset Capa.	yes[h]	unk.	yes	unk.
Ext. View Allowed	yes	unk.	-	-
Other Characteristics			dynamic replay seat buffet carr or takeoff/landing	

[a]As existing in studies referenced in Table 1.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).
[d]One window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. 11).
[e]McDonnell-Douglas Electronics Corporation.
[f]CCTV camera model target projectors.
[g]CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.
[h]Crew instructed not to view display during reset.
[i]Motion seat disabled during Uliano et al. study.

by an experimenter. Some symptoms, such as increased pallor, facial or limb perspiration, change in breathing activity, change in facial expression, and increased swallowing, may be relatively subtle in their manifestation and therefore necessitate thorough knowledge of the subject's normal appearance. Others such as violent burping, loss of balance, guttural heaving, and, of course, frank emesis are more obvious.

Crampton (1955) demonstrated the efficacy of using color photographs of motion-sick individuals to identify the progression of overt symptoms from sickness onset to full emesis. Uliano et al. (1986) found that experimenters could reliably assess pre-post simulator differences in subjects' physical appearance when using a structured Likert rating scale. Likewise, subjects used the same scale to self-rate their own facial appearance pre-post exposure. Strong agreement was obtained between the self-ratings and the experimenters' ratings. Both rating techniques demonstrated sensitivity to reduced subject illness with increased simulator exposure across a three-day period. Experimenter-provided ratings were also performed on photographs of subjects (rather than from direct view), but no additional information was obtained and inter-rater reliability suffered as a result. In any case, direct observation of symptomatology may be useful in augmenting instrumented physiologic measurement and/or self-evaluation.

Instrumented Physiological Measures

Changes in bodily cardiovascular, gastrointestinal, respiratory, biochemical, and temperature regulation functions often arise with simulator sickness. Several physiological measures have been electronically or electro-optically instrumented and

Table 3. Summary of Published Studies on Driving Simulator-Induced Sickness.

Reference Report	Barrett & Nelson ([illegible])	Barrett & Nelson ([illegible])	Barrett & Thornton ([illegible])
Simulator Designation	[illegible] I	[illegible] II	[illegible] I & II
Type of Study	laboratory	laboratory	laboratory
Intent	simulator evaluation	virtual image display evaluation	perceptual style differences[e]
Simulator Tasks			
Scenario	freeway driving w/stops	freeway driving w/stops	freeway driving w/stops
Duration	[illegible] min.	[illegible] min.	[illegible] min.
Subjects			
Type	male engineering dept. employees	male engineering dept. employees	male engineering dept. employees
Number	[illegible]	[illegible]	[illegible]
Active/Passive	active	active	active
Independent Variables	emergency stop, speed	emergency stop, speed	emergency stop, speed
Dependent Measures[a]	D,S	D,S	D,S,Q
% Incidence Sickness	[illegible]	72	
% Leaving Simulator	[illegible]	[illegible]	30
Signs/Symptoms[b]			
Queasiness			
Sweating	x	x	
Nausea	x	x	
Emesis	x		
Eyestrain		x	
Headache		x	
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation	x		
Visual Dysfunction			
Ataxia			
Dizziness	x	x	
Vertigo			
Aftereffects			
Other	upset stomach faint feelings		subject rating of discomfort, subject estimate of discomfort duration, No. trials subject able to stay in sim., rod & frame test
Habituation Effects[c]			
Experience Effects[d]			
Instructor/Student Effects			
Significant Effects			extremely field independent, more susceptible

[a]How obtained: Q=Questionnaire, I=interview, R=instrumentation, D=Direct observation, S=Subject comment.
[b]A number indicates % incidence; x indicates occurrence reported, but not by %.
[c]Symptoms lessen with exposure to simulator.
[d]More experienced real-world vehicle operators more susceptible.
[e]Post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson data.
[f]Stand-on-one-leg test for ataxia.

transduced directly from subjects in simulator experiments. A brief discussion of the demonstrated success of each of these measures follows.

Cardiac activity. The most popular and easily-obtained metric of cardiovascular activity is that of heart rate, or similarly, pulse rate transduced at a peripheral artery. Interbeat interval is sometimes also measured. These measures may be obtained via a variety of techniques, including palpation, cardiotachometry, electrocardiography, phonocardiography, and plethysmography (Stern, Ray, and Davis, 1980). The last of these techniques relies on blood volume changes in a bodily member such as an arm, leg, finger, or earlobe. The volume changes may be sensed through photoelectronics (detecting opacity changes), impedance measurement, or strain gauge measurement. Of all the cardiac measurement techniques, photoelectric plethysmography obtained using an earlobe transducer may be the most easily administered and least intrusive to the vehicular control task.

Money (1970) reported that a motion-sick individual may exhibit either increases or decreases in heart rate from baseline levels. In a study where subjects viewed a film of fast driving on curvy roads (but were not actively controlling the vehicle), Parker (1964) reported an increase (from baseline) in subjects' heart rates in response to the film and a decrease in finger pulse volume. The film also produced other definitive symptoms of motion sickness in subjects. Using photoelectric plethysmography, Casali and Wierwille (1980) found no changes in pulse rate as a result of the simulator task, though other physiological measures were sensitive. In conclusion, limited evidence exists for

Table 3. Summary of Published Studies on Driving Simulator-Induced Sickness. (Continued)

Reference Report	Testa (1969)	Reason & Diaz (1971)	Casali & Wierwille (1980)	Frank, Casali, and Wierwille (1987)
Simulator Designation	UCLA I	[illegible]	VPI&SU	VPI&SU
Type of Study	Laboratory	Laboratory	Laboratory	Laboratory
Intent	simulator sickness	simulator sickness	simulator sickness	simulator sickness driving performance
Simulator Tasks				
Scenario	two-lane winding mountain road	winding perimeter road	freeway driving	freeway driving
Duration		10 min.	20 min.	21 min.
Subjects				
Type	male college students	students/technicians	students	simu. drivers
Number	40	13 male/16 female	64	27 male/27 female
Active/Passive	active	passive	active	active
Independent Variables	perceptual style, instructional set	restricted vision, sex, driving experience	lateral accel. cueing, delayed dynamic feedback, simulator enclosure, perceptual style	synchronous/asynchronous visual and motion system delay of 0, 140, 340 msec; perceptual style
Dependent Measures[a]	R,Q	Q	R,Q	D[f], R, Q
% Incidence Sickness	100	90		
% Leaving Simulator		1 case		
Signs/Symptoms[b]				
Drowsiness				
Sweating	x	29		
Nausea		42		
Emesis				
Eyestrain				
Headache		45		
Pallor		29	x	
Respiration Changes	x		x	x
Skin Resistance Changes			x	
Heart Rate Changes				
Fatigue/Drowsiness		3		
Disorientation				
Visual Dysfunction				
Ataxia				x
Dizziness		71		
Vertigo				
Aftereffects				
Other	rod & frame test, embedded figures test, instructional set	bodily warmth-48% stomach awareness-42% increased salivation-19% dry mouth-6%	yaw deviation, no. of steering reversals	questionnaire, yaw deviation, no. of steering reversals, ataxia tests
Habituation Effects[c]				
Experience Effects[d]		x		
Instructor/Student Effects				
Significant Effects	sweating, respiration, perceptual style, instructional set	females more susceptible, experienced more susceptible	illness and performance measures degraded by enclosure, delayed dynamics, and tilt sim. of lat. accel; no perc. style effect	illness and performance measures degraded with increasing visual or motion delay; visual update should lead motion to minimize discomfort and achieve best performance; no perc. style effect.

[a]How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.
[b]A number indicates % incidence; x indicates occurrence reported, but not by %.
[c]Symptoms lessen with exposure to simulator.
[d]More experienced real-world vehicle operators more susceptible.
[e]Post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson data.
[f]Stand-on-one-leg test for ataxia.

the application of heart rate measures in studies where only mild levels of sickness are expected to occur.

Respiration rate. The measure of respiration rate, or breaths-per-unit time, has proven to be a sensitive indicant of simulator sickness, but the direction of its change (increase or decrease) from baseline is inconsistent across studies. The same is generally true of individuals' respiratory responses to motion sickness (Reason and Brand, 1975). In the Parker (1964) driving film study, a decrease in respiration rate was found in subjects after they experienced the vection effects of the film. Conversely, Testa (1969) found increases in respiration rate in response to a film-based simulator experiment in which nearly all subjects became ill. In the driving simulator studies of Casali and Wierwille (1980) and Frank et al. (1987), an absolute difference score between baseline respiration rate and simulator exposure respiration rate was obtained. In both studies, respiration rate was found to be a reliable measure of simulator discomfort. Degraded simulator conditions, such as those including large amounts

Table 4. Driving Simulator Characteristics.[a]

Sim. Designation	Goodyear Aerospace I	Goodyear Aerospace II	UCLA I	General Motors Technical Center
Actual Vehicle	automobile	automobile	automobile	automobile
Type Vehicle	full-size sedan	full-size sedan	full-size sedan	general
Application	research	research	research & driver rehab.	research
Visual System				
Type	CCTV projection	CCTV monitor	motion picture	motion picture
Image Source	model board	model board	film	film
Medium	spherical screen	CRT	spherical screen	spherical screen
Infinity ∞ cueing	viewing distance	reflective ∞ optics	viewing distance	reflective optics
Lighting Cond.	daylight	daylight	adj. by film	adj. by film
H/V FOV (deg)[b]	50/39	54/unk.	150/unk	77-90/unk.
Scene Content	road & periphery	road & periphery	film of actual road	film of actual road
Motion System				
Type	fixed-base	fixed-base	fixed-base	cascade
Deg of Freedom[c]	-	-	-	tilt sim. of LN,LT accel.
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	-	-	yes	yes
Cockpit Environ.				
Cab type	car body	car body	car body	enclosed custom
No. Crew	driver	driver	driver, passenger	driver
Audio	engine, drivetrain	engine, drivetrain	engine, drivetrain	engine, drivetrain, tire
Operating Proced.				
Part/Whole Task	whole	whole	whole	whole
Typ. Task Length	30 min.	30 min.	unk.	unk.
Freeze Caps.	-	-	-	-
Slew/Reset Caps.	-	-	-	-
Ext.View Allowed	unk.	unk.	unk.	unk.
Other Characteristics				

[a]As existing in studies referenced in Table 3.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

of delay, yielded larger absolute value shifts in respiration rate from baseline than did normal simulator conditions.

Respiration rate may be obtained with several methods, including thermistor air temperature measurement, chest strain-gauge measurement, thorax impedance, pressure pneumography, spirometry, and capacitive-coupling chest movement transduction. Capacitive-coupling movement transduction has been applied successfully and without interference in several simulator-based studies (Casali, Wierwille, and Cordes, 1983).

Skin resistance/conductance. As previously noted, cold sweating often appears with the onset of motion sickness, though it is sometimes absent in some subjects (Crampton, 1955). Sweating may be observed as an increase in skin conductance (micromhos) or as a decrease in skin resistance (ohms). Skin potential (endosomatic) measurement is obtained without applied current while skin resistance/conductance (exosomatic) entails the use of a low-level excitation current Both measures are usually obtained using silver-silver surface electrodes, amplification/conditioning circuitry, and a strip chart recorder. Though care must be taken in electrode placement and record interpretation, the instrumentation of electrodermal metrics is relatively straightforward.

Cold sweating by simulator-sick subjects has been directly observed by several researchers (e.g., Barrett and Nelson, 1965 and 1966; Kellogg et al., 1980). Parker (1964) instrumented the volar surface of the forearm and found increases (from baseline) in skin conductance (increased perspiration) in response to his vection film. (Electrode placement on the arms may tend to interfere with vehicular control in a simulator. Parker's subjects were passive in that they only watched the driving film.) Testa (1969) also reported increased perspiration in response to a driving simulator, using forehead electrode placement. Casali and Wierwille (1980) reported decreased forehead skin resistance (increased perspiration) when subjects were enclosed in a box-like simulator cab, but the measure was not sensitive to other degraded simulator conditions. Frank et al. (1987) did not find the measure to be sensitive in their study. It should be noted that although forehead electrode placement may be convenient for driving or flying tasks, it may not be the best location to transduce skin resistance changes during motion sickness. McClure and Fregly (1972) reported that the response profile of forehead resistance demonstrates a relatively long latency to sweat onset followed by a gradual rise of

Table 4. Driving Simulator Characteristics.[a] (Continued)

Sim. Designation	General Precision Sim-L-Car	North American Rockwell	VPI&SU
Actual Vehicle	automobile	automobile	automobile
Type Vehicle	general	general	adjustable car
Application	research	research	research
Visual System			
Type	point-light proj.	CCTV projection	CGI
Image Source	transparency	model board	hybrid CGI
Medium	flat, rear-projected screen	screen	monochrome CRT
Infinity ∞ cueing	refraction, 6 ft. viewing distance	unk.	refractive ∞ optics
Lighting Cond.	sunset	unk.	dusk, night
H/V FOV (deg)[b]	45/unk.	~ 35/32	~ 48/30
Scene Content	road & objects	road & signs	road & periphery, other vehicles
Motion System			
Type	fixed-base	cascade	cascade
Deg of Freedom[c]	-	V; tilt sim. of LN, LT accel.	R, Y, LN, LT
g-seat/g-suit	-	-	-
g-display dim	-	-	-
Vibration	-	yes	yes
Cockpit Environ.			
Cab type	car components	enclosed custom	open/enclosed custom
No. Crew	driver, passenger	driver	driver
Audio	engine, drivetrain	engine, road noise	engine, drivetrain road noise, tire
Operating Proced.			
Part/Whole Task	whole	whole	whole
Typ. Task Length	10 min.	unk.	20-120 min.
Freeze Capa.	-	-	-
Slew/Reset Capa.	-	-	-
Ext. View Allowed	unk.	unk.	not by subjects
Other Characteristics			operation in dark room

[a]As existing in studies referenced in Table 3.
[b]H-horizontal, V-vertical, FOV-field-of-view.
[c]P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

response. This should be taken into account when applying the measure across a simulator run.

Pallor. Paleness of the skin is considered to be one of the most frequently-occurring signs of motion sickness (e.g., Crampton, 1955). Unlike nausea and emesis, pallor is generally thought to result from hyperactivity in the sympathetic portion of the autonomic nervous system. The constriction of blood vessels responsible for its appearance is likely an adrenergic effect of sympathetic nervous system activity, though other chemical substances may play a role as well (Money, 1970). In any case, pallor may be directly observed by the experimenter, either from the subject's face itself or from facial photographs (e.g., Uliano et al., 1987). Pallor measurement may also be electronically-instrumented using photo-optical sensors to provide a measure of skin transmissivity (Casali and Wierwille, 1980).

Two studies have demonstrated the effectiveness of pallor as a dependent measure using fiber-optics photo-optical sensors on subjects' earlobes. Significant baseline-to-simulator exposure increases in pallor were found in simulator conditions designed to induce discomfort in these studies (Casali and Wierwille, 1980; Frank et al., 1987). These results, coupled with the reliability of occurrence of the symptom in motion-sick individuals, indicate that pallor should be given serious consideration as a valid measure in simulator sickness studies. However, as with any physiological index, care must be taken to control for individual differences and to account for extraneous influences, such as physical workload or temperature effects, on the measure.

Facial temperature. A limited amount of support exists for the use of facial temperature measurement in simulator sickness research. Parker (1964) reported increases in subjects' facial temperatures in response to vection. To the authors' knowledge, no simulator-based study has incorporated facial temperature (or bodily temperature) as an instrumented metric. A thermistor adhered to the surface of the skin is the typical transducer for facial temperature measurement.

There are many influences, in addition to that of a state of motion sickness, which may alter facial temperature. Care must be taken to control for, or partial out, these

Table 5. Reports of Simulator Sickness Incidence (without experimentation).

Simulator Designation	Vehicle	Active/Passive	Sample Size	Incidence
General Motors Tech. Ctr.[a]	generic auto	active	50 plus[b]	2 cases plus[b]
North American Rockwell[c]	generic auto	active	40	3 cases
V/STOL[d]	jet-lift	active	1	1 case
2F112[e]	F-14 fighter	active	65	16%
2F106[f]	SH-2F helo.	active	28	13%[h]
2F64C[e,f]	SH-3 helo.	active	34	13%[h]
2F64C[e,g]	SH-3 helo.	active	153	59%
2F110[e]	E-2C turboprop	active	79	49%
2F117[e]	CH-46E helo.	active	160	29%
2F87[e]	P-3C turboprop	active	55	44%
2F121[e]	CH-53D helo.	active	208	36%
2E7[e]	F/A-18 fighter	active	102	33%
2F132[e]	F/A-18 fighter	active	26	23%

[a] Belnke and Williams (1968)
[b] Precise figures not provided
[c] Breda, Kirkpatrick, and Shaffer (1972)
[d] Sinacori (1967)
[e] Kennedy, Dutton, Ricard, and Frank (1984)
[f] Simulator located on west coast
[g] Simulator located on east coast
[h] Differences may be partially due to differences in operating procedures and length of training flights.

effects. Changes in ambient temperature, humidity, workload, stress, and metabolism are but a few factors which may be influential.

Gastrointestinal activity. The gastrointestinal response has not been instrumented and investigated in simulator sickness studies, though it warrants attention due to its utility in motion sickness research. Subjects often report vague sensations such as stomach queasiness, fullness, and nausea, though these simulator-induced symptoms have not been quantified using known measures of altered gastric motility. There appears to be considerable potential benefit for the use of electrogastrography in documenting gastric disturbances in simultor-sick subjects.

Evidence for the relationship between tachygastria and motion sickness lies in the work of Stern, Koch, Leibowitz, Lindblad, Schupert, and Stewart (1985). Motion sickness was produced in 14 of 21 subjects who viewed a rotating drum conveying the experience of vection, or illusory self-motion. In cue-conflict theory, a visual-vestibular mismatch results from this experience in that the subject senses movement through the visual channel, things he or she is moving, but never actually changes position. (A similar conflict can be said to result from a fixed-base simulator experience.) Stern et al., using electrogastrograms (EGG) recorded from cutaneous electrodes on the abdomen, found that dominant EGG frequencies shifted from a normal 3 cpm to an abnormal 5-8 cpm (tachygastria), in subjects who were vection-induced motion-sick. Of the seven subjects who did not become motion-sick, the normal EGG pattern of 3 cpm did not change during motion.

Because a clear relationship between EGG frequency and motion sickness is evident, it appears that electrogastrography should be given serious consideration for use in simulator sickness research. A review of instrumentation and procedures for this technique appear in Stern et al. (1980).

Postural Equilibrium Measures

Loss of balance and ataxia are common problems noted by trainees and subjects after exiting a dynamic simulator. The simulator presents an altered sensory environment which usually entails considerable vection, and some adaptation to this environment occurs in the operator's visual and vestibular sensory systems. Upon return to the "normal" environment, balance and equilibrium may be disrupted until the person progresses through re-adaptation. Such effects may be measured using pre-post simulator postural equilibrium tests.

Several ataxia tests have been applied in simulator studies, including the walk-toe-to-heel, walk-on-floor-eyes-closed, stand-on-preferred-leg, and stand-on-nonpreferred-leg tasks. Evidence for the utility of these exists in Crosby and Kennedy (1982), Kennedy et al. (1984), Frank et al. (1987), and Uliano et al. (1986). The latter two studies employed the two stand-on-leg tests, demonstrating them to be useful indicants of visual/vestibular disruption correlating with other sickness metrics. Recent evaluations by Thomley, Kennedy, and Bittner (1986) have led to the recommendation that the stand-on-leg tests be selected for determining highly transitory effects such as might occur following simulator exposure. Pre-post simlator data from these tests must be interpreted with care due to the potential influence of pre-exposure practice on post-simulator scores. If vestibular disruption occurs, test scores should decrease post-exposure; however, practice may mitigate this effect.

Other Measures

Pre-post exposure performance tests. There is some speculation that simulator exposure may influence a person's ability to perform perceptual, cognitive, and psychomotor tasks. This is considered to be a result of the altered sensory experience rather than a direct indicant of illness, though illness may exacerbate the effect. Research on a variety of simple pre-post simulator tasks has been limited in scope, and the results have not been promising, at least with regard to simulator effects. No significant simulator effects were found using a simple arithmetic test in the Casali and Wierwille (1980) driving simulator study. Similarly, performance on a grammatical reasoning task was not found to be a sensitive measure by Uliano et al. (1986). Test data from several simulators in the Kennedy et al. (1984) survey is reported to be currently under analysis. These results should shed more light on the utility of pre-post exposure performance tests. At present, little hard evidence exists to support their use in simulator-sickness studies.

Vehicle control performance measures. In degraded simulator configurations which may induce discomfort, such as those with substantial transport delay, vehicle control performance be adversed affected. Several on-line measures reflecting different aspects of vehicle controllability and tracking task difficulty have been applied to tap these performance effec· (e.g., Casali and Wierwille, 1980; Frank et al., 1987; Uliano et al., 1986). Typical ısures have included the number of small and large control reversals, as well as devia..ıon in yaw, lateral position, longitudinal position, altitude, and speed. Though somewhat simulator- and task-specific, these indices should prove useful in a battery intended for control performance measurement.

Measures for Sickness-Susceptibility Prediction

Though not useful for identification of a state of simulator-induced sickness, several other metrics have been applied in attempts to predict individual susceptibilities. Uliano et al. (1986) tested the Motion History Questionnaire, a self-report form which addresses a subject's prior history of motion exposure and related sickness, and found it to be unsuccessful in predicting simulator sickness susceptibility. Barrett and Thornton (1968) reported that field-independent subjects (measured on a Rod-and-Frame test of perceptual style), were more susceptible to simulator sickness than field-dependents. However a review of the related literature and the results of two subsequent studies (Casali and Wierwille, 1980; Frank et al., 1987) have failed to support the use of individual perceptual style as a valid predictor of simulator sickness susceptibility (Frank and Casali, 1986).

Due to the potential benefit of a predictive metric for identifying individuals who may require a reduced, or less intense, course of exposure to a simulator, it is recommended that research on predictive tests be continued in conjunction with other simulator-based studies. Data collection on such metrics usually entails a minimal time addition to an experiment, so this research may be "piggy-backed" at little expense.

RECAPITULATION

This paper has attempted to provide insight into the etiology, and particularly the symptomatology, of simulator-induced sickness. Though the published research documented in the tables herein has been relatively limited in scope, several important findings have resulted. It appears evident that simulator sickness is a serious problem, but one which is amenable to laboratory investigation. Potentially-provocative simulator characteristics, such as control loop delay and lag, can be targeted, studied, and have bounds placed on their design parameters. The dynamic and physical characteristics of existing simulators which induce operator sickness must be addressed in future simulator designs, otherwise the problem will persist and even expand with new simulator applications.

To conduct research on the causes of simulator sickness, an accurate symptomatology is needed, and the researcher must be armed with valid, reliable metrics of this symptomatology. Much progress has already been made in this regard. Because the syndrome is typicalpy polysymptomatic, a multivariate paradigm appears most useful in sickness assessment, incorporating a battery of metrics. As indicated herein, specific self-report measures, instrumented physiologic indices, and ataxia tests are prime candidates for such a battery.

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Previous versions of Tables 1-5 appear in Casali and Frank (1986).

DISCUSSION

KENNEDY: A very nice review, John. I wanted to add a couple of things on unpublished data that may be useful. Navy researchers in Orlando have done some electrogastrogram (EGG) studies of simulator sickness and have had difficulty replicating the findings of Stern et al., so question remains about this measure. As for other measures, there is some suggestion, particularly with head-coupled systems, that there may be a recalibration of the vestibulo-ocular reflex (VOR). This might be a useful physiological indicant to add to your list. Dark focus was tried in the simulation studies in Orlando; there were changes in dark focus in those persons who had extensive symptomatology. This was attempted again in another simulator with another population, pilots. The two simulator sickness conditions were not identical. The first one was deliberately designed to produce simulator sickness in college students - who were slightly myopic on the average - and there were changes in dark focus that were reliable in those persons who were sick. In the next study using dark focus as an index, changes were not in the same direction, but this may be attributable to several factors. Subjects were pilots; this was their first time in a simulator; workload was high. These subjects may have been excited. I mention this because for a long time there have been arguments about: Is the symptomatology of motion sickness a parasympathetic or a sympathetic issue? Possibly it is worthwhile returning to the issue of autonomic nervous system balance, the internal milieu, if you will. Sickness may be parasympathetic initially, but excitement may develop when the subject perceives the onset of sickness. Looking for a symptom that is only going to go in one direction may not be appropriate because some of the differences may depend upon different people perceiving their own bodily changes. Initially the shift may be in a parasympathetic direction and then subsequently it may be in a sympathetic direction. Indeed, two drugs known to be effective in reducing motion sickness seem consistent with this set of thoughts. To underscore the notion about the performance changes, we did carefully examine pre/post changes, and there were no obvious differences in a battery of tests administered to 400 subjects.

CASALI: Yes, and we've tried several different tests ourselves and have not seen any pre/post differences. The electrogastrogram measurement was included in this survey because, to my knowledge, it had not been directly instrumented in simulators. If we look at motion sickness from the standpoint that it is nausea and vomiting, with the knowledge that nausea and vomiting can occur after the stomach has been denervated, then we can separate that aspect of motion sickness from the autonomic nervous system. There is, of course, speculation about the mobilization of other variables I mentioned, e.g., pallor, whether or not it is under direct sympathetic-parasympathetic control or whether during motion sickness there is some other chemical transmitter circulating. But I agree about the EGG. I'm glad to hear there are simulator data on it.

CHAIRMAN: We're behind our schedule, but I would like to make one short comment. I think there is a need for some standardization in the tests that are being used to look at simulator sickness, and I think you've laid out some examples of things that could be included.

Modelling Operator Contr[illegible]l Performance and Well-Being as a Function of Simulator Visual and Motion System Transport Delays

by

LCDR Lawrence H. Frank, MSC, USN, Ph.D.
Head, Human Factors & Operational Analysis Branch
Pacific Missile Test Center
Point Mugu, CA 93042 USA

Professor John G. Casali, Ph.D. and Professor Walter W. Wierwille, Ph.D., P.E.
Department of Industrial Engineering & Operations Research
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061 USA

SUMMARY

The role of visual-motion coupling delays and cueing order on operator performance and uneasiness was assessed in a driving simulator by means of a response surface methodology central-composite design. The most salient finding of the study was that visual delay appears to be more disruptive to an individual's control performance and well-being than is motion delay. Empirical multiple regression models were derived to predict 10 reliable measures of simulator operator driving performance and comfort. Principal components analysis on these 10 models decomposed the dependent measures into two si[illegible]ificant models which were labeled vestibular disruption and degraded performance. Examination of the empirical models revealed that, for asynchronous delay conditions, better performance and well-being were achieved when the visual system led the motion system. A secondary analysis of the role of subject gender and perceptual style on susceptibility to simulator sickness revealed that neither of these independent variables was a significant source of variance.

INTRODUCTION

Modern vehicle simulators are controlled by digital computer systems which are needed to perform a massive array of control calculations. In part, these calculations are used to mimic the dynamic responses of a specific vehicle, monitor and respond to the operator's control activities and instructor or expe[illegible]imenter inputs, provide feedback data to an instructor-operator station, and provide computer-image generation (CIG) for a visual simulation of the external-vehicle environment.

As the number of calculations increases, there is a concom[illegible]tant increase i[illegible] the transport delay (i.e., a delay wherein an input is exactly reproduced at the end of a delay period). The greater the number of faces or edges required in a CIG display, the greater the calculation time and the greater the transport delay. Since the computer typically calculates the simulated vehicle's current position before it calculates (usually serially) the CIG visual scene, delays occur. This problem can be exacerbated even furt[illegible] by the current practice of using separate computers of differing update frequenc[illegible] for the motion and visual subsystems. In several flight simulators, for exampl[illegible] [illegible]e motion subsystem updates at 30 Hz, whereas the visual subsystem has a 15 Hz update. Using a faster visual subsystem update rate would reduce the time delay.

The occurrence of simulator transport delay can result in at least two undesirable consequences: First, an operator's control performance is degraded (1). Second, the operator may experience increased discomfort or uneasiness (2). This latter consequence is one form of the malady known as 'simulator sickness.' Simulator sickness can have several negative implications including compromising the validity of the simulation and consequently the generalisability of the resultant simulator data [illegible]o actual system or transfer task (3).

Although the precise etiology of simulator sickness is not known, it is believed to result from a conflict or mismatch among sensory cues (4). This premise, known as the perceptual conflict theory, postulates a referencing function in which motion information, signaled by the eyes, vestibular apparatus, or the proprioceptors, is at variance wi[illegible] the[illegible] [illegible]ts' expected values (5, 6). Current philosophy in simulator desi[illegible] di[illegible] the [illegible] onset of the motion subsystem should lead the visual subsystem. This [illegible]ionale st[illegible] [illegible]rom two factors: First, since the position of the simulated vehicle is calcul[illegible]ed prior to the CIG updating the new visual scene, it is functionally convenient to allow a delay between the motion and visual subsystems. Second, many simulator design engineers believe that humans perceive vestibular and kinesthetic cues of motion before they perceive visual cues. This is a tenuous assumption.

Reaction time (RT) experiments have shown the dominance of vision over kinesthetic and auditory stimuli. [illegible]ough simple RT to a tone or to a kinesthetic stimulus is faster than to a visu[illegible] [illegible]mulus, when either auditory or kinesthetic cues are combined with vision, their R[illegible] [illegible]ases and vision dominates (7, 8, 9, 10). Young (11) noted that circularvection can influence non-visual acceleration thresholds. When inertial accelerations are applied in a direction opposite to that of the visually-induced motion, it takes longer for them to be detected. On the other hand, complimentary vestibular and visual onset cues give rise to a more rapid experience of visually-induced motion.

According to the Federal Aviation Administration, all Phase II and Phase III simulators must have the motion subsystem lead the visual subsystem, but by not more than 150 ms (12). Whiteside (13) has commented that this is the reverse of what things ought to be. Similarly, Kennedy, Frank, and McCauley (14) have emphasized that the philosophy in simulation is different depending upon whether visual or inertial cues are being addressed. In terms of visual fidelity, the goal has been to replicate the real world as closely as possible. In contrast, to obtain motion fidelity, some simulation designers have set about to fool the vestibular system through suprathreshold stimulation and washout.

There are performance data which permit speculation that, in some cases, it may be better for the visual subsystem to lead the motion subsystem. For example, in a study on the effects of visual-motion display mismatch in a single axis compensatory tracking task, Shirachi and Shirley (15) have shown that, for a condition in which the simulated aircraft dynamics were of low gain (subjectively satisfactory to the pilots), visual lead produced less tracking error than the converse relationship.

In summary, it is readily apparent that motion can be detected in many ways by the human sensory system. The perception of velocity and orientation is dominated by vision in the steady state and for low frequencies below 0.1 Hz (11). At higher frequencies and with rapid acceleration, vestibular cues appear to dominate. Similarly, the temporal sequencing of perceptual sensors is state dependent. Experiments on simple reaction time have shown that such factors as stimulus intensity, expectancy, and temporal uncertainty all interact and affect simple reaction time. Clearly, neither the proprioceptive modality nor the visual modality is independent of the other. In addition, review of the literature on visual-motion coupling strongly suggests that visual lead may produce better operator performance and less simulator sickness in many cases.

The purpose of the study was to perform a parametric evaluation of simulator visual-motion coupling delays and cueing order from which design recommendations could be made to optimize control performance and minimize operator discomfort. The goal of the research was to develop empirical models and concomitant response surfaces from which simulator design recommendations could be derived.

Independent Variables

Two independent variables were selected for study: motion-system transport delay and visual-system transport delay. Review of the literature on transport delays in operational vehicle simulators reveals that delays up to 400 ms have occurred, with most falling below 300 ms (16, 17). In order to be able to statistically generate second-order response surfaces for later analysis, three levels of delay are both necessary and sufficient. Transport delays of 0, 170, and 340 ms were evaluated in this experiment. The selection of these levels of delay was based upon the literature reviewed, the desire to have a statistically orthogonal response surface design, and the limitations imposed in quantizing the delays.

Of secondary interest were three other independent variables: perceptual style, past motion sickness history, and gender. Some authors have reported that field-independent individuals appear to be more susceptible to simulator sickness than field-dependent individuals (e.g., 18, 19). Similarly, an individual's past motion sickness history has been shown to be moderately predictive of future motion sickness (5) and simulator sickness (21), and females appear to be more susceptible to motion sickness than males (5).

METHOD

Experimental Design

Primary design. A two-factor, between-subjects, orthogonal, second-order, response surface central composite design, with equal replication, was the primary design in this study. An orthogonal design was used to provide uncorrelated estimates of the response model regression coefficients, thereby facilitating the interpretation of possible second-order effects. In addition, a between-subjects design was selected to eliminate the possible occurrence of learning, practice, or order effects across treatment conditions.

For an orthogonal response surface methodology (RSM) design with only two independent variables, it can be readily shown that this design is equivalent to a conventional 3 x 3 factorial design with nine treatment conditions.

Secondary design. Embedded within the above design, a secondary design appropriate for assessing perceptual style and gender was employed. Although, based upon a review of the literature by Frank and Casali (20), it was not expected that a subject's perceptual style would influence his or her susceptibility to simulator sickness, it was decided to block the subjects according to perceptual style, as measured by a rod-and-frame test (RFT), to enable unambiguous interpretation of the data.

Subjects

The subjects were 27 male and 27 female paid volunteers aged between 18 and 48 years, with a mean age of 25.68 years. The distance driven per year ranged from 644 to 40,231 km (400 to 25,000 miles) with a mean of 13,724 km (8,528 miles). None of the subjects had previous simulator experience. All subjects had a valid driver's license and a minimum of 20/30 far static visual acuity as measured by a wall chart Landolt-C test.

Driving Simulator Apparatus

The primary apparatus used in this study consisted of a computer-controlled automobile simulator with a four degree-of-freedom motion base and a five degree-of-freedom visual system located in the Virginia Polytechnic Institute and State University Vehicle Analysis and Simulation Laboratory. A detailed description of the simulator has been reported by Wierwille (22).

Measurement Apparatus

Rod and Frame. The rod-and-frame apparatus consisted of a square frame, 1.08 m (42.75 inches) on a side, and within it, a rod 1.02 m (40.50 inches) long. Both the rod and the frame were constructed from 19 mm (0.75 inch) tubular pipe covered with reflective tape and could be moved independently of each other by the experimenter. The rod-and-frame apparatus was housed in a 3.20 m (10.5 feet) long, 1.42 m (56 inches) wide, 1.98 m (6.5 feet) high structure covered in a double layer of opaque black 'ground cloth.' The interior corners of the enclosure were curved to eliminate possible cues to verticality. This structure was, in turn, housed in an air-conditioned room. The subject's eye-to-frame distance was 2.17 m (85.5 inches). This distance was selected to ensure that the frame's retinal-image size was the same as Witkin, Lewis, Hertzman, Machover, Messner, and Wapner (23). During experimentation, only the rod and frame were visible to the subject.

Driving simulator measures. The driving measures were as follows:

(a) Number of steering reversals. Two measures of steering reversals were computed: small steering reversals (SREV) and large steering reversals (LREV). Small steering reversals and LREV were defined as the number of times the magnitude of the steering movement exceeded 2 deg or 5 deg, respectively, after steering wheel velocity ; ssed through zero.

(b) Yaw standard deviation. Vehicle yaw was given by the angle in the horizontal plane between the simulated vehicle longitudinal axis and the instantaneous roadway tangent.

(c) Frequency of seat movement. Seat movement was measured as a change in seat pad and backrest pressure of the simulator operator's seat. The signal amplitude of a linear potentiometer positioned in each location was set to ensure that only driver movements and not simulator motion responses were recorded.

Physiological sensors. Three physiological measures were used in this study:

(a) Skin resistance. Skin resistance was measured by two metallic electrodes incorporated into a rubber headband worn by the subject.

(b) Pallor. Pallor was measured by a small photoelectric module attached to the antihelix of the subject's right ear. The sensor body was attached to the headband containing the skin resistance electrodes.

(c) Respiration. The apparatus used for the measurement of respiration frequency has been described in detail elsewhere (24).

Postural disequilibrium. Two postural stability tests, the stand-on-preferred-leg (SOPL) test and the stand-on-non-preferred-leg (SONPL) test, recommended by Thomley, Kennedy, and Bittner (25) for determining highly transitory effects such as might occur following simulator exposure, were used.

Simulator sickness severity index. The subject self-evaluation form used in this study was a version of Wiker, Kennedy, McCauley, and Pepper (26), which has been modified by Kennedy, Dutton, Ricard, and Frank (27) for specific use in simulator sickness studies.

Motion sickness history questionnaire. The Pensacola MSQ was used to assess past motion sickness history of the subjects (see 5 or 28 for a more detailed discussion).

Procedure

Rod-and-Frame Test. Series 3 of the rod-and-frame test (RFT) was administered in accordance with the protocol described by Oltman (29). The subjects' scores on the RFT were independently rank-ordered for each gender and divided into thirds. This procedure yielded nine subjects per third for each gender. One subject from each third was assigned to one of the nine treatment conditions.

Pre-simulator exposure. Prior to entering the simulator, each subject was administered the SOPL and SONPL postural disequilibrium tests. Each subject was then assisted into the simulator and instructed to fasten the seat belt. The physiological sensors were then fitted to the subject. Each subject was given a sheet of written instructions for the driving task and asked to read them carefully. The subjects were told to relax and rest while the experimenter calibrated the recording equipment. Room illumination was reduced to approximate twilight and the physiological monitoring system was checked to ensure that it was functioning properly.

After approximately 5 min, the experimenter returned to the subject, retrieved the written instructions, and orally briefed the subject on the driving task. The subject was told to relax for about 10 min longer and that the experiment would then begin. After the subject had been sitting for at least 10 min in the deactivated simulator, baseline measures of respiration, skin resistance, pallor, and number of seat movements were taken every minute over a 5-min period.

Simulator exposure. At the appropriate time, the subject was advised that the simulator was to be activated and that they were to have a 2-min practice session to 'get the feel' of the simulator. At the end of 2 min, the experimenter told the subject that the experimental driving session was to begin, to accelerate to 55 mph (88.5 km/hr), and to try maintaining that speed and the right-hand lane position throughout the remainder of the experiment. The preprogrammed driving scenario lasted 21 min and alternated between curved and straight stretches of road.

Post-simulator exposure. Upon completion of the simulated driving task, the physiological sensors were removed from the subject, the seat belt was unbuckled, and the subject was assisted from the simulator. The subject was immediately administered the postural disequilibrium tests and then asked to fill out the self-evaluation form for use by the experimenter in the simulator sickness severity index (SSSI) calculation. Following this, the subject filled out the motion sickness history questionnaire.

Data Reduction

The following methods were employed to reduce the raw data derived for each variable to a form appropriate for statistical analysis.

Rod-and-Frame Test. For each subject, the mean number of degrees by which the rod deviated from true vertical was computed across the eight experimental trials.

Driving measures. A subject's yaw deviation score (YAW) was calculated as the mean value of the two yaw standard deviation values computed during the final 5 min of the experimental run. The numbers of SREV and LREV were represented by the cumulative total of the number of times steering reversals equaled or exceeded 1 deg or 5 deg, respectively, over the final 5 min of the simulator exposure. For seat movement, the total number of seat movements during the 5-min baseline period was subtracted from the total number of seat movements during the last 5 min of the simulated driving task. This difference score was referred to as SEAT. In addition, the total number of seat movements (TSEAT) made during the driving scenario was computed.

Physiological measures. For each physiological measure, a single difference score was computed between the subject's mean baseline value and his or her mean value during the final 5 min of the simulated driving task. Since the motion sickness literature indicates that respiration may either increase (30) or decrease (31) with sickness, depending upon the individual, an absolute value of breath cycles per second (BCS) difference score was used.

Postural disequilibrium. The difference between a subject's mean score on the post-simulator exposure tests and a subject's mean score on the pre-simulator exposure tests yielded each subject's stability measure in seconds. A combined (COMB) score was also formed by adding the results of the SOPL and SONPL tests and computing a mean. The combined score also represented a difference score between the pre-simulator and post-simulator tests.

While administering the ataxia tests, a large variability in the subject's ability to maintain stability on the pre-simulator exposure test was observed. Because of this, it was felt that a percentage score might produce a more sensitive measure of any vestibular disturbance induced by the experimental treatments. Consequently, percentage SOPL (PSOPL), percentage SONPL (PSONPL), and percentage COMB (PCOMB) scores were computed by forming a ratio of the respective post-simulator exposure mean score to the pre-simulator exposure mean score, subtracting this value from 1.0, and multiplying by 100.

Simulator sickness severity index. Each subject's simulator sickness severity index (SSSI) was computed following the procedure of Kennedy, Dutton, Ricard, and Frank (27). Each subject's final symptomatology categorization score consisted of an integer value between 0 and 7, inclusive. The larger the SSSI score, the greater the subject's discomfort. In addition, the total number of symptoms reported by each subject was also tallied (TSYM).

Motion sickness history questionnaire. The procedure described by Moore, Lentz, and Guedry (28) was followed in scoring the Pensacola MSQ.

For ease of reference, Table 1 presents the list of the dependent measures and their abbreviations. Note that RFT and MSQ scores were not included since they represent independent variables.

Table 1. A List of the Experimental Dependent Measures and Their Abbreviations

Yaw Standard Deviation	(YAW)
Small Steering Reversals	(SREV)
Large Steering Reversals	(LREV)
Difference in Seat Movement	(SEAT)
Total Number of Seat Movements	(TSEAT)
Difference in Pallor	(PAL)
Difference in Skin Resistance	(RES)
Difference in Breath Cycles Per Second	(BCS)
Simulator Sickness Severity Index	(SSSI)
Total Number of Symptoms Reported	(TSYM)
Stand-On-Preferred-Leg Test	(SOPL)
Stand-On-Non-Preferred-Leg Test	(SONPL)
Combined Stand-On-Leg	(COMB)
Percent Stand-On-Preferred-Leg	(PSOPL)
Percent Stand-On-Non-Preferred-Leg	(PSONPL)
Percent Combined Stand-On-Leg	(PCOMB)

RESULTS AND DISCUSSION

The response surface methodology data analysis essentially consisted of two statistical analyses. First, for each dependent variable, a least-squares multiple-regression analysis was performed to determine the first-order polynomial model. Second, an analysis of variance was performed on the derived regression model. The results clearly demonstrated that visual and motion system delays are detrimental to both an individual's control performance and well-being. Ten significant ($p < 0.05$) empirical models were found which predict a subject's simulator driving performance (YAW, SREV, LREV), vestibular disturbance (SOPL, SONPL, COMB, PSOPL, PCOMB), and well-being (BCS, SSSI) as a function of visual-motion coupling delays.

Examination of model lack of fit and Mallows' Cp statistic values suggested that, with the exception of SSSI, the introduction of higher-order effects would not meaningfully improve each first-order model's description of the functional relationship between performance and the independent variables. A second-order model was found to be more appropriate for SSSI. Table 2 presents the formulae for the 10 models. (In the formulae, both V, the visual system delay, and M, the motion system delay, are specified in ms.) Due to the small magnitude of some regressor coefficients all values are carried out to six decimal places. Due to space limitations, the response surfaces for each of the 10 models are not presented.

Table 2. Significant Regression Models (V = visual delay, M = motion delay)

Dependent Variable		Regressors
Breath cycles/s	=	0.000777 + 0.000027 V + 0.000171 M
Yaw standard deviation	=	6.657954 + 0.007635 V + 0.003452 M
Small steering reversals	=	214.77778 + 0.141176 V + 0.049340 M
Large steering reversals	=	17.796296 + 0.1093[illegible]4 V + 0.072386 M
Simulator sickness severity index	=	2.199074 + 0.010539 V + 0.007925 M
		- 0.000018 VxV - 0.000012 MxM
		- 0.000013 VxM
Stand-on-preferred-leg	=	- 1.089259 - 0.017667 V - 0.001820 M
Stand-on-non-preferred-leg	=	- 1.389222 - 0.003197 V - 0.011197 M
Combined stand-on-leg	=	- 1.400491 - 0.007308 V - 0.007902 M
Percent stand-on-preferred-leg	=	2.864814 + 0.124143 V + 0.006422 M
Percent combined stand-on-leg	=	16.400926 + 0.075817 V + 0.024167 M

Obviously, there is a danger in applying the derived models to other simulators. However, it is expected that the general relationship between the dependent variables and their regressors would be substantially the same, although the coefficient weightings would, no doubt, change.

The univariate analyses provided an assessment of how the combined influence of the independent variables affected a specific dependent variable. Multivariate techniques, such as principal components analysis, can be used to test the effects of several dependent variables, thereby helping to isolate underlying behavioral dimensions. Principal components analysis on the 10 significant polynomial models decomposed the dependent measures into two significant models which were labeled vestibular disruption and degraded performance. These two models are:

$$\text{Vestibular disruption} = -1.62641 + 0.00643\,V + 0.00314\,M$$

$$\text{Degraded performance} = -1.08030 + 0.00377\,V + 0.00269\,M.$$

For general design recommendations, perhaps the most useful models are the two derived from the principal components analysis. These models represent a composite of the 10 significant models with each predicting one specific outcome. Examination of these models clearly indicates that when asynchronous delays occur in a simulator, visual system movement should begin before motion system movement to produce the least amount of uneasiness. Similarly, operator control performance is better with visual lead, although the effect is not as pronounced as with uneasiness. These findings are in direct conflict with the Federal Aviation Administration's design guidance for Phase II and Phase III simulators (12) and general simulator design philosophy.

This experiment certainly does not represent the definitive study on simulator visual-motion coupling delay. Many other variables interact with delay. However, the results of this study strongly suggest that visual delay is far more disruptive to a simulator operator's control performance and physical comfort than is motion delay. The results also suggest that, when asynchronous delays occur in a driving simulator, visual scene movement should begin before movement of the inertial system. The first-order models produced by the principal components decomposition demonstrate a linear relationship between increased vestibular disturbance, degraded performance, and increases in delay.

Again, it must be emphasized that the models are not definitive, but they can at least provide a relative rank-ordering among various design alternatives. It is in this manner that their use is recommended.

A secondary analysis of the role of subject gender, perceptual style, and past motion sickness history on susceptibility to simulator sickness revealed that none of these independent variables was a significant source of variance.

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ENQUETE SUR LE MAL DES SIMULATEURS DE VOL COUPLEE A UNE ETUDE NYSTAGMOGRAPHIQUE

par

Méd Lt Col G.De Heyn*, Méd Maj P.De Graff** et Méd Col P.Vandenbosch***
Force Aérienne Centre de Médecine Aérospatiale
Quartier Roi Albert 1er
Rue de la Fusée 70
1130 Bruxelles
Belgium

Le mal des simulateurs, apparenté au mal des transports, est une cinétose due aux progrès de la technologie et aux impératifs budgetaires et de sécurité.

Cette pathologie nouvelle touche des pilotes expérimentés et résulte d'un conflit de sensations dans un environnement inhabituel.

Nous avons réalisé une enquête auprès d'une unité de chasse de la Force Aérienne Belge pour évaluer la fréquence du mal des simulateurs ainsi que les manifestations ressenties.

10% des pilotes interrogés sont régulièrement sujet au mal des simulateurs, 25% le sont occasionnellement à des degrés divers.

D'autre part nous avons essayé d'objectiver les troubles de l'équilibre par une étude nystagmographique portant sur 12 pilotes durant leur entrainement sur simulateur de vol. Nous avons été frappés par la pauvreté des mouvements oculaires durant le vol simulé. Les mouvements oculaires nystagmiques n'apparaissant que rarement et fugitivement, principalement en fin de virage. Ils sont toujours de faible amplitude. Il n'a pu être établi une relation entre les manifestations vestibulaires objectives et les sensations subjectives du mal des simulateurs.

AN INVESTIGATION OF SIMULATOR SICKNESS AND AN ELECTRONYSTAGMOGRAPHIC STUDY

by

Méd LtCol DE HEYN G. (*), Méd Maj DE GRAFF P. (**),
Méd Col VANDENBOSCH P. (***)

Simulator sickness, which is related to travel sickness, is a product of high technology, safety requirements and budgetary limitations.

This new pathology affects experienced pilots and is the result of conflicting sensations, experienced in an unfamiliar environment.

We conducted a survey of a Belgian Air Force fighter squadron in order to evaluate the frequency of simulator sickness and the symptoms experienced.

Ten per cent of the pilots questioned regularly experienced simulator sickness and twenty five per cent felt it occasionally in varying degrees.

We also attempted to objectify the problems of vertigo and disorientation by means of an electronystagmographic study of 12 pilots during their training on a flight simulator. We were surprised by the poor ocular response during the simulated flight. Nystagmic movements appeared rarely and then only fleetingly, mainly at the end of a turn. They were all of low amplitude. We were not able to establish a correlation between the objective vestibular responses and the subjective feelings of simulator sickness.

(*) Centre de Médecine Aérospatiale - Chef de Service ORL
(**) Chef de Service Médical 10 W Tac
(***) Centre de Médecine Aérospatiale - Commandant

PHYSIOPATHOLOGIE DU MAL DES SIMULATEURS

Suite à une longue évolution se chiffrant en millions d'années, tous nos récepteurs sont physiologiquement adaptés à la locomotion terrestre naturelle.

Depuis quelques dizaines d'années l'homme habitué à évoluer dans le champ do la pesanteur terrestre a révolutionné son environnement et ses modes de déplacement. Dans le domaine aéronautique nos capteurs sensoriels sont particulièrement inadaptés aux nouveaux modes de déplacement.

L'appareil otolithique, les fuseaux neuro musculaires, les organes tendineux de Golgi, les récepteurs proprioceptifs sont sensibles au vecteur champ de pesanteur. Les canaux semi-circulaires sont sensibles aux accélérations angulaires.

Les divers systèmes sont complémentaires de la vision. Lorsque celle-ci ne peut remplir son rôle et que les autres systèmes sont sollicités par un environnement gravito inertiel-inhabituel apparait la désorientation spatiale.

Ainsi sans apport visuel un sujet soumis à une rotation à vitesse constante autour d'un axe passant par la tête ne percevra pas le mouvement réel de rotation.

Nos capteurs sensoriels peuvent cependant s'adapter à des situations nouvelles inhabituelles - Notre organisme intégrera alors harmonieusement des informations paraisant contradictoires, susceptibles d'entrainer des illusions sensorielles.

Chaque type de transport a ses caractéristiques propres auxquelles l'organisme s'adapte. Que des pilotes entrainés, ne connaissant plus les manifestations désagréables du mal de l'air, soient sujets à des malaises lors de leur entrainement sur simulateur de vol peut paraître paradoxal, mais les conflits de sensations sont différents de ceux des vols réels.
Sur un simulateur à plate-forme fixe le pilote est soumis à des sensations visuelles de mouvement de grande amplitude alors que les récepteurs kinesthésiques et vestibulaires ne lui donnent que peu d'informations de mouvements.
De plus les informations visuelles fournis par l'écran du simulateur donnent une impression de clair obscur où la notion de relief est diminuée, ce qui accroit la difficulté d'orientation.

Par ailleurs, après son entraînement sur simulateur, le pilote doit se réhabituer à un environnement physiologique normal.
L'orientation spatiale, l'équilibre postural, la locomotion reposent sur l'intégration de données provenant des appareils visuels, vestibulaires, kinesthésiques, tactiles et auditifs.
Cette intégration de données sensorielles ne pourra se réaliser harmonieusement que si le support psychologique le permet.
Des sujets anxieux et stressés ressentiront plus les ambiguités du système d'orientation spatiale et seront plus facilement sujets aux cinétoses.

ETUDE ELECTRONYSTAGMOGRAPHIQUE SUR SIMULATEUR DE VOL

Méthodologie

Durant leur entraînement sur simulateur de vol 12 pilotes de F-16 âgés de 25 à 36 ans ont été testés sur le plan vestibulaire par électronystagmographe.
Un électronystagmographe monocanalaire enregistrait les mouvements oculaires horizontaux grâce à trois électrodes autocollantes situées respectivement à l'angle externe de chaque oeil et entre les sourcils.
Ces électrodes ne gênaient en rien les mouvements de la tête. La sensibilité de l'électronystagmographe était réglée sur 10 mm V, la vitesse de déroulement du papier était de 25 mm/sec

Durant toute la durée du vol sur simulateur les mouvements oculaires étaient enregistrés en continu - Le déroulement du tracé était suivi dans la salle de contrôle du simulateur ce qui permettait de juger seconde par seconde les réactions oculaires en fonction du programme de vol et de dépister immédiatement l'apparition d'un nystagmus horizontal.

Après son entraînement sur simulateur le pilote remplissait un questionnaire nominal sur ses impressions de vol et la description des troubles ressentis éventuellement.

ETUDE ELECTRONYSTAGMOGRAPHIQUE SUR PROGRAMME DOG FIGHT

Deux pilotes du 10 W Tac ont été suivis durant ce programme d'une durée de 40 min.
La philosophie générale de ce programme comprend un lâchage de bombe sur cible au sol suivi d'un combat aérien avec un adversaire. Il peut être décomposé en ses divers points:

1) START UP ENGINES (contrôle de départ)

2) TAKE OFF (décollage)

3) BOMB RANGE (lâchage d'une bombe suivi d'un virage à gauche avec boucle de 360° pour revenir dans l'axe de départ)

4) CLIMB OUT/LOFT accélération de 4.5 G/Z sec avec cabré suivi de looping.

5) DOG FIGHT combat visuel engagé avec avion ennemi

6) RECOVERY vol aux instruments

7) EMERGENCY panne du système hydraulique

8) LANDING atterrissage

Durant le suivi du tracé nous avons été frappés par le peu de mouvements oculaires durant la période de vol.
Seuls les points 1 et 8 comportent de nombreux mouvements oculaires et correspondent au contrôle visuel des instruments de bord.
Pour les autres points les mouvements oculaires sont peu importants et épousent logiquement les exigences du programme (ex : contact visuel avec la cible, repérage de la piste ou de la panne au tableau de bord).
Durant le vol aux instruments les mouvements oculaires sont particulièrement pauvres.
Il n'y a eu aucun épisode pouvant évoquer un accès de nystagmus.

ETUDE ELECTRONYSTAGMOGRAPHIQUE SUR PROGRAMME ACRO

Etonnés par la pauvreté des réponses oculaires sur programme DOG FIGHT, nous sommes passés à un programme comprenant de nombreuses manoeuvres acrobatiques susceptibles d'entrainer des illusions sensorielles.
Six pilotes du 10 W Tac et 4 pilotes du 1 W Ch ont été suivis sur programme ACRO qui s'il ne durait que 25 minutes était nettement plus mouvementé et pouvait être décomposé en ces divers points suivants :

1) START UP ENGINES (contrôle de départ)

2) TAKE OFF (décollage)

3) LOOPING

4) ROLL/LEFT/RIGHT (tonneau)

5) 4 POINT ROLL (tonneau décomposé par palier de 90°)

6) BARRELL ROLL (manoeuvres lentes de la pointe de l'avion au-dessus et en dessous de la ligne d'horizon).

7) STEEP TURN LEFT/RIGHT (looping horizontal à la vitesse de 250 noeuds).

8) SLOW SPEED RECOVERY (cabré à 90° suivi d'un looping lorsque la vitesse diminue - Cette manoeuvre est répétée 3 fois).

Les points 1 à 8 s'effectuent à haute altitude (high level).

9) HIGH SPEED PASS OVER RUNWAY
(looping au-dessus de la piste d'atterrissage).

10) Circuit d'atterrissage (TOUCH AND GO).

11) PAMPA STRAFING PASS (tir au canon mais l'arme s'enraye).

12) PASS : Vol à base altitude au-dessus de la piste.

13) Atterrissage sans moteur.

L'examen des tracés de mouvements oculaires comme pour le programme DOG FIGHT montre avant décollage et après atterrissage de nombreux mouvements oculaires dus au contrôle des instruments de bord par le pilote.

Durant les manoeuvres acrobatiques proprement dites les mouvements oculaires sont rares, mais à la fin de celle-ci apparaissent quelques secousses qui traduisent probablement une relaxation du pilote qui observe son environnement.

Des secousses à caractère nystagmographique ont été observées chez quatre pilotes.
Elles étaient de durée brève, d'intensité peu importante et ne survenaient qu'une à deux fois par vol à la fin d'un virage (Ex : manoeuvre STEEP TURN).
Trois autres pilotes avaient au départ un tracé parasité par des contractures musculaires, faciales et palpébrales. Ce parasitage cessait en cours d'exercice et le tracé se normalisait dans la phase LOW LEVEL au vu de la piste d'atterrissage, ceci probablement relaxation musculaire et psychologique en fin d'exercice.

ENQUETE NOMINATIVE APRES L'ENTRAINEMENT SUR SIMULATEUR

Dix pilotes sur les douze avaient présenté lors de vols précédants des manifestations de cinétose de simulateur, mais aucun pilote n'a avoué avoir ressenti de malaises durant l'exercice suivi par enregistrement ENG. Au dépouillement du questionnaire personnalisé quatre pilotes avaient eu de légers problèmes d'instabilité lors de vols précédants.
De ces quatres pilotes un seul signale régulièrement un état de déséquilibre lors d'accélérations importantes en début de vol. Ces manifestations désagréables disparaissent après une phase d'adaptation. Le tracé ENG de ce pilote ne montre aucune phase nystagmographique.
La discordance entre cette enquête nominative et la réalité des faits nous a fait établir un questionnaire anonyme adressé à tous les pilotes de la base du 10 W Tac.

ENQUETE ANONYME AUPRES DES PILOTES DU 10 W Tac SUR LA FREQUENCE ET LES MANIFESTATIONS DU MAL DES SIMULATEURS

1. Cinétose et âge des pilotes.

31 pilotes du 10 W Tac âgés de 23 à 40 ans ont accepté de répondre à l'enquête anonyme. Si le total d'heures de vol réel s'échelonnait de 400 à 3.300, le nombre d'heures d'entraînement sur simulateur varient de 50 à 200.

Douze pilotes sur les trente et un ont ressenti sur simulateur des malaises à des degrés divers.
La proportion de pilotes sensibles à cette cinétose semble être plus importante chez les pilotes expérimentés plus âgés.

Age	20 - 25	26 - 30	31 - 35	36
Air Sickness	3	3	3	3
No Symptoms	6	7	4	2

Parmi les douze pilotes ayant été sujets au mal des simulateurs, trois l'ont été plus régulièrement et leur tranche d'âge est celle des plus de 36 ans.

2. Manifestations de la cinétose.

95 % des pilotes sensibles décrivent un état vertigineux,
50 % un sentiment de malaise généralisé,
10 % sont nauséeux.

Pour 90 % des pilotes, ces troubles surviennent lors de manoeuvres acrobatiques, 10 % ressentent ces manifestations également lors de vol aux instruments, de pannes et de vol à basse ou haute altitude.
Les malaises persistent après l'entraînement sur simulateur pour 75 % des pilotes. Pour la moitié de ceux-ci les troubles de l'équilibre ne dépassent pas subjectivement le quart d'heure. Seize pour cent des pilotes disent ressentir les effets de la cinétose jusqu'à deux heures après la fin de l'entraînement sur simulateur.
Un seul pilote sur les trente et un à dû occasionnellement interrompre son programme d'entraînement.
La durée du vol sur simulateur influence trente pour cent des pilotes susceptibles de développer des malaises.
Dix neuf pour cent des pilotes en général préfèrent s'entraîner avec verrière d'avion relevée car ils développent un sentiment de claustrophobie lorsque celle-ci est rabattue. Cette tendance à la claustrophobie touche vingt-cinq pour cent des sujets ayant développé une cinétose sur simulateur.

CONCLUSIONS

L'enquête anonyme révèle que 38 % des pilotes ont présenté des manifestations du mal des simulateurs essentiellement sous forme de troubles de l'équilibre.
Un pourcentage très voisin a été trouvé lors d'une enquête réalisée au Canada sous le Aurora Flight Deck Simulator soit 36 %.
L'analyse objective des mécanismes neurologiques reste cependant difficile.
Cette étude confirme l'importance des mécanismes corticaux dans l'étiologie des cinétoses.
Les rares et fugitives secousses nystagmiques de faible amplitude observées chez les pilotes entraînés sur simulateur de vol à plate-forme fixe s'expliquent logiquement par une excitation vestibulaire des canaux semi-circulaires bien moindre que celle des vols réels.
La pauvreté des mouvements oculaires est due à une fixation visuelle sur un écran proche du sujet, situation qui n'exige que des balayages oculaires réduits.
Il nous a été difficile d'établir une corrélation entre nystagmus et illusion sensorielle car aucun des pilotes interrogés après leur prestation n'a avoué avoir ressenti le moindre malaise.
Quoique nous ayons assuré ces pilotes que toutes les données physiologiques et médicales recueillies durant l'expérimentation ne seraient pas consignées dans leur dossier médical d'aptitude, la méfiance à l'égard du médecin expérimentateur l'a emporté, ce que nous regrettons car seule une collaboration étroite entre physiologistes et pilotes pourra faire progresser nos connaissances.

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HEAD-MOUNTED SPATIAL INSTRUMENTS: SYNTHETIC REALITY OR IMPOSSIBLE DREAM

by

Stephen R.Ellis, Arthur Grunwald and Mordekhai Velger
NASA Ames Research Center
Moffett Field, California USA

Summary

A *spatial instrument* is defined as a spatial display which has been either geometrically or symbolically enhanced to enable a user to accomplish a particular task. Research we have conducted over the past several years on 3D spatial instruments has shown that perspective displays, even when viewed from the correct viewpoint, are subject to systematic viewer biases. These biases interfere with correct spatial judgements of the presented pictorial information. It also has been found that deliberate, appropriate geometric distortion of the perspective projection of an image can improve user performance.

These two findings raise intriguing questions concerning the design of head-mounted spatial instruments. The design of such instruments may not only require the introduction of compensatory distortions to remove the naturally occurring biases but also may significantly benefit from the introduction of artificial distortions which enhance performance. These image manipulations, however, can cause a loss of visual-vestibular coordination and induce motion sickness. Additionally, adaptation to these manipulations is apt to be impaired by computational delays in the displays of the image. Consequently, the design of head-mounted spatial instruments will require an understanding of the tolerable limits of visual-vestibular discord.

Introduction

The introduction of relatively low cost, interactive, high performance 3D computer graphics work-stations such as the IRIS 2400 Turbo or the Megatek 928, and the certain prospect for further miniaturization and cost reduction, has provided aerospace designers with powerful research tools for creating new media for interactive, information displays.

This flexibility raises many practical design challenges and interesting theoretical questions, but since many of these new information displays may be helmet or head mounted, particularly prominent questions concern guaranteeing the perceptual stability of the display's image. Indeed, it is shown in this paper that selecting a head-mounted format limits design freedom in the definition of the displays in ways that do not constrain conventional panel-mounted formats.

Analysis

An understanding of the relevant design questions is best provided by an analysis of the linear transformations that the spatial information must undergo before presentation to the user. In general, the information is first defined as sets of vectors, polygons, or polyhydra positioned in an inertial reference frame some times called the "real world" coordinate systems (Foley and Van Dam, 1982).

Prior to presentation to the viewer, this information must be transformed by scaling, rotation, translation, and projection to position it in an "eye coordinate system" determined by the position and direction of a viewing vector. This transformation process is commonly represented as a series of matrix operations and is referred to as the "viewing transformation".

Subsequent use of this spatial information by the viewer requires that he perform further coordinate transforms to bring it into a useful frame of reference. For example, if the subject is required to make an egocentric direction judgement based on information on a 3D map, he must further transform the information into a body or even a hand centered coordinate system by a process similar to the viewing transformation. These are the transformations typically used in telerobotics.

Exocentric direction judgements or other exocentrically oriented tasks would seem to require an additional transformation to place them at the exocentric position, as suggested by Piaget (1956), however, these tasks can be shown to be geometrically reducible to sequences of egocentric tasks which result in ego-centric direction vectors that are then simply subtracted from each other. (Grunwald and Ellis, 1986) (see fig. 1)

In order to understand how the spatial information presented in pictures may be used, it is helpful to distinguish between images which may be described as *spatial displays* and those that were designed to be *spatial instruments*. One may think of a *spatial display* as any systematic mapping of one space onto another. A picture or a photograph is a spatial display.

A *spatial instrument*, in contrast, is a *spatial display* that has been enhanced either by geometric or symbolic techniques to insure that the communicative intent of instrument is realized. A simple example of a *spatial instrument* is an analogue clock. In a clock the angular positions of the arms are made proportional to time, and the viewer's angle estimation task is assisted by radial tic marks designating the hours and minutes.

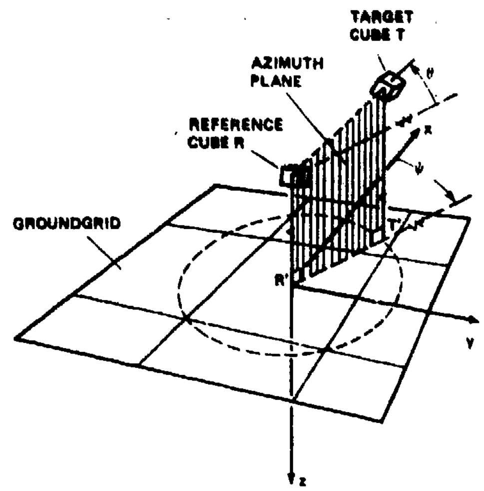

Figure 1 The relative direction of one object (cube) with respect to another and a reference direction x is given by the difference in the judged egocentric azimuth rotation of two objects: the ground grid which provides the reference and the azimuth plane defined by perpendicular drops from the cubes to the grid.

A second aspect of the definition of a *spatial instrument*, which the clock example also illustrates, is that the communicated variable, time, is made proportional to a spatial property of the display, such as an angle, area, or length and is not simply encoded as a character string.

The *spatial instruments* that we wish to focus attention on are generally interactive. That is to say that the communicated information flows both to and fro between the viewer and the instrument. Some of this bidirectional flow exists for practically all *spatial instruments* since movement of the viewer can have a major impact on the appearance of the display. However, the displays we wish to focus attention on are those encorporating at least one controlled element, such as a cursor, which is used to extract information from and input information to the instrument.

Spatial instruments have a long history. One of the first ever made was an astrolabe uncovered in 1901 near Antikythera, Greece but not fully described until the middle '50's by De Solla Price (1959) who was able to deduce much of its principles of operation by x-raying the highly corroded remains. Most notably was his discovery that the device used differential gearing to convert sidereal months to lunar months. Here the communicated variables are the positions of the planets.

Though many previous spatial instruments have been mechanical and often associated with astronomical calculations (King, 1978) they need not be so.

Maps certainly meet the definition. The map projection may be chosen depending upon the geographical feature of importance, straight line mapping of compass courses as in Mercator projections or area conservation as in Lambert-type, equal-area projections. (Bunge, 1965) The projection choice illustrates the geometric enhancement of the map. The overlaying of latitude and longitude lines illustrates the symbolic enhancement.

But more modern media may also be adapted to enhance the spatial information that they portray as the reference grid used by Muybridge illustrates (Muybridge, 1953)

Contemporary spatial instruments are found throughout the modern aircraft cockpit, the most notable probably being the attitude direction indicator or ADI which displays a variety of signals related to the aircraft's attitude and orientation with respect to terminal navigation beacons.

More recent versions of these standard cockpit instruments have been realized with CRT based instruments which have generally been modeled after their electromechanical predecessors (Boeing, 1983). The computer graphics and CRT display media, however, allow the conception of totally novel display formats for demanding new aerospace applications.

Grunwald and Ellis (Grunwald and Ellis, 1987) have described, for instance, a more pictorial spatial instrument to assist informal, complex, orbital navigation, proximity operations, and rendezvous in the vicinity of the space station, (see Figure 2). The definition of this instrument entailed a number of specific graphical enhancements which may be classified as either geometric, symbolic or both. For example, a geometric enhancement was introduced by providing a display mode in which the axis along which spacecraft typically follow reentrant looped paths is transformed into a time axis which does not exhibit these loops. This transformation may assist obstacle avoidance and out of plane maneuvering during small orbital changes. The use of a time axis may also be a technique to avoid visual illusions associated with perspective projections of the trochoidal paths that describe the relative motion paths of one spacecraft with respect to each other (Grunwald and Ellis, 1987).

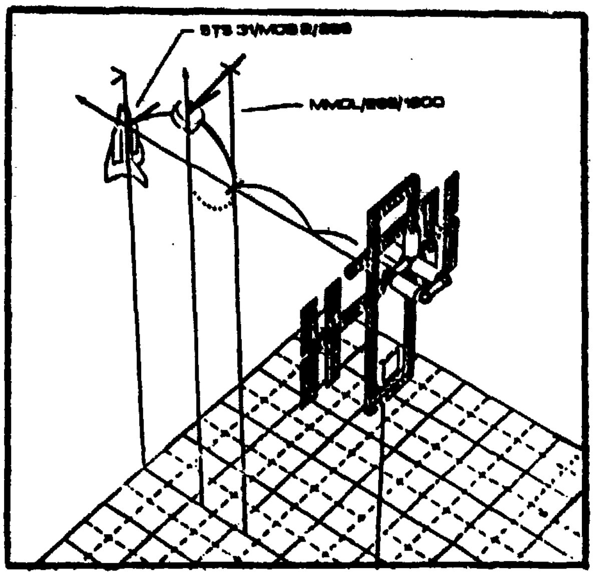

Figure 2 Sample proximity operations display. The solid curved lines show a planned orbital rendezvous between an orbital maneuvering vehicle (CMV) and the space station. The dotted line is a predicted flight path for the OMV. The projecting vectors show body axes of the craft.

Geometric Enhancement

In general, there are various kinds of geometric enhancements that may be introduced into spatial displays, but their common feature is a transformation of the metrics of either the displayed space or of the objects it contains. A more familiar example is found in relief topographic maps for which it is useful to exaggerate the vertical scale. This technique has also been used for experimental traffic displays for commercial aircraft. (Ellis, McGreevy, & Hitchcock, 1987)

Another type of geometric enhancement important for displays of objects in 3D space involves the choice of the position and orientation of the eye coordinate system used to calculate the projection. Azimuth, elevation and roll of the system may be selected to project objects of interest with a useful aspect. This selection is particulerly important for displays without stereoscopic cues, but all types of displays can benefit from an appropriate selection of these parameters. (Ellis, Kim, Tyler, McGreevy and Stark, 1985; Kim, Ellis, Tyler, Hannaford, and Stark, 1987.)

Because of its dramatic effect on the image, selection of the field of view angle is particularly interesting. Only changing the field of view angle simply magnifies the image producing an image which corresponds to an optic array geometrically similar to that optic array that a viewer would experience from the modeled eye point. Selecting a very wide field of view angle results in a minimized image, but also can introduce marginal distortions if a planar projection surface is used to produce the image. An additional source of distortion can arise if the display is viewed from a point other than the modeled eye point in the eye coordinate system. The effects of these latter distortions may, however, be modulated by the viewer's awareness of the picture plane (Pirenne, 1970; Ellis, Smith, McGreevy, 1987).

Significant design features can be achieved by joint variation of the field of view angle as well as the distance from the modeled eye point to reference objects in the display (McGreevy and Ellis, 1986; Ellis, et al., 1987; Adams, 1975). Though this combined manipulation may introduce marginal distortions, it allows control over the projected sizes of objects in the image and, for example, allows definition of a projection that will always include a designated volume of the object space. This is a useful property of a situation awareness display which is not preserved in a display by changes in the field of view alone.

The introduction of deliberate spatial distortion into a spatial instrument can be a useful way to improve the communication of spatial information to a viewer since the distortion can be used to correct underlying natural biases in spatial judgements. For example, exocentric direction judgements (Howard, 1982) made of extended objects in perspective displays, can for some response measures exhibit a "telephoto bias". That is to say that the subjects behave as if they were looking at the display through a telephoto lens. This bias can be corrected by introdution of a compensating wide-angle distortion. (McGreevy and Ellis, 1986; Grunwald and Ellis, 1987)

Unnatural scaling of displayed objects can also be used to control their prominence to insure, for example, that they never become vanishingly small. (see Fig.3). Object scaling is particularly effective at achieving nonlinear exaggerations. Unnatural object scaling can, however, increase display clutter since objects may interpenetrate, but the fact that objects and their component axes may be independently scaled generally provides the designer with techniques to reduce this problem.

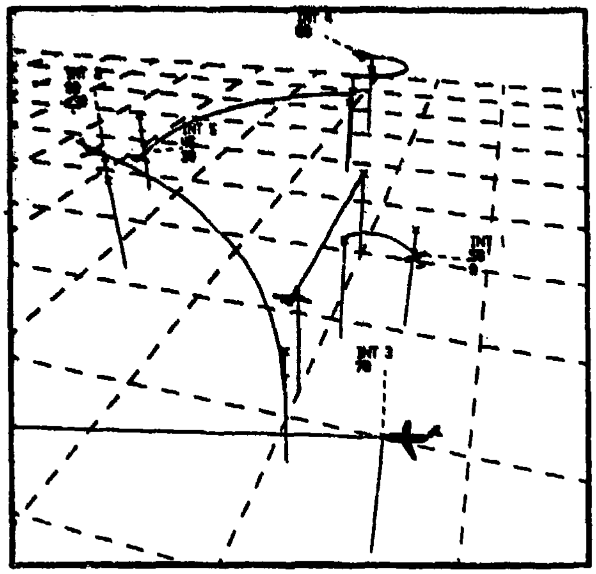

Figure 3 Sample cockpit display of air traffic. Own ship is at the center of the display. 1 minute predictors project out of all aircraft symbols. Reference lines are dropped perpendicular to the reference grid.

Symbolic Enhancement

Symbolic enhancements generally consist of objects, scales, or metrics that are introduced into a display to assist pick-up of the communicated information. The usefulness of such symbolic aids can be seen, for example, in displays to present air traffic situation information which focus attention on the relevant "variables" of traffic encounter, such as relative altitude, as opposed to less useful "properties" of the aircraft state such as absolute altitude (Falzon, 1982).

One way to present an aircraft's altitude relative to a pilot's own ship on a perspective display is to draw a grid at a fixed altitude below the "ownship" symbol and drop reference lines from all aircraft symbols onto the grid. If the "ownship" altitude is marked on these reference lines, then the distance from the other aircraft symbols to the mark is proportional to the relative altitude. If the aircraft are given predictor vectors that show future position, similar reference lines can be dropped from the ends of the predictor lines.

The reference lines not only serve to clarify the target's ambiguous aspect but also can improve perception of the target's heading difference with a pilot's ownship. This effect has been shown in a recent experiment examining the effects of reference lines on egocentric perception of azimuth of extended objects in perspective images created by a microcomputer graphics system. This experiment provides a detailed example of how psychophysical evaluation of display formats can be used to assess their information display effectiveness.

In this experiment 10 subjects viewed static perspective projections of aircraft-like symbols elevated at three different levels above a ground reference grid: a low level below the view vector and almost on the grid, a middle level co-linear with the viewing vector, and a high level above the view vector by the same amount as the low level was below it. (see Fig.4). The aircraft symbol has straight predictor vectors projecting forward showing future position above the reference grid. In one condition reference lines were dropped only from the current aircraft position, in the second condition lines were dropped both from current and predicted position.

The subjects viewed the entire configuration of aircraft symbol and grid from a fixed eye position 28 cm from the projection surface. This position was from the display surface and at the center of projection for a viewing vector set to 0 degrees azimuth and −22.5 deg elevation. Nine different azimuth rotations of the image were presented: 0 to 180 in 22.5 degree increments. The subject's task was to adjust the egocentric direction of a horizontal dial to indicate the azimuth rotation of the aircraft. Azimuth rotation was crossed with a number of reference lines in a factorial repeated measures experiment.

The first result of the experiment was that subjects made substantial errors in their estimation of the azimuth rotation of the aircraft; they generally saw it rotated more towards their frontal plane than it in fact was ($F = 23.4$, $df = 8,72$; $p. < .001$). This corresponded to clockwise errors for actual clockwise rotations up to 90 degrees. The errors reverse for rotations greater than 90 degrees.

The second result is that the error towards the frontal plane for the symbols with one reference line increased as the height of the symbol increased above the grid ($F = 4.1$, $df = 2,18$, $p < .34$). Most significantly, however, as shown in figure 5, introduction of

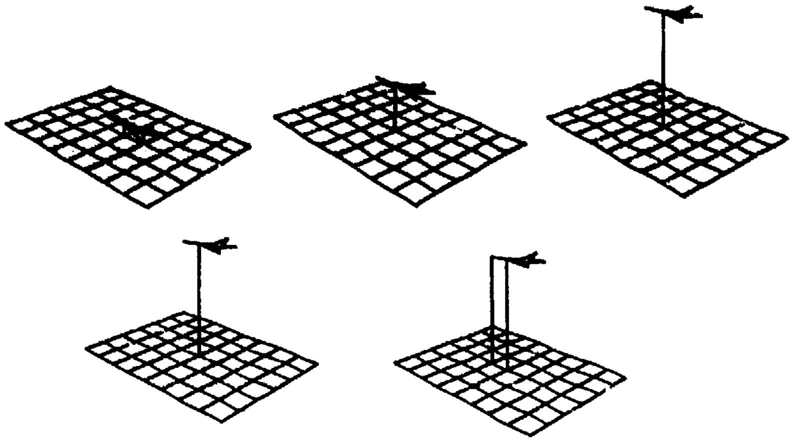

Figure 4 Five views of sample stimuli used for the experiment which illustrate the three heights of the aircraft symbol above the grid and the two reference line conditions. Viewing elevation = -22.5 deg, azimuth = 45 degrees.

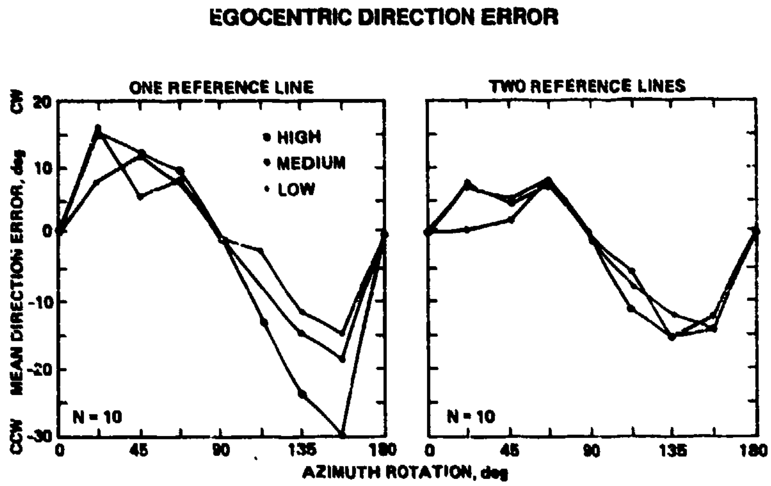

Figure 5 Mean clockwise and counterclockwise egocentric direction judgement for clockwise azimuth rotation.

the second reference line totally eliminated the effect of height, reducing the azimuth error in some cases about 50% ($F = 2.402$, $df = 16,144$, $p < .003$).

A more detailed geometric and perceptual analysis of this result is beyond the scope of this paper; however, these experimental results show in a concrete way how appropriately chosen symbolic enhancements can provide not only qualitative but quantitative improvement in pictorial communication.

Combined geometric and symbolic enhancements

Some enhancements combine both symbolic and geometric elements. One good example is provided by techniques connecting the photometric properties of objects or regions in the display with other geometric properties of the objects or regions themselves. Russell and Miles (1987), for example, have associated the optical density of points in space with the norm of the gradient of the concentration of a dissolved component and produced striking visualization of three-dimensional distributions of the compound. Similar techniques have been applied to solid models derived from sequences of CAT scans and allowed a kind of "electronic dissection" of medical images by control of the transparency of the different tissue types contained in the X-ray images (Phoenix data systems). Though this technique can provide absolutely remarkable images; one could for example "see the wind" (poem refer) by making optical density proportional to velocity; one of the challenges of its use, generally not yet met, is the introduction of metrical aids to allow the viewer to pickup quantitative information from the photometric transformation.

Discussion

The different types of enhancement are important in particular for head-mounted displays because they interact differently with the image and the viewer. The global geometric enhancements are particularly important for head-mounted displays since they interfere with visual-vestibular coordination and can result in motion sickness.

Computer generated, helmet-mounted images were probably first produced by Ivan Sutherland in 1970 (Sutherland, 1970) and have more recently been produced somewhat more elaborately at several other laboratories. (Furness, 1986; Fisher, McGreevy, Humphries, Robinett, 1986)

When Sutherland developed his display, the required hardware and software investment was substantial and available only to well funded laboratories. In contrast today, the display technology has become so inexpensive that a system adequate for creditable research can be assembled within a budget of a few thousand dollars.

Presentation of the computer generated image display on a head mounted display strongly encourages the viewer to interpret the projection as a virtual space which is expected to interact with his movements as if it were a real space. This kind of interpretation also occurs, but to a lesser extent, with ordinary pictures presented in the normal panel mounted format. The interpretation of a virtual space can give rise to pictorial illusions of depicted orientation (Goldstein, 1987; Ellis, Smith, and McGreevy, 1987), but these effects are far weaker with panel mounted displays than with those that are helmet-mounted.

One reason for the difference is that the helmet displays often include collimating optics, (Weintraub *et al.*, 1985) producing true virtual images and interfering with viewers ability to locate the surface of the picture (Nagata, 1986). Furthermore, the helmet displays generally present wider fields than the panel mounted displays. These viewing conditions, which trigger the normal binocular reflexes associated with vergence accommodation, coupled with the vestibular effects of head movement result in a viewing situation that requires careful calibration to insure perceptual stability. If stereoscopic presentation or head driven motion parallax are used, this requirement is assured.

The difficult with this format is that most of the interesting geometric enhancements destroy the required calibration. This difficulty is true by definition for the enhancements, such as differential scaling of the axes, that operate on the display space itself, but it is also true, though to a lesser extent, of enhancements such as differential object scaling because familiar size can be the overriding cue to apparent distance (Ittelson, 1951). This effect may have operational significance and explain errors pilots make when using virtual image displays (Roscoe, 1984; 1987).

The loss of visual stability due to improper correlation between visual and vestibular movement arises from both voluntary and involuntary head movement. Large voluntary head movements can produce the most obvious loss of stability if the gains and phase lags between the image movement and vestibular ocular reflex (VOR) do not match. Fortunately, the VOR is adaptable and can adjust its gain and phase response (Bertoz and Melville-Jones 1985), though time lags resembling transport delays may preclude this adaptation. Small involuntary head movements cause relative movement between the head and the viewing axis of the eye which is inertially stabilized by the VOR. In this situation the head-mounted display screen moves and blurs the image. Thus the normal operation of the VOR is actually counterproductive. Measurement of the actual head movement can provide a signal to allow compensatory, inertial stabilization of the display by displacement on the screen by adaptive filters which can model the VOR (Velger et al., 1987).

Besides loss of visual stability, geometric enhancements can interfere with visuo-motor coordination. This interference is particularly evident if the display includes a hand-controlled cursor. Under these circumstances an improperly calibrated or and intentionally distorted display resembles the view through a prism and lens system that introduces an optical distortion into the lines of sight. As known at least from the time of Helmholtz (1856), the visuo-motor system can completely adapt to the kind of conformal transformation such system can produce. Short time delays, on the order of 100 msec., can, however, substantially degrade or block this adaptation. (Held, Efstathiou and Greene, 1966).

Allowable Enhancements for Helmet Mounted Instruments

In view of the many intrinsic problems with purely geometrical enhancement, the safest enhancements for helmet mounted instruments seem to be symbolic, the kind of added information overlays that have been used on aircraft heads-up-displays for years.

These displays typically transpose much of the information already available in aircraft cockpits into a more integrated form and present it on a large combining plate, or beam splitter, so the information is available "head up" and can be seen when the pilot looks out the window (Weintraub, Haines and Randle, 1985). In addition to the usual moving tape, cursors numerical readouts, these displays often have a small graphics image projected to correspond in shape, size and position to an out-the-window object such as a runway. Maintaining good calibration for such an overlap between a display-generated graphics object and the projection of a real external object represents a significant challenge in a wearable helmet not using skull screws to maintain its position on the users head. Indeed, helmet mounted displays of this sort have been suggested as useful nausea-inducing apparatus to attempt to habituate astronauts to the sensory discordance of weightlessness before they begin space travel. (Parker, Renschke, Arrott, Homick, and Lichtenberg, 1986.)

Never the less, symbolic use of three-dimensions also seem to be an allowable enhancement. For example, one can imagine three-dimensional icons representing records in a hierarchical data base for which the third dimension could represent depth of nesting. Another interesting possibility for symbolic aid could be transient 3D "yardsticks" used in combination with a 3D cursor used to designate pairs of objects to be compared. Once two objects are selected, a line symbolicly designating their separation could be temprorarily generated to display a binary relation between them.

Among the geometric enhancements, those least likely to cause visual stability problems are those that act on the real world coordinates of the displayed objects themselves: the object scaling transformations. Provided that the transformed objects do not markedly violate the viewers implicit assumptions about the size and shape, these transformations act early enough so that their effect may interpreted simply as changing the shape and size of the objects. They would unfortunately interfere with manual manipulation of the objects, but as long as this is carried out symbolically with a cursor and not with a simulated "hand" with many degrees of control which must be adapted to the conditions of the display space, these size and shape transformation should not be too aversive.

Finally, the photometric transformations illustrated by Russell and Miles (1987) are unlikely to have untoward consequences for head mounted instruments and may prove useful if combined with metrical aids allowing them to present more quantitative information.

In the final analysis the limits we face in the definition of helmet mounted instruments are not really classically technological, but intellectual. The technological limits we face in the design of these tools will be foreseeably over come by time, effort and the natural progress in optical and electronic fabrication. The development of spatial instruments is limited not by our manufacturing capabilities but by our imagination and by our understanding of human spatial perception.

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INFLUENCE OF VECTION AXIS AND BODY POSTURE ON VISUALLY-INDUCED SELF-ROTATION AND TILT

I. P. Howard and B. Cheung
Institute for Space and Terrestrial Science, Human Performance Laboratory
York University, North York, Ontario, Canada, M3J 1P3

J. Landolt
DCIEM, 1133 Sheppard Ave. North York, Ontario, Canada, M3M 3B9

SUMMARY

Yaw vection is induced by a scene rotating about the spinal axis (z axis), pitch vection by a scene rotating about an axis in the mid-frontal plane (y axis) and roll vection by a scene rotating about an axis parallel to the line of sight (x axis). Each of these axes can be vertical or horizontal, making six conditions in all, of which only four have been studied previously. We studied vection and illusory body tilt under all six conditions, with a full rotating field, reduced somesthetic cues and in a situation in which body rotation could occur. Yaw vection around a vertical axis was strongest. Forward pitch vection was stronger than backward pitch vection. Contrary to previous reports, for most subjects backward illusory tilt was much stronger than forward illusory tilt. Two subjects experienced 360° body rotation in the horizontal-pitch condition. The direction of pitch axis asymmetry was found to be consistent and not related to the asymmetry of vertical optokinetic nystagmus.

INTRODUCTION

An erect observer exposed to a scene moving horizontally usually experiences full continuous body rotation (circularvection) after about 20 seconds. An upright observer surrounded by a scene moving vertically or by one rotating about the visual axis, typically experiences a limited degree of body inclination or tilt (up to about 15 degrees) accompanied by a paradoxical sensation of body rotation (1). The limited sensation of body tilt or inclination has been ascribed to the absence of otolith stimulation that would accompany real tilt. This theory gains support from the fact that pitch vection is more pronounced when subjects are upside down; a position in which the utricles are less sensitive (2). Continuous vection without tilt sensations is produced when the subject is supine and exposed to rotation of the scene about the visual axis, because in this situation the effects of gravity are irrelevant (3). Young et al. (5) measured roll vection in the weightless conditions of space and found that its onset latency was generally shorter than for either vertical or horizontal roll vection on earth. It is not clear from this study how zero-gravity conditions affected sensations of illusory body tilt. This would presumably depend upon whether the subject imagined himself sitting up or lying down. If he imagined himself sitting up the experience of roll vection should be much the same as on earth until the subject has learned not to expect gravity-related sensations when the body tilts.

According to the utricular-restraint theory, vection without illusory tilt should occur when the vection axis is vertical, and vection should be accompanied by a sensation of tilt whenever the vection axis is horizontal. In neither case should it matter what posture the subject is in. However, this may not be the whole story. In previous studies the moving displays did not fill the whole visual field and no attempt was made to minimize somesthetic cues. Furthermore, subjects sat in an ordinary chair with their feet on the ground and were thus predisposed to believe that they would not rotate. The present experiments were designed to overcome these limitations.

Another aim of these experiments was to make comparisons between related stimulus conditions, in order to understand why illusory body tilt is limited. We may experience limited tilt of the body when looking at a visual display rotating around the visual axis

(Fig. 1f), not only because of the effects of gravity receptors, but also because we rarely see the world turn full circle about the visual axis. The proper comparison condition is one in which the supine subject looks up at a display rotating about the visual axis (Fig. 1e), that is, a condition in which the restraint of gravity is removed but the factor of visual experience is still the same. To take a second example, we may experience limited illusory pitch when looking at an upward rotating display (Fig. 1d) because we rarely see the visual world rotate this way. The proper comparison condition in this case in that in which the recumbent subject looks at a display rotating towards the feet or the head (Fig. 1c). Finally, if visual experience is responsible for limited illusory body tilt then subjects should experience full unimpeded vection when lying down and looking at a visual display rotating about the visual axis (Fig. 1b) because this type of visual motion is very common, as when we see a scene rotating around the vertical body (Fig. 1a). In previous studies tests have been made in only four of the possible six stimulus configurations, which means that proper comparisons have not been made between equivalent stimulus conditions.

METHODS

Apparatus The main apparatus was a hollow nine-foot diameter fiberglass sphere. The inside was painted white and covered with randomly spaced black dots, varying in size from 1 cm to 5 cm. The sphere could be rotated about either a vertical or horizontal axis. The change in axis was accomplished by adjusting a jack which either lowered the sphere onto bearings at the side or raised it to engage bearings above and below. When the sphere was on the vertical axis the support for the subject was inserted into the lower bearing in such a way that it engaged a drive system which enabled the experimenter to rotate the subject and the sphere independently about the same vertical axis One support was a chair which held the subject in a vertical sitting posture (Fig 1a) and another was a horizontal bed which supported the subject in either a supine (Fig 1e) or recumbent posture (Fig. 1c). When the sphere was on its horizontal axis, the vertical subject support was removed and a horizontal boom was moved along a track through the centre of one of the side bearings. Supports for the subject could be attached to the end of this boom. One of these supported the subject in a vertical sitting posture, either facing the axis of rotation (Fig. 1f) or facing at right angles to the axis (Fig. 1d), and the other supported the subject in a supine posture, like an animal on a spit (Fig. 1b). A motor driven shaft passed through the boom so that the subject could be rotated independently of the sphere about the same horizontal axis. In all conditions the subject's head was at the centre of rotation of the sphere. In those conditions in which the vection axis was horizontal, the subject's body was encased in a box lined with inflated air bags and was strapped with a five-point harness on the outside of the air bags. There was thus pressure on all sides of the subject's body. A two-way microphone-speaker system allowed experimenter and subject to communicate without having to press controls.

Stimulus Conditions We define **yaw vection** as that occurring about the mid-body axis (z axis), **pitch vection** as that occurring about an axis in the mid frontal plane of the body (y axis) and **roll vection** as that occurring about the visual axis (x axis). Each of these vection axes can be either vertical or horizontal, which makes up the six conditions illustrated in Figure 1. Quantitative results have been published for only three of these conditions; the vertical-yaw (Fig. 1a), the horizontal-pitch (Fig. 1d), and the horizontal-roll (Fig. 1f) conditions. In the three vertical-axis conditions (Fig. 1a, c and e) the gravity sensors are irrelevant to the experience of vection. These are referred to as the gravity-irrelevant conditions. Each of these conditions has a matching horizontal-axis condition (Fig. 1b, d and f respectively) in which the subject sees the same visual motion but in which the gravity sensors would be expected to restrain vection. We shall refer to these as gravity-relevant conditions. Thus, the vertical-yaw condition, in which the upright subject watches a horizontally moving display (Fig. 1a), is gravity irrelevant and is therefore one in which full unimpeded vection is usually experienced. This condition is matched by the gravity-relevant, horizontal-yaw condition in which the supine subject watches a display rotating from side-to-side across the visual field (Fig. 1b). In this condition, the utricles and somesthetic system in-

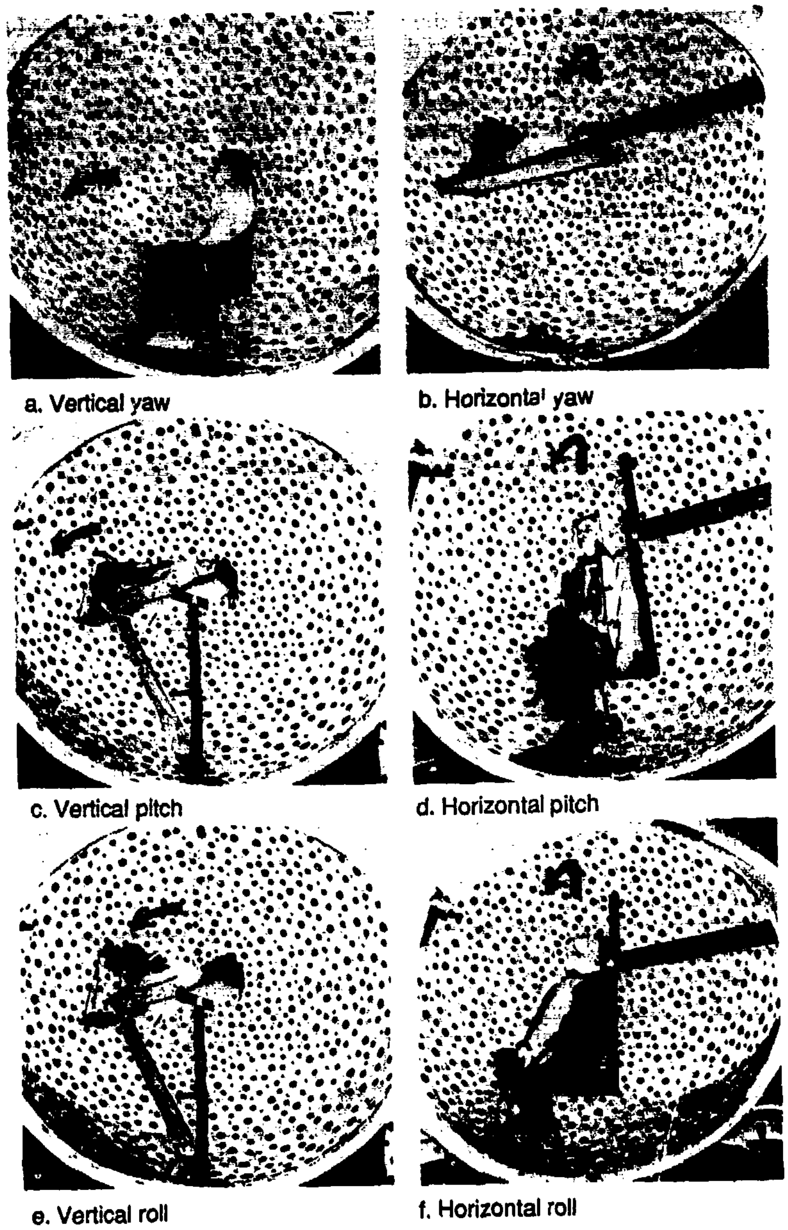

Figure 1. Stimulus conditions. Yaw denotes stimulus rotation about the mid-body axis, pitch about the y-body axis and roll about the visual axis. Vertical and horizontal refer to the orientation of the axis of scene rotation.

form the subject that the body is not rotating with respect to gravity. The three matched pairs of conditions of this sort are set out side by side in Figure 1.

The sphere was rotated around the stationary subject at velocities of 30, 45 and 60°/s in both clockwise and anticlockwise directions. Each trial lasted 60 seconds. During 30-second intervals between trials the subject was in the dark and was asked to open the eyes for the new trial when the sphere had reached a steady velocity. At ten-second intervals through each trial the subject was asked to report the magnitude of vection by calling out a number between zero and four. 'Zero' signified no vection and 'four' signified that the subject felt that the body was rotating inside a stationary sphere. Numbers 'One', 'two' and 'three' indicated intermediate levels of vection. In those conditions in which the vection axis was horizontal the subject was also required to report the angular extent to which the body seemed to be tilted or inclined to gravity. Subjects used a scale of 0, 10, 20, 30, 45, 60, and 90 degrees for these judgments. In the main experiment nobody reported values beyond 90 degrees. Before each gravity-relevant trial, subjects were actually tilted through each of the designated angles between 0 and 90 degrees to left and to right and were told what angle that was. They were then tested with corrections until they were able to recognize each of these angles accurately. This procedure trained subjects in making tilt judgments and convinced them that the support could turn. For each stimulus condition, subjects were tested for each stimulus velocity in both directions. Trials were presented at random. A subject was tested on only one stimulus condition on a given day and the order in which conditions were tested was counterbalanced across subjects. Seven adult subjects were tested on all conditions of the main experiment.

RESULTS

From each trial the magnitude of vection was indicated by the mean of the six numerical estimates that subjects made. The magnitude of illusory body tilt was derived in the same way.

The main results with regard to vection magnitude are as follows. Yaw vection, for both vertical and horizontal axes was significantly stronger than pitch vection, which in turn was significantly stronger than roll vection (Figure 2). Vection around a vertical axis was on average significantly stronger than vection around a horizontal axis for all body postures (Figure 3). The magnitude of vection was the same for the two directions of scene motion except that downward pitch vection (induced by upward scene rotation) was significantly stronger than upward pitch vection (Figure 4). For roll vection there was a significant trend for the magnitude of vection to decrease with increasing velocity of the stimulus, but no significant effect of velocity was found for the other vection axes (Figure 5).

The main results with respect to illusory tilt are as follows. Illusory tilt occurred, as expected, only when the vection and gravity axes were orthogonal, that is, in gravity-relevant conditions. The mean results for 7 subjects averaged across stimulus velocity are shown in Figure 6. Statistical analysis revealed that there was a strong asymmetry of illusory tilt for pitch vection. For all but one subject, at all stimulus velocities, illusory tilt backwards was much stronger than illusory tilt forwards and all these subjects were aware of this asymmetry. One subject experienced a strong opposite asymmetry. The asymmetries for the other axes were not significant. For each axis of vection the degree of illusory tilt increased with stimulus velocity up to 45°/s (Figure 7).

SUPPLEMENTARY EXPERIMENTS

The most striking result of the main experiment is the strong asymmetry of illusory body tilt for pitch vection about a horizontal axis. For all but one subject illusory pitch backward (induced by downward stimulus motion) was stronger than illusory pitch forward. Young et al. found the reverse asymmetry in four subjects who were tested in a flight simulator (2). Only one of our subjects behaved like those of Young et al. The difference between the two studies could be due to random sampling of subjects or to differences in the stimulus. The most obvious difference is that a flight simulator display contains a stationary window frame whereas our display had no stationary features. We there-

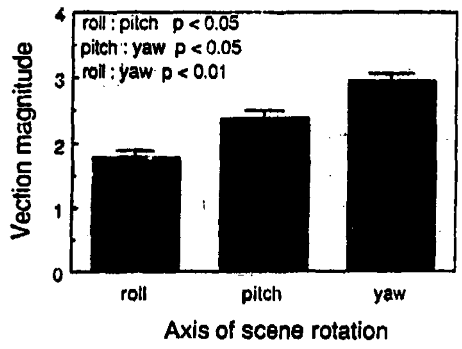

Figure 2. Mean vection magnitude of seven subjects for yaw, pitch and roll axis. Error bars are standard errors of the mean.

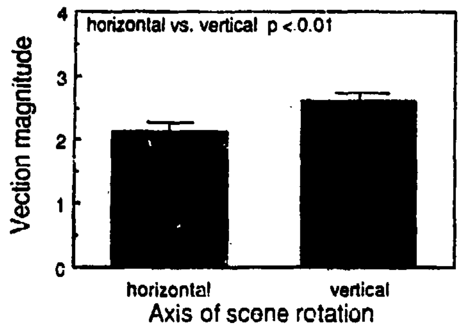

Figure 3. Mean vection magnitude for all horizontal axis conditions compared with that for all vertical axis conditions.

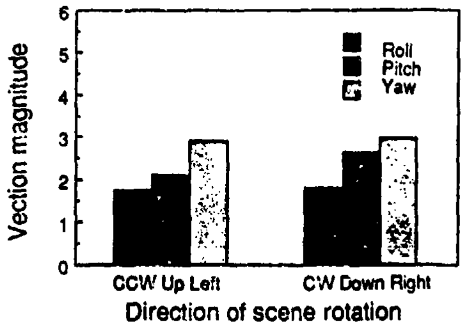

Figure 4. Mean vection magnitude as a function of direction of scene motion for each vection axis.

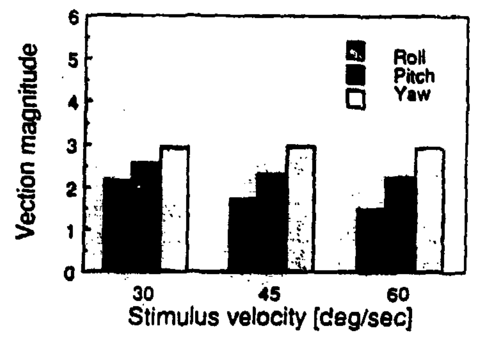

Figure 5. Mean vection magnitude for each vection axis as a function of stimulus velocity. Only vection about the roll axis showed a significant decline with increasing velocity.

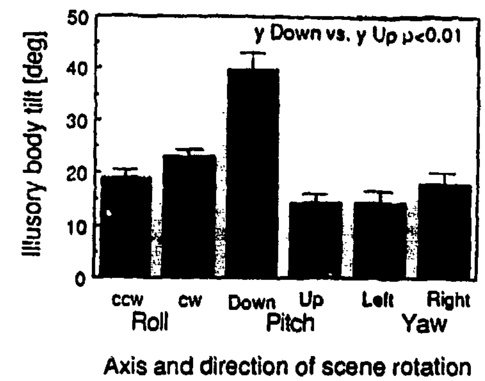

Figure 6. Mean illusory body tilt for each direction about each vection axis for only gravity-relevant conditions (horizontal axis of scene rotation).

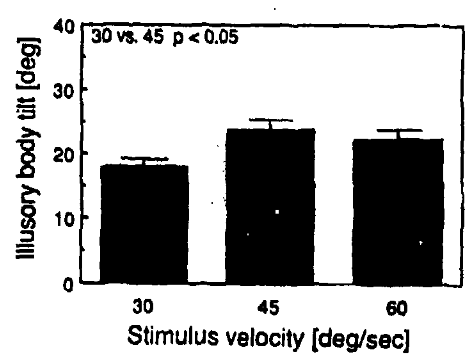

Figure 7. Mean illusory body tilt averaged across three gravity-relevant stimulus conditions as a function of stimulus velocity.

fore retested the subjects on the gravity-relevant conditions but with a stationary 30 cm square frame suspended just in front of the moving display, straight ahead of the subject. The results are shown in Figure 8. For pitch vection, all subjects showed the same directional asymmetry that they had shown without the frame. Thus, directional asymmetries of illusory pitch are consistent from day to day and are not related to the presence or absence of a fixed frame. In addition, there was a significant trend for clockwise roll vection to be stronger than counterclockwise roll vection. All subjects experienced the very striking impression that the frame was displaced from the horizontal or vertical by the same amount as the body.

In a second supplementary experiment we explored whether the asymmetry in illusory body pitch is related to asymmetries in vertical optokinetic nystagmus (OKN). It has been reported that the gain of OKN with slow phases in an upward direction is, for most people, stronger than that with slow phases in a downward direction (4). After testing nine more subjects we found a second subject with stronger illusory tilt towards the feet. We recorded the slow phase velocity of upward and downward OKN of the two subjects with this type of asymmetry and of two subjects with the other type of tilt asymmetry. All four subjects showed the normal preponderance of OKN with upward slow phases, although, as can be seen in Figure 9, this asymmetry of OKN showed only for stimulus velocities over 30°/s. These results demonstrate that there is no reason to suppose that asymmetries of OKN and of illusory pitch are related.

DISCUSSION

For each type of vection (yaw, pitch and roll) the magnitude of vection was higher for gravity-irrelevant conditions than for gravity-relevant conditions. We conclude that the gravity sense organs restrain the sensations of vection. Vection was strongest for the vertical-yaw condition, which makes sense because motion of the visual world produced by yaw is the most common type of visual motion that we experience. We often rotate the vertical body full circle around a vertical axis but rarely rotate it far around the pitch or roll axes.

In all conditions in which the vection axis was vertical, all subjects experienced unimpeded vection through a full circle and in all conditions in which the vection axis was horizontal, subjects experienced only partial rotation of the body. We have thus not produced any evidence that the factor of visual experience causes vection to be confined to less than complete rotation. However, an experience reported by one subject is suggestive. The subject was supine and looking at a display moving around the body axis (Fig. 1b). At first he experienced a moderate degree of vection associated with a limited degree of sideways body tilt. After a while the body seemed to tilt in the direction of the feet, occasionally seeming to become vertical. When this happened full unimpeded vection was experienced. The perceptual system had removed the paradoxical experience of continuing self rotation combined with limited tilt by 'concluding' that the body was vertical. No subject reported a similar resolution of paradoxical sensations in any of the other conditions, and this could be because the condition in which this resolution of the paradox was adopted was the only one which resulted in a familiar experience.

The mean magnitude of illusory body tilt was about 24° at a stimulus velocity of 45°/s, which is about twice the magnitude of tilt reported by Held et al. at that stimulus velocity. But our display filled the visual field, somesthetic cues were reduced and the subject was primed to expect the body to rotate. The largest illusions of body tilt occurred for most subjects in the condition in which they were vertical and looked at a display moving towards their feet. The mean value of tilt for this condition was about 38 degrees, and for several subjects it often reached 60 or 90 degrees. When screening subjects for the supplementary experiment we found two people who experienced full head-over-heels vection under these circumstances. The gravity sensors do not restrain vection as much as previous evidence suggested. If experiments like the ones reported here were conducted under water the true contribution of the utricular organs to the restraint of vection could be revealed.

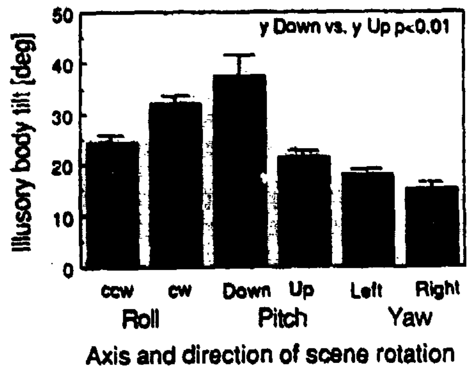

Figure 8. Mean illusory body tilt for nine subjects under the same conditions as in Figure 7. except for the addition of a fixed 30 cm frame in front of the moving display.

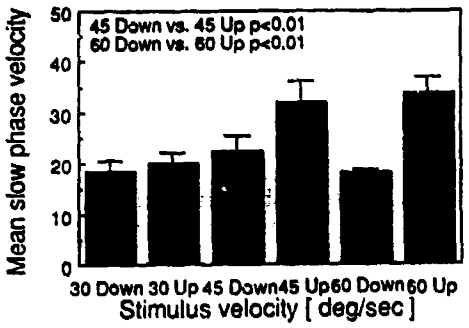

Figure 9. Mean velocity of the slow phase of vertical OKN for four subjects as a function of the velocity and direction of stimulus motion. The difference between up and down nystagmus was significant only for velocities above 30 °/ sec.

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VECTION AND THE SPATIAL DISPOSITION OF COMPETING MOVING DISPLAYS

I. P. Howard, M. Ohmi and W. Simpson
Institute of Space and Terrestrial Science, Human Performance Laboratory
York University, North York, Ontario, Canada, M3J 1P3

J. P. Landolt
DCIEM, 1133 Sheppard Ave., North York, Ontario, Canada, M3M 3B9

SUMMARY

In Experiment 1 we investigated the relative effectiveness of two superimposed displays in generating circular vection as a function of (i) the separation in depth between them, (ii) their perceived relative distances, and (iii) which display was in the plane of focus. Circularvection was found to be governed by the display that was perceived to be more distant, even when it was actually nearer. Vection was not affected by whether the near or far display was in the plane of focus, nor by which display was fixated or pursued by the eyes. In Experiment 2 we asked whether the generally held belief that vection is induced most effectively by the peripheral stimuli is due to an artifactual effect of perceived distance. The experiment assessed the separate contributions of foreground-background and central-peripheral placement of competing displays. It was found that both factors contribute in an interactive way to the experience of vection. In Experiment 3 we investigated how linear forward vection induced by a looming visual display is affected by the near-far relationships of competing displays

EXPERIMENT 1 CIRCULAR VECTION AND THE RELATIVE DISTANCE OF COMPETING DISPLAYS

Introduction When an upright stationary observer views a visual display that rotates about the mid-body axis, the impression created is that the display is at rest and the observer is rotating. This illusion of self rotation is called circularvection (1,2). Natural scenes rarely rotate with respect to the head unless the head rotates. Furthermore, the vestibular system is an unreliable indicator of self rotation except during and just after acceleration. Therefore it is not surprising that scene rotation is interpreted as self rotation, even when the body is not rotating. There is a conjunction of visual and vestibular inputs into the vestibular nuclei (3) and the parietal cortex (4) which probably explains why visual inputs can so closely mimic the effects of vestibular inputs.

When a person rotates in a normal three-dimensional environment, stationary parts of the scene move relative to the head. Since the more distant parts of a scene are unlikely to rotate with the person, their movement relative to the head provides a more reliable indicator of self rotation than does the rotation of nearer objects. It follows that circularvection should be related to the motion of the more distant of two superimposed displays. In line with this expectation Brandt et al. (5) found that vection was not affected by a stationary object in front of the moving display but was reduced when the object was seen beyond the display. In Brandt's experiment binocular disparity was the only cue to depth and the two stimuli differed in size. Furthermore, there is some doubt whether depth was the crucial factor as opposed to the perceived foreground-background relationships of the competing stimuli. Experiment 1 was designed to control for these factors.

Method There were two visual displays; a background display which filled the subject's field of view and rotated around the subject at an angular velocity of 30°/s, and a foreground display which was stationary. The moving display consisted of randomly placed black dots on the inside of a translucent white vertical cylinder, radius 60 cm. The dots of the stationary display were similar to those of the moving display and were mounted on a transparent cylinder just inside the translucent cylinder. Both displays were transilluminated by diffuse white light at a level of 40 cd/m^2.

The subject sat at the centre of the two concentric cylinders with the head fixed in a helmet. The displays were viewed monocularly with the gaze at the centre of the displays. The stationary display was set in random order at each of four distances from the subject's eye: 36, 44, 52, and 59 cm. The absence of binocular cues to depth allowed the perceived depth order of the two displays to reverse spontaneously, even when they were well separated in depth. At each distance, subjects were asked, in one trial, to focus within the plane of the display with slightly sharper dots (the near display) and, in another trial, to focus in the plane of the display with less sharp dots (the far display). An instruction to look at the far or near display would have been ambiguous because the displays were designed to reverse their apparent depth order. Similarly, an instruction to look at the moving or stationary display would have been ambiguous because which display appeared to move varied according to whether or not the subject was experiencing vection. Each trial lasted about 150 s, during which time the subject was asked to report two events. The first was the onset or offset of vection. Since all subjects reported complete vection when vection was present, this report was sufficient. The second event was any apparent reversal of the depth order of the two displays. Reversal of depth was easy to notice because of the slight differences in appearance of the two sets of dots. Four subjects were tested.

Results A time course of the presence or absence of vection and a time course of changes in apparent depth were obtained for each trial. All subjects showed similar trends and a typical example of the time courses of these two events is shown in Figure 1. In all cases vection was experienced whenever the display that was perceived as the more distant was moving and was never experienced whenever the display perceived as more distant display was stationary. Changes in the experience of vection were closely linked to reversals of apparent depth. We derived a cross correlation function which served as an index of coincidence of these two events, the details of which are given in Ohmi et al. (6).

The dependance of vection on the perceived relative depth of the two displays was not affected by whether subjects focused on the moving display or on the stationary display, nor by changes in distance between the two displays. When the displays were virtually coplanar, the moving display seemed to slide over or under the stationary display and the spontaneous reversal was that of foreground-background rather than primarily one of depth. Vection was perceived only when the display that was perceived as background was moving.

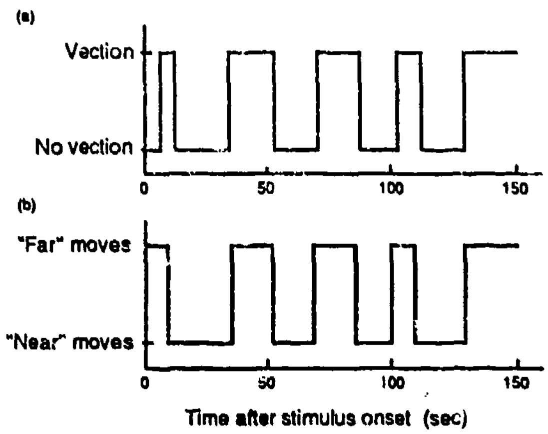

Figure 1. The time course of (a) changes in the experience of circular vection and (b) changes in the perceived relative depth of the moving display of one subject. The background display was 60 cm and the foreground display 36 cm from the subject. In this condition the subject focused on the background display.

Conclusion We conclude that circular vection is totally under the control of whichever of two similar displays is perceived as background. This dominance of the background display does not depend on depth cues, because circularvection is dominated by a display that appears more distant, even when it is nearer. We think that perceived distance is an incidental property of that part of the scene interpreted as background. When subjects focused on the moving display optokinetic pursuit movements of the eyes occurred, and when they fucused on the stationary display, the eyes were stationary. But such a change in the plane of focus had no effect on whether or not vection was experienced, as long as the apparent depth order of the two displays did not change.

Thus sensations of self rotation are induced by those motion signals that are most reliably associated with actual body rotation, namely, the signals arising from that part of the scene perceived as background. Vection sensations are not tied to depth cues, which makes sense because depth cues can be ambiguous, and they are not tied to whether the eyes pursue one part of the scene or another, which also makes sense because it is headcentric visual motion that indicates self motion and this is just as well detected by retinal image motion as by motion of the eyes.

EXPERIMENT 2 CIRCULARVECTION AND THE CENTRAL-PERIPHERAL AND NEAR-FAR PLACEMENT OF STIMULI.

Introduction Brandt et al. reported that circularvection is much more effectively induced by a moving scene confined to the peripheral retina than by one confined to the central retina (7). In these studies, the central retina was occluded by a dark disc which may have predisposed subjects to see the peripheral display as background and it may have been this rather than its peripheral position which caused it to induce strong vection. Similarly, when the stimulus was confined to the central retina subjects may have been predisposed to see it as a figure against a ground, which may have accounted for the small amount of vection evoked by it. Experiment 2 was designed to measure the separate and interactive contributions of the factor of central versus peripheral placement and the factor of near versus far placement of competing stimuli to the generation of circularvection.

Method The apparatus is depicted in Figure 2. The subject was seated with the head at the center of a 1.3 m diameter vertical cylinder which could be rotated in either direction. The cylinder was made of white translucent plastic and its inner surface was covered with randomly arranged black opaque dots, 2 cm in diameter and with a mean density of 735 $/m^2$. The cylinder was transilluminated at a level of 10 cd/m^2. A white transilluminated belt containing a similar array of black dots ran over rollers and concave strips of plastic so that it looked like a section of the large cylinder. This display of dots was placed above the subject's head and reflected by a sheet of transparent plastic onto a matching black occluder in the centre of the large display. The subject thus saw a 28° square surrounded by the large cylindrical display. The small display could be moved so that it appeared to be suspended 12.5 cm in front of, in the same plane as, or 12.5 cm beyond the peripheral display as if seen through a square hole. In some conditions, one or the other of the displays was occluded. Both displays moved at an angular velocity of $25^o/s$ across the subject's field of view, either in the same direction or in opposite directions.

The stimulus conditions are set out in Table 1. In each trial subjects looked at the center of the display for two minutes and reported the direction and strength of circularvection by setting a five-position switch, with the central position indicating no vection. The switch settings were digitized and recorded by a computer together with a record of the time at which each change of the switch occurred. A value of +1 was assigned to full vection in a direction opposite to the motion of the visual display and a value of -1 to full vection in the same direction as the display. Values of +0.5 and -0.5 were assigned to intermediate levels of vection. When the two parts of the display moved in opposite directions, the motion of the peripheral display was taken as reference. A mean vection score for each trial was derived by multiplying the duration in seconds of each constant setting of the switch by the value of that setting, adding these sums over the two-minute period, and dividing by 120 (the duration in seconds of a trial). Thus the mean score for each trial varied between -1 and +1. Trials were separated by two-minute rest intervals during which subjects sat with the lights on but the displays stationary.

The order of sessions (center near, coplanar and center far) was counterbalanced and the order of conditions within sessions was randomized. Eight men and one woman between the ages of 23 and 60 years served as subjects. All but three were naive about the nature of the experiment.

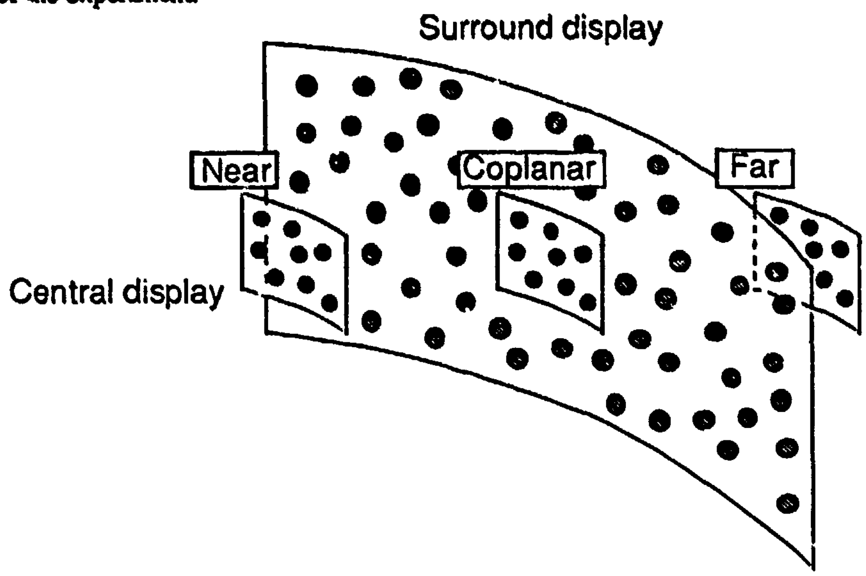

Figure 2. Showing the spatial dispositions of the central and peripheral parts of the display used in Experiment 2. The subject was seated at the centre of the cylindrical display and centered the gaze on the middle of the centre display. The two displays could be moved in the same or in opposite directions, or could be blacked out. The central display was reflected onto a matching black square on the larger display.

Both parts of display moving

- Moving in same direction
- Moving in different direction

Only one part of display moving

- Centre stationary - surround moving
- Surround stationary - centre moving

- Centre black - surround moving
- Surround black - centre moving

Table 1. Types of display used in Experiment 2. Each type of display was presented in random order with the central part nearer than, beyond or in the same plane as the surround part of the display.

__Results__ In Figure 3 the mean vection ratings for the nine observers are plotted as a function of the relative distance of the central display (near, coplanar and far) and the type of display. Since there was no significant difference between vection for leftward and rightward moving displays the data from the two directions of motion were combined. The displays in which both fields were moving in the same-direction elicited higher vection ratings than the displays in which they were moving in opposite directions (means 0.82 and 0.42; $F(1,8) = 8.305$, $p < .019$). The direction of vection was opposite to the motion of the peripheral field, indicating that the addition of the oppositely moving center reduced but did not reverse vection. There was no effect of centre depth in these conditions ($F(1,8) = .305$, NS).

The relative contributions of centre and surround fields to vection can be seen by comparing displays where only the surround was moving (center-still and center-black conditions) with displays where both centre and surround were moving in the same direction (same-direction condition). This comparison showed that if centre motion (in the same direction) was added to surround motion then there was no increase in vection ($F(2,16) = .383$, NS). As expected, no effect of depth of the centre was seen for displays in which only the surround was moving ($F(2,16) = .012$, NS).

The center-still and surround-still pair of conditions and the center-black and surround-black pair of conditions were matched in all respects except the location of the moving field (centre or surround). In both cases, vection was much higher when the moving field was the surround (center-still rating .76 vs surround-still rating 0.09: $F(1,8) = 27.556$, $p < .001$; center-black rating 0.79 vs surround-black rating 0.32 : $F(1,8) = 17.592$, $p < .003$). If the stationary field was visible, there was an interaction between its peripheral-central location and its depth ($F(2,16) = 5.601$, $p < .014$). That is, the pattern of vection ratings for near, coplanar, and far fields was different for centre-still and surround-still conditions. There was no main effect of Centre Depth ($F(2,16) = 3.360$, NS). If the stationary field was black, the pattern of ratings for near, coplanar, and far fields was the same (no Location x Centre Depth interaction, $F(2,16) = .786$, NS). There was a main effect of Depth of Centre (mean ratings for near, coplanar, far: 0.59, 0.48, 0.60: $F(2,16) = 3.773$, $p < .044$). Thus, if a stationary field was black, then less vection was obtained for coplanar centers than for near or far centers.

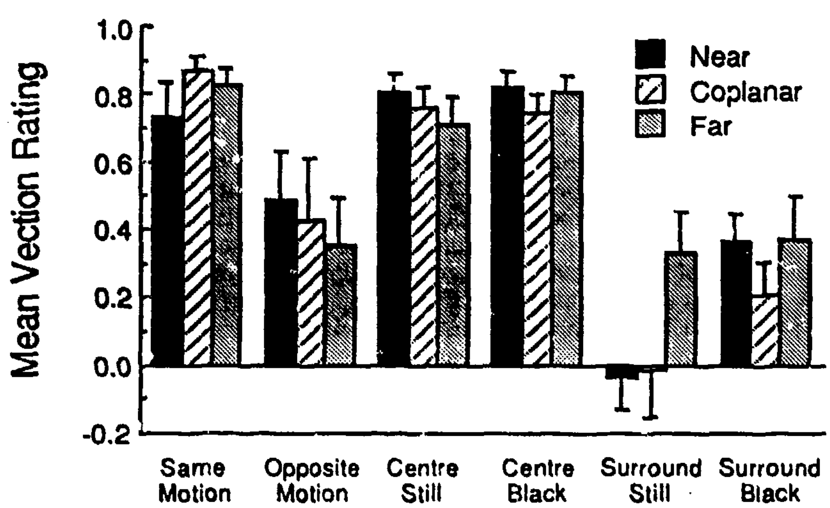

Figure 3. Mean vection ratings of nine subjects plotted as a function of the relative depth between the central and peripheral parts of the display and the type of display. A vection rating of 1.0 signifies full vection in a direction opposite to the motion of the display. When the two parts of the display moved in opposite directions, the motion of the peripheral part was taken as reference. The error bars are standard errors of the mean.

The final comparison of interest was that between displays with moving centers and either still (visible) or black surrounds. In the surround-black conditions, there were no disparity cues when the central field was near, only when it was far. Vection ratings were lower in the surround-still than in the surround-black condition (mean rating 0.09 vs 0.32; $F(1,8) = 10.019$, $p < .013$). There was no main effect of Depth of Centre ($F(2,16) = 3.463$, NS), but there was a significant interaction between Surround Type and Centre Depth ($F(2,16) = 9.237$, $p < .002$). Thus the pattern of ratings for near, coplanar and far fields was different for still surrounds and black surrounds (as is plainly visible from Figure 3). The pattern for surround-still was the more interesting. If the center was moving and the surround was still but visible, little vection was obtained except when the moving field was further away than the surround.

Discussion This experiment has confirmed that, all things being equal, vection is driven better by peripheral stimuli than by central stimuli. Indeed it is driven just as well by a moving peripheral display with the centre black or visible and stationary as it is by a full-field display. However, if the centre of the display is moving in a direction opposite to that of the peripheral part then vection is reduced. Thus a moving central display can weaken the effect of a moving peripheral display but not to the extent of reversing vection. If the peripheral part of the display is visible but stationary then the direction of vection is determined by the central part of the display but only if the moving central field is farther away than the surround. This result is understandable when we realise that this sort of stimulation is produced, for example, when an observer looks out the window of a moving vehicle. The moving field seen through the window indicates that the viewer is moving along with the part of the scene surrounding the window. When the surround is black, the relative distance of the moving central display has little or no effect. The reason for this is probably that a central display in front of a black surround provides virtually no cues to its location in depth and subjects are at liberty to perceive it as being beyond the surrounding black display.

EXPERIMENT 3 ILLUSORY FORWARD MOTION AND THE RELATIVE PLACEMENT OF STIMULI

A looming, or radially expanding, display in the frontal plane induces forward vection - an illusory sensation of forward motion of the body along the line of sight (7,8). In Experiment 3 we examined whether forward linear vection, like circularvection, is governed by the display perceived to be in the background.

Method A microcomputer was programmed to produce a looming display of 64 randomly distributed dots on an oscilloscope screen. The radial movement of each dot simulated the movement of a dot approaching the subject at constant velocity along a path parallel to the visual axis. The display was presented sequentially to give a sensation of a continuously approaching display of dots which induced a sensation of forward motion of the self through a tunnel of dots towards a distant focal point.

A display of 512 randomly distributed stationary dots was superimposed on the display of looming dots on each of two oscilloscope screens viewed through mirrors to form a stereoscope. The stationary display on one oscilloscope was shifted laterally to give a disparity of ± 90 min of arc between the looming display and the stationary display. Thus the stationary display could be placed stereoscopically either beyond or nearer than the moving display. The radius of the combined display was 20° of visual angle.

There were three conditions; (i) only the looming display was presented, (ii) the stationary display was presented nearer than the looming display and (iii) the stationary display was presented beyond the looming display. Subjects viewed the displays for 1 min while continuously estimating the strength of forward vection by moving a lever connected to the microcomputer.

In another condition of the experiment a similar display was used but binocular disparity cues were eliminated, leaving the subject free to perceive one or other of the superimposed displays as more distant. The subject was required to report the strength of vection as well as any spontaneous reversals of depth order between the two displays. Three adults, who had experienced circular vection and had normal eyesight, served as subjects.

Results Responses of subjects were digitized in three levels and then averaged over the 1 min trial period. As all subjects showed similar trends, the strengths of forward vection averaged across subjects for the three conditions in which binocular cues were present are shown in Figure 4. When the display of stationary dots was presented in front of the display of looming dots, the strength of forward vection was the same as when only the looming display was presented. On the other hand, when the stationary display was presented beyond the looming display the strength of forward vection was reduced to about 20 % of its value when there was no stationary display. A two-way analysis of variance confirmed that the effect of Condition was statistically significant [$F(2,8) = 12.50$, $p < .02$]. The results of this experiment are consistent with those of Experiment 1 for circular vection, and indicate that, as before, the background display controls vection. However, whereas circular vection was totally suppressed for all subjects when the background display was stationary there was some residual forward vection under these conditions.

In the conditions in which binocular cues were not present, responses of subjects were digitized in three levels and then averaged separately for the time periods during which the stationary displays appeared to be in front of the looming display and for the time periods when the stationary displays appeared to be beyond the looming display. All subjects showed similar trends. The stationary display did not significantly suppress forward vection when it appeared in front of the looming display. When the stationary display appeared beyond the looming display, the strength of forward vection was reduced to about 40 % of its strength when only the looming display was presented. Although this reduction was smaller than when binocular cues were present, a three-way analysis of variance confirmed that the effect of Apparent Depth Order (in front-beyond) was statistically significant [$F(1,71) = 197.62$, $p < .001$].

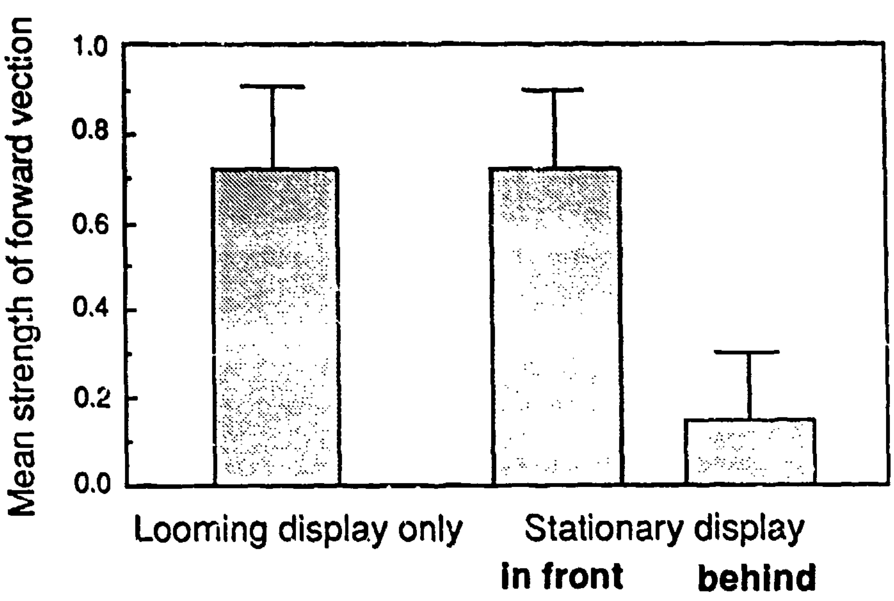

Figure 4. Mean strength of forward vection when the looming display was presented alone, and when the stationary display was presented nearer than the looming display or beyond the looming display. Vertical bars are standard errors of the mean.

Conclusion We conclude that when a display of stationary dots is superimposed on a display of looming dots, forward vection is to a large extent controlled by the display which is more distant or which appears more distant. Subjects interpret a stationary display nearer than a looming display as moving forward with them like a dirty windshield in a car. In this respect forward and circular vection are alike. For forward vection this is the only reasonable interpretation for subjects, because if subjects regard a stationary display in front of a looming display as fixed in space, it will eventually hit subjects if they feel forward vection or hit the approaching display if they do not feel forward vection. On the other hand, although circularvection was completely inhibited when the background display was stationary there was still weak forward vection with a stationary background display. This difference makes sense because, for forward body motion, the image of a distant scene is virtually stationary whereas, for circular body motion, it is not.

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CUES FOR TRAINING VERTIGO, PROVIDING SUGGESTIONS FOR THE MANAGEMENT OF SIMULATOR SICKNESS

Marcel E. Norré, M.D., Ph.D. Dpt Otoneurology & Equilibriometry
The University of Leuven Hospitals LEUVEN (Belgium).

Clinical experience with exercise treatment for vertigo has confirmed the extreme adaptibility of the balance system (6,7,8,9). Vestibular Habituation Training (V.H.T.) for provoked (positioning) vertigo provides some interesting cues in the scope of the theme of this meeting, related to simulator sickness.

For a good understanding of the problem, some fundamental notions have to be precised.

VERTIGO is a subjective sensation, caused by and resulting from a dysfunctional state of the balance system. Dysfunction becomes conscious, whereas normal functioning remains unconscious. Vertigo is comparable with the different kinds of motion sickness, because of the similarities in the pathogenesis of both manifestations (10). Simulator sickness can be categorized under motion sickness.

We would like to emphasize some cues of the treatment we have used for more than 10 years in some types of vertigo. We present them to the experts as a material for information and consideration.

As vertigo is the result of dysfunction in balance, a clear definition of the balance system is necessary.

Balance consists in a complex sensori-motor system, which serves two goals (11) : 1/ the stabilization of the visual field and 2/ the maintenance of the erect standing position.
These goals are achieved by appropriated reflexes, elaborated by the centers of the brainstem. To this aim the centers are informed about changes in spatial orientation by three sensors: vision, vestibular and proprioceptive systems.
The centers also dispose of adaptive possibilities, which are the basis of exercise treatment (6,8,9).

The dysfunction causing vertigo may be situated in the balance system at the peripheral sensory level or at the level of the centers. Exercise treatment concerns peripheral vertigo, which is the result of a sensory mismatch.

Each situation of spatial relationship and each change in this situation have to be signalled to the centers, in rest as well as during movement. The incoming sensory pattern is a "known" one, compared with former experience (reference pattern). Correspondance with the expected pattern allows normal and automatic procedure for elaborating the adequate reflexes.

If one sensor is disturbed, the resulting input is changed and gets opposed to the one of the other sensors and a sensory mismatch results. Automatic procedure is no more possible and the situation becomes conscious as "vertigo". It is accompanied by panic, whereas at the same time there is an overflow to the neurovegetative centers.

Two types of peripheral vertigo can be distinguished: 1/ spontaneous vertigo which is the result of a dysfunction causing a lasting sensory mismatch in the situation of rest as well as when moving. It is the result of a disturbance affecting the vestibular system for a short or long time. 2/ provoked vertigo occurs only by moving and here a persistent dysfunctional state becomes only manifest (i.e. causing a sensory mismatch) when the system has to signal change in spatial relationship. The vertigo is limited, shortlasting and can also be elicited deliberately (6,7).

The balance system disposes of adaptive mechanisms which have been studied intensivaly (1,3,4) and which constitute the basis upon which the exercise treatment is founded (6,8,9). These adaptive mechanisms belong to the central processing.

According to the data which are provided by these studies and which are also resulting from the experiences gathered by daily application, following requirements can be put forward for exercise treatment.

The vertigo that can be treated by exercises is a peripheral vertigo. This means that the dysfunction has its origine at the level of the sensory input, causing a sensory mismatch. It is a vestibular vertigo, i.e. the dysfunction is located in the vestibular sensor. As exercise treatment appeals to the adaptive mechanisms of the centers, central disturbance is a countra-indication for exercise treatment.

The vertigo has to be produced by a non-fluctuant, steady state of dysfunction in the vestibular system (9). This limits the application to "provoked vertigo". This vertigo results from the working situation of the system: i.e. when movements, changes of position have to be informed to the centers. In rest the situation is normal or normalized.

Experiments have shown that the repeated exposure of the whole system to the condition producing the sensory mismatch is the very stimulus favoring the development of adaptation (3,4). It is an error-controlled process. It can be conceived as a pattern rebuilding (6).

Habituation, studied in the field of the vestibular functioning, furnished the main characteristics of this adaptation: response decline of the disabling effect, specificity and retention of the effect (2,5).

In this way the exercises have to be selected individually.

It is the progressive development of adaptation and the specificity of the resulting adaptation, that are the fundamental reasons for which the peripheral dysfunction has to be stable.

Progressive development can hardly be achieved when the underlying dysfunction is always changing. The habituation effect is strictly limited to the type of stimulus used and when the dysfunction is labile and changing, the incoming stimulus pattern is changing and cannot bring about a sufficient habituation effect.

These characteristics have been confirmed in the clinical application of V.H.T. The experience in patients shows the progressive reduction of the number of positive cases during therapy (table 1). Each case is tested for provoked vertigo and a score is computed. Also the progressive reduction of the mean of the scores of the cases still positive at each step allows to follow the degree of provoked vertigo. Progressive evolution is obvious.

Table 1.

Evolution during VHT treatment

Examination no	1	2	3	E
n of posit cases	40	29	14	3
mean of the scores	105	47	43	9

ex no 1: after one week; 2: after two weeks, 3: after three weeks. E: endevaluation after 6 weeks.
positive case shows at least one maneuvre positive at the test-battery
mean of the scores at the VHT-testbattery for the cases still positive.

The specificity of the positive maneuvres is also confirmed by the clinical experience. The 19 M of the test-battery were subdivided in groups according to the direction of the eliciting maneuvre. It is clear that each patient has an individual pattern of positive maneuvres, as is illustrated in table 2.

Table 2. Specificity of the positive maneuvres.

Of the 19 maneuvres : 12 can be positive with (M+Ny+) or without nystagmus (M+Ny-)
7 never show nystagmus (M+Ny-)

The positive M+Ny+ belong to one or more subdivisions

All M+ belong to only one subdivision n=17
M to the right (series I/R): n=9
M to the left (series I/L): n=8

The M+ belong to two subdivisions n=16
I/R+I/L: n=3
I/R+I/Mi: n=9
I/L+I/Mi: n=4

The M+ belong to the three subdivisions n=7

Sham exercises, i.e. movements not provoking vertigo, avoidance therapy, non-treatment give a significant less effect. This proves that the repeated exposure of the patient to the positive maneuvres is the only efficient way for treatment (table 3).

These data confirm that :
- habituation effect is possible for provoked vertigo
- the course of the therapeutic effect corresponds with the assumptions and shows the typical characteristics

- the specificity of the habituation effect, here the therapeutic effect, linked to the provoking maneuvre is clearly shown.

TABLE 3. CHECK FOR EFFICACY OF VHT.

Reduction VHT scores :	100%	+75%	75-25%	-25%
A. Group C: Normally treated cases (N=20)	4	10	6	0
B. Group D: treated by sham exercises (N=20)	0	1	9	10
C. Group E: non-treated cases (N=28)	1	3	10	14

Evaluation of the results after two weeks of exercises for groups C and D, after at least two weeks for E.

These are the basic experiences in VHT treatment, which we esteem to be interesting.

Which is now the LINK TO SIMULATOR SICKNESS ?

First of all we would like to emphasize that we don't mean that these persons suffer of vertigo. The disabling sensation, called motion sickness, means only a disturbance similar to vertigo (10).

In both, the sensory observation of the environment by the three sensors results in a **sensory mismatch**. In vertigo it is one of the sensors that works in a wrong way and in motion sickness it is an unusual presentation of the environment structure that causes the mismatch.

Provoked vertigo as well as motion sickness is linked to actual working of the system. In both situations the system has to work up changing relationships: in the provoked vertigo the changing situation has no contradiction in se related to a normal working schedule of the system, whereas it has in motion sickness.
In both cases it must be possible to re-organize the effect of the changed sensory input by central adaptation.

Our clinical experience confirmed it: repeated exposure to the mismatch is the very stimulus and has a positive effect in provoked vertigo. Persons with motion sickness can be habituated in the same way as we observe it for our patients with provoked vertigo: i.e. progressively by exposure and specifically, related to the stimulus pattern of the exposure (10).

However the characteristics, especially the specificity of the effect, lead to an important remark related to simulator sickness:

Adaptation is very specific, which means that only the situation to which the system is exposed gets adapted with exclusion of the other similar situations. We saw this specificity effect confirmed in our patients. So far as and as much as the sensory pattern in the simulator is different from the sensory pattern experienced in real flight, adaptation to the simulator condition may cause trouble in the flight condition. Both have to be identical or ressemblant as near as possible.

The only valuable advise is to reduce sensory mismatch as much as possible and to approach the situation of flight as much as possible.

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DISCUSSION

GUEDRY: Thank you for your very interesting presentation. Your work pertains to the situation mentioned by Benson in which the sensory rearrangement results from the medical state of the subject. I would like to comment on work in various labatories in the United States and other countries, indicating that several different procedures can be used to provide a more general adaptation to various provocative motion conditions. I do not mean to imply, however, that these other procedures would necessarily be appropriate for the categories of patients in your study.

VIOLETTE: Comments (in French) could not be translated due to technical difficulty.

PREADAPTATION TO THE STIMULUS REARRANGEMENT OF WEIGHTLESSNESS: PRELIMINARY STUDIES AND CONCEPTS FOR TRAINER DESIGNS

D. E. Parker and M. F. Reschke

Department of Psychology, Miami University,
Oxford, Ohio 45056
Space Biomedical Research Institute,
Johnson Space Center,
Mail Code SD5
Houston, Texas 77058

SUMMARY

An effort to develop preflight adaptation training (PAT) apparatus and procedures to adapt astronauts to the stimulus rearrangement of weightless spaceflight is being pursued. Based on the otolith tilt-translation reinterpretation model of sensory adaptation to weightlessness, two prototype preflight adaptation trainers (PAT) have been developed. These trainers couple pitch movement of the subject with translation of the visual surround. Subjects were exposed to this stimulus rearrangement or to a control condition of no rearrangement for periods of 30 m. The hypothesis that exposure to the rearrangement would attenuate vertical eye movements was supported by two experiments using the Miami University Seesaw (MUS) PAT prototype. The Dynamic Environment Simulator (DES) prototype failed to support this hypothesis; this result is attributed to a peculiarity of the DES apparatus. A final experiment demonstrated that changes in vertical eye movements were not a consequence of fixation on an external target during exposure to a control condition. Together these experiments support the view that preflight adaptation training can alter eye movements in a manner consistent with adaptation to weightlessness.

Following these initial studies, concepts for development of operational preflight trainers were proposed. The trainers are intended to: demonstrate the stimulus rearrangement of weightlessness; allow astronauts to train in altered sensory environment; modify sensory motor reflexes; and reduce/eliminate space motion sickness symptoms.

INTRODUCTION

Current estimates suggest that about 50% of the shuttle astronauts experience space motion sickness (SMS) during the initial 24-72 hours of orbital flight. Symptoms range from lethargy to vomiting, leading to reduced performance efficiency and sense of well-being. Further, the consequences of vomiting during extravehicular activity are potentially serious (1).

It has been noted that weightlessness rearranges the relationships among signals from visual, skin, joint, and vestibular receptors. Congruence between vestibular signals and those from other receptors as well as between the vestibular otolith and semicircular canal receptors is disrupted by the absence of gravity. This lack of congruence between sensory signals leads to sensory conflict, which appears to be the basic mechanism underlying space motion sickness (2).

People adapt to stimulus rearrangements. For example, adaptation to the stimulus rearrangement produced by prisms is revealed by motor responses, such as eye movements, as well as by sensory reactions, such as self-motion perception (3,4,5). Analogous changes are seen during adaptation to weightlessness, when relationships between visual, vestibular, and somatosensory signals are altered. Adaptation is indicated by reduced subjective disturbance to voluntary motion after 24 to 72 hours of orbital flight, as well as by perceptual and physiological reflex changes noted during flight, reentry and immediately after landing (2).

SMS can be viewed as a side effect of adaptation to weightlessness. The adaptation process occurs as the result of sensory compensation and/or sensory reinterpretation. Sensory compensation occurs when the signal from one type of receptor is attenuated and signals from other receptors are augmented. In the absence of an appropriate graviceptor signal in weightlessness, information from other spatial orientation receptors, such as the eyes, the vestibular semicircular canals, and the neck position receptors, can be used by astronauts to maintain spatial orientation and movement control. Alternatively, signals from graviceptors may be reinterpreted by the brain. On Earth, information from graviceptors is interpreted by the brain as linear motion (translation) or tilt with respect to gravity. Because stimulation from gravity is absent during orbital flight, interpretation of the graviceptor signals as tilt is meaningless. Therefore, during adaptation to weightlessness, the brain reinterprets all graviceptor output to indicate translation. This is the otolith tilt-translation reinterpretation (OTTR) hypothesis (1).

STUDIES WITH PROTOTYPE TRAINERS

Previous Research

Results from several experiments with the PAT prototype trainers have been reported previously. One experiment (6) examined the amplitude of horizontal eye movements elicited by roll stimulation as a consequence of exposure to the PAT stimulus rearrangement. The largest change in eye movement amplitude was found when the subject received both visual and tactile stimulation during exposure to the rearrangement. A second experiment (7) indicated that the eye movement changes produced by 30-m exposures to the stimulus rearrangement persisted beyond the training period. Attempts to replicate the findings of the initial experiments with a different prototype trainer were unsuccessful; however, it was found that eye movement responses could be altered by manipulation of the phase relationship between roll motion of the subject and visual surround translation. Finally, the effects of exposure to a PAT stimulus rearrangement condition associated with increased retinal slip versus one associated with reduced retinal slip were examined (8). No differences in horizontal eye movement amplitudes as a consequence of this manipulation were observed.

These preliminary observations indicated the need for further experimentation to elucidate the specific physiological and perceptual responses to the stimulus rearrangement produced by these trainers.

Hypotheses

Before undertaking the experiments described in this paper, we postulated that vertical eye movement amplitude would be reduced following exposure to the PAT stimulus rearrangement as compared to a control condition of no stimulus rearrangement. This hypothesis was based on the OTTR model of sensory-motor adaptation to weightlessness.

The OTTR model suggests that otolith signals normally may be interpreted as either tilt or as translation. During PAT exposure, the translation interpretation is facilitated and the tilt interpretation is repressed. If the training is successful and the translation interpretation persists following the exposure, the trainee should perceive less tilt and greater translation during real pitch stimulation following the training than prior to it. Further, diminished compensatory vertical eye movements should be observed.

Bases for these predictions are illustrated in Fig. 1, which shows the eye movement required to maintain gaze on an imagined floor-fixed target, X, during forward pitch. Figure 1-A illustrates hypothesized reduced tilt self-motion perception following training. Note that the head in the POST-PAT panel is tilted forward less than in the PRE-PAT panel. This is intended to represent the subject's perceived tilt, not the real tilt. If this were correct, smaller vertical eye movements would be required to maintain gaze on the imaginary floor-fixed target after PAT training.

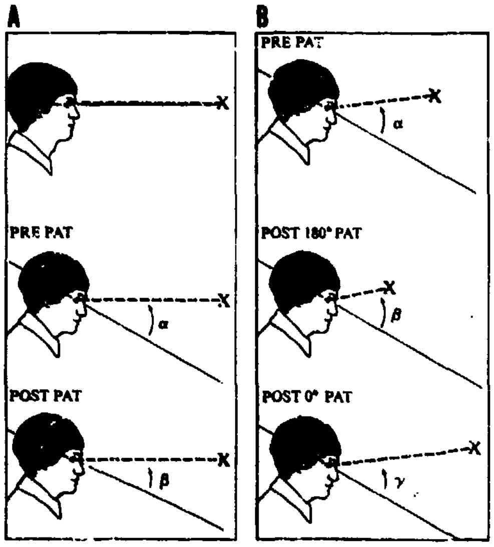

Fig. 1. 1-A: It is hypothesized that PAT training could result in reduced perceived pitch amplitude. If this is correct, smaller vertical eye movements would be required to maintain gaze on an imaginary floor-fixed target. 1-B: It is hypothesized that PAT training could result in a translational motion aftereffect and that 0° PAT training would result in backward translation during forward pitch while 180° PAT training would produce forward translation during forward pitch. The consequence of translational motion aftereffects would be decreased vertical eye movement amplitude following 0° PAT and increased amplitude after 180° PAT.

Figure 1-B illustrates hypothesized eye movement changes as a consequence of a translation aftereffect. If translational self-motion perception were increased following training, there would be no change in the subject's perception of tilt; rather, perceived distance to the imaginary target would be altered. The perceived distance to the imaginary target before training is indicated by the dotted line, A. Following a PAT training condition that correlates forward pitch with forward translation, the perceived distance, B, to the imaginary target would be decreased. An opposite effect should be associated with the condition where forward pitch is correlated with backward translation. Consequently, the amplitude of the vertical movement required to maintain gaze fixation would be increased or reduced, depending on the particular stimulus rearrangement.

Four experiments were undertaken to examine vertical eye movements, self-motion perception and motion sickness symptoms as a function of exposure to the sensory rearrangement produced by the PAT prototypes. The main question addressed in these studies was: do eye movements evoked by pitch head motion change relative to baseline as a consequence of exposure to the PAT stimulus rearrangement?

Experiment 1

This experiment examined the amplitude of vertical eye movements elicited by pitch stimulation following PAT training.

Method

Sixteen subjects from the Johnson Space Center Neurophysiology Laboratory subject pool completed this experiment. All had passed an Air Force Class III physical examination and none reported prior auditory or vestibular difficulties.

The protocol and general purpose of the experiment were explained to the subjects. They were also instructed about how to report self-motion perception and motion sickness symptoms in terms of the Pensacola diagnostic categories (6).

The MUS PAT prototype that has been described previously was used (1,6). The apparatus produced pitch head motion of +/- 12° around an axis located at the subject's larynx. The oscillation frequency of the pitch motion and the visual surround (box) was set to 0.25 Hz. Silver-silver chloride electrodes for recording vertical eye movements were located on the right supra- and infra-orbital ridges and on the right mastoid. The subject was seated in the apparatus with a large black collar to prevent downward vision and was secured by waist and head restraints. A large box with a random design and colored lights on the inside walls was placed over the seated subject, and the front wall of box translated away from the subject during forward pitch.

Amplified eye movement and pitch motion signals were digitized and stored using an LSI 11/23 computer. The signal was also displayed on an oscilloscope during the experiment. Vertical eye movements were sampled during pitch oscillation for 55 s under each of the following conditions: (a) a baseline condition without the box and while fixating on a floor-fixed stationary target; (b) a second baseline condition in darkness (wearing light-excluding goggles) while fixating on an imaginary image of the floor-fixed stationary target; (c) in the darkness after 15 m of PAT or NO-PAT exposure; and (d) in the darkness after an additional 15-m period of PAT or NO-PAT exposure. During both the PAT and NO-PAT conditions, the subjects were exposed to continuous sinusoidal pitch motion. Each recording was preceded by a 30-s stabilization period. Eye movement calibration was performed after each 55-s recording.

The experiment required two days for each subject. During one day the subject was exposed either to the PAT condition (box moving with respect to the subject to produce visual surround translation during pitch motion) or to the NO-PAT condition (box fixed to achieve a stationary visual surround relative to the subject). One-half of the subjects were exposed to the NO-PAT condition on their first day.

Motion sickness symptoms were checked each 15 m (5 m into each adaptation period) or as reported, and the experiment was terminated if the subject accumulated 7 or more points.

The subjects were asked to indicate whether they perceived their self motion to be primarily translation or primarily tilt and whether touching the walls of the box produced any changes in motion perception. They also were asked to do whatever was required to enhance the translational self-motion perception. Eye movements were monitored throughout the experiment to ensure subject understanding and cooperation. Also, the investigator talked with the subjects to maintain alertness.

Results and Discussion

Eye movement response power at the stimulus frequency was determined using Fourier analysis. The ratios of response power post-PAT compared to pre-PAT and post-NO-PAT compared to pre-NO-PAT were calculated for each subject; the results are illustrated in Fig. 2. Averaged across subjects, this ratio was 0.60 for the PAT condition and 1.02 for the NO-PAT condition. Using a Wilcoxon matched-pairs signed-ranks test, this difference is statistically significant ($T = 32$, $N = 16$, $p < 0.05$, one tail). These data indicate that eye movement gain is reduced following exposure to the PAT exposure as compared to the control condition.

Four subjects were unable to complete the experiment due to motion sickness.

Thirteen of the 16 subjects reported translation during PAT exposure. Of these, 7 reported that the translational self-motion was not perceived when their eye were closed. The sensation was often described as similar to moving on a skateboard back and forth across a small bump.

The prediction that eye movement gain would be reduced following PAT was supported. However, a one-tailed test was required to support this conclusion. The small differences obtained may have been a consequence of the fact that the visual surround was fixed with respect to the subject during the NO-PAT condition. In order to stabilize gaze, the subjects had to suppress vertical eye movements evoked by pitch motion during the NO-PAT exposure. Consequently, both the PAT and the NO-PAT conditions would tend to result in reduced eye movement gain.

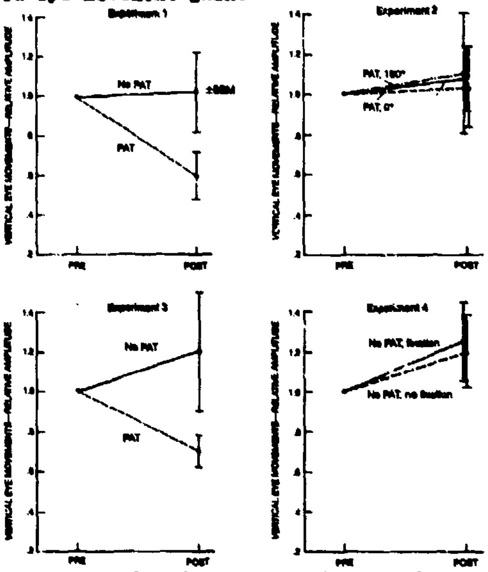

Fig. 2. Vertical eye movement amplitudes were smaller following PAT training using the MUS prototype (Experiments 1 and 3). No amplitude changes were observed following training using the DES prototype (Experiment 2). Eye movement amplitude was not affected by fixation instructions during a "control" condition (Experiment 4).

Experiment 2

Experiment 2 replicated Experiment 1 using a different trainer. Also, effects of the phase relationship between visual surround motion relative to the pitch motion were examined. It was predicted that vertical eye movement amplitude would be decreased following 0° PAT and increased following 180° PAT (see Fig. 1-B).

Method

Eleven subjects from the Wright-Patterson Armstrong Aerospace Medical Research Laboratory Acceleration Effects Panel completed this experiment. All had extensive prior experience in unusual acceleration environments and had passed an Air Force Class III physical examination. The instructions were the same as for Experiment 1.

The DES PAT prototype that has been described previously was used (7). It produced pitch head motion of +/- 12° at 0.25 Hz around the interaural axis. Eye movement recording was the same as for Experiment 1.

The experiment required 3 days for each subject. On one day the box (visual surround) was fixed relative to the subject (NO-PAT); on a second day the front wall of the box moved away from the subject during forward pitch (0° PAT); and on a third day the box moved toward the subject during forward pitch (180° PAT). The rest of the procedure was as in Experiment 1 except that no observations were performed with the subject fixating on a floor-fixed stationary target. The order of exposure conditions across subjects was counterbalanced and subjects were assigned randomly to the different orders.

Results and Discussion

Averaged across subjects, the ratios of eye movement response amplitude before and after exposure were 1.07 for NO-PAT, 1.03 for 0° PAT and 1.11 for 180° PAT (see Fig. 2). Using the Wilcoxon matched-pairs, signed-ranks test, these differences did not approach statistical significance (NO-PAT vs. 0° PAT: $T = 30.5$, $N = 11$, p = NS; NO-PAT vs. 180° PAT: T = 24.5, N = 11, p = NS; 0° PAT vs. 180° PAT: T = 20, N = 11, p = NS). Ocular response amplitude was not modified by the PAT training.

Exposure duration was truncated for two subjects due to motion sickness. Each was able to complete the experiment protocol using 20-m rather than 30-m exposure durations.

Nine of the subjects reported translational self-motion perception during PAT exposure. Of these, one experienced translation only during 180° PAT. One of the two subjects who did not report translation experienced significant motion sickness.

The results from Experiment 1 were not replicated by Experiment 2. Although excellent data were obtained, as judged by the coherence values, there were large differences across subjects. No trends in support of the hypotheses are apparent in the data.

The major difference between Experiments 1 and 2 that may account for the different results is the fact that both the subjects and the visual surround were enclosed in a cab in the DES apparatus. Consequently, the subjects were unable to practice fixating on a stationary, floor-fixed target in Experiment 2. Further, the visual surround was fixed with respect to the subject during NO-PAT exposure, as in Experiment 1. As suggested above, this would tend to reduce vertical eye movement gain.

Other differences between Experiments 1 and 2 that may account for the disparity in the results include the following: (a) The subjects in the Experiment 1 were naive concerning the hypothesis and basic simulation, whereas nearly all of the Experiment 2 subjects had participated in previous PAT studies and were partially familiar with the experimenter's expectations. (b) The MUS provides pitch around the subject's larynx while the DES pitch axis corresponds to the subjects's interaural axis.

Experiment 3

Experiment 3 replicated Experiment 1 except that the visual surround was removed during the control condition.

Method

Nineteen subjects from the Johnson Space Center Neurophysiology Laboratory subject pool completed this experiment. Instructions and apparatus were the same as in Experiment 1.

Eye movements and subjects' reports were recorded in the same manner as for Experiment 1. The only difference was that the box (visual surround) was removed during NO-PAT exposure.

Results and Discussion

Averaged across subjects, the ratios of eye movement response amplitude before and after exposure were 0.70 for the PAT condition and 1.20 for the NO/PAT condition (see Fig. 3). This difference is statistically significant ($T = 38.5$, $N = 19$, $p < 0.025$, two tails).

Four subjects experienced mild motion sickness symptoms during exposure to the PAT condition. Self-motion perception was a combination of tilt and translation with little pure translation reported.

These results show that eye movement gain changes can be produced by training in the MUS PAT prototype. Further, the size of the decrease was comparable in magnitude to that obtained in Experiment 1.

The differences between eye movement gains after the PAT and NO-PAT conditions in Experiment 3 were more consistent than those found in Experiment 1. This suggests that removing the box and allowing the subject to view the normal laboratory environment during NO-PAT exposure did enhance the difference between the PAT and NO-PAT conditions.

Experiment 4

Experiment 4 addressed the possibility that instructions regarding gaze fixation during the NO-PAT condition may have accounted for the results observed in Experiments 1 and 3.

Method

Ten subjects from the Johnson Space Center Neurophysiology Laboratory subject pool participated in this study; instructions and apparatus were the same as for Experiment 1.

The subjects were exposed on two successive days to two NO-PAT conditions. During one of these they were instructed to maintain fixation on a target light located 35 cm from their eyes. During the other NO-PAT condition, the subjects were instructed to look around the laboratory and not maintain fixation on any particular location. The box (visual surround) was not used in this experiment.

Results and Discussion

Eye movement amplitudes (a) after pitch exposure with target fixation relative to before exposure with target fixation and (b) after exposure without target fixation relative to before exposure without target fixation were calculated. Averaged across subjects, this ratio was 1.28 for pitch exposure with target fixation and 1.19 for exposure without target fixation (see Fig. 2). The difference between these ratios does not approach statistical significance (T = 23, N = 10, p NS).

No motion sickness symptoms were reported during this experiment. Self motion was not assessed.

Experiment 4 indicated that fixation on a target light during passive pitch under NO-PAT condition could not by itself account for the differences obtained in Experiments 1 and 3.

General Discussion

Experiments 1 and 3 support the view that PAT training prior to weightless spaceflight could teach astronauts to reinterpret signals from the otolith organs in a manner consistent with the OTTR model. In other words, training may facilitate a translation interpretation of the signals from these organs and suppress a tilt interpretation.

Several investigators have noted that relatively brief (about 30 m) exposure of animals to stimulus rearrangements results in eye movement gain changes. Of particular interest in this regard are the cross-VOR studies performed by Peterson and his colleagues (9). They reported gain changes in eye movements evoked by pitch in animals that had had their semicircular canals surgically plugged. This indicates that adaptive responses can be mediated principally by the otolith receptors.

While vertical eye movement gain was relatively readily altered in Experiments 1 and 3, no consistent phase shifts were obtained. This is in agreement with the report by Gonshor and Melvill Jones (10) that alteration of eye movement phase may require much longer exposure to stimulus rearrangement than does alteration of gain.

Two days of continuous exposure were required to elicit significant gain changes in the left-right reversing prism studies performed by Gonshor and Melvill Jones. This is in contrast to the relatively brief exposures in the studies reported here. The difference in the exposure time required to elicit a change may be related to the requirements of the stimulus rearrangement; the stimulus rearrangement associated with left-right reversal seems more demanding that that produced by the PAT trainer.

The data from these experiments suggest large differences between individuals. This has been observed in previous sensory-motor adaptation studies and has been attributed to a variety of factors including the ways in which different people ordinarily weight different spatial orientation cues (4).

PREFLIGHT ADAPTATION TRAINER DESIGNS

On the basis of the the sensory conflict approach to SMS, sensory compensation and the OTTR hypothesis, concepts for preflight adaptation apparatus and training procedures have been developed. Development of trainers to simulate the stimulus rearrangement of weightlessness can be approached in two ways: (a) graviceptor stabilisation to evoke sensory compensation and (b) graviceptor-visual rearrangement to evoke sensory reinterpretation.

Graviceptor stabilization: Although gravity cannot be eliminated on Earth, its contribution to spatial orientation in the simulated environment can be negated. This could be achieved by keeping the gravity vector constant with respect to the trainee as the trainee changes orientations within the simulated environment; perceived orientation changes could be produced through visual environment changes around a fixed trainee who could still engage in simulated motion. This would achieve graviceptor stabilization.

Graviceptor-visual rearrangement is based on the OTTR hypothesis. We suggest that an astronaut could be taught to reinterpret graviceptor output provoked by head tilts on Earth by providing movement of the visual surround appropriate to a weightless environment during those head tilts.

The proposed PAT simulations of weightlessness are based on an emerging understanding of the neural basis of spatial orientation. This view suggests that sensory and motor reactions associated with orientation and motion can be supported by appropriate visual input in the absence of normally congruent graviceptor cues from the otoliths and other organs (1).

Simulation of weightlessness could be accomplished with a set of four "part-task" PAT trainers. Three trainers would stabilise the otolith receptors with respect to gravity and one would use passive pitch or roll movement to simulate translation in weightlessness.

Concepts for the design of the part-task trainers are illustrated in Fig. 3. For the Mode A apparatus, the trainee's head would be held in the upright position to maintain graviceptor output constant. A visual scene representing the shuttle middeck or Spacelab would be presented to him via projectors and a screen or a helmet-mounted display. The scene would move in a manner dependent on attempted head movements by the trainee and/or inputs to hand controllers. The attempted head movements could be detected by force transducers in the head restraint. Signals from the force transducers or hand controllers could activate a robot arm (in a nearby mockup) which would carry an array of video cameras, and the visual scene recorded by the cameras would be seen by the trainee. Alternatively, a computer-generated imagery system could be used. In this apparatus, visual feedback would be appropriate for the commands from the hand controllers and the attempted head motions. However, gravity information transduced by the otolith and somatosensory receptors would not change, thereby achieving graviceptor stabilization.

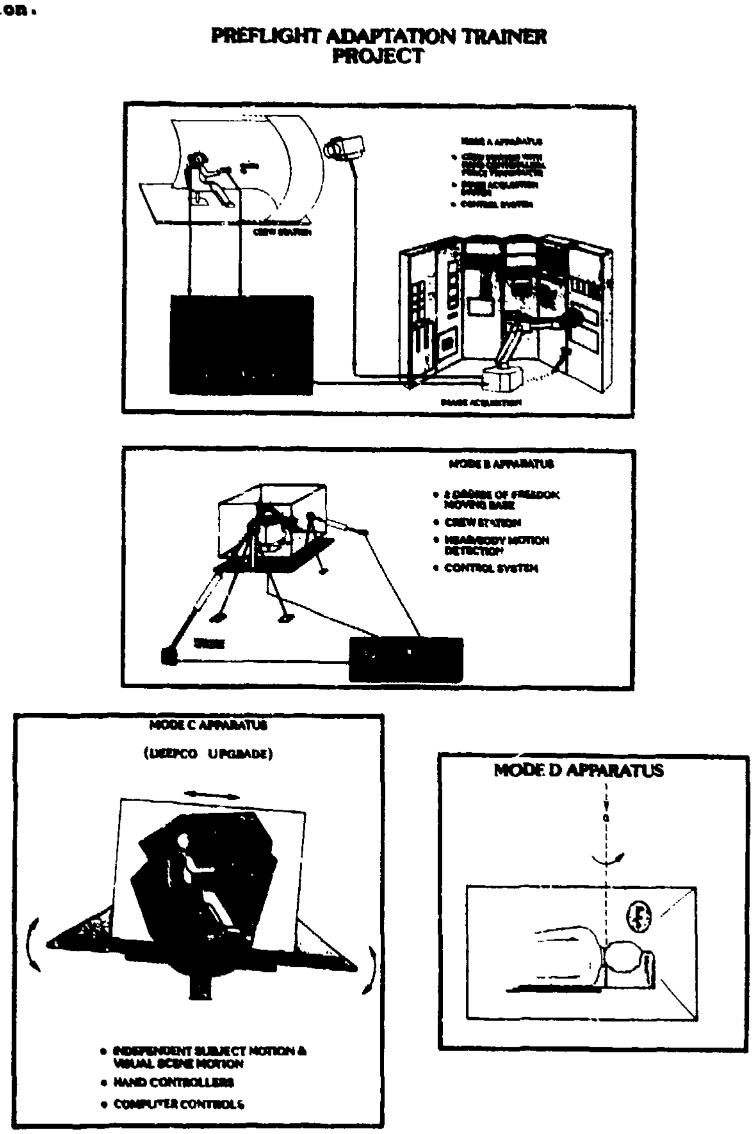

Fig. 3. Design concepts for four "part-task" preflight adaptation trainers. See text.

The Mode B apparatus could employ a two-degree-of-freedom moving base to stabilize the otolith receptors with respect to gravity during active head/body movement (pitch, roll and yaw) by the trainee. Both the trainee and the visual scene would be located on the moving base. The trainee's movements would be detected by a head tracker which would provide the input signals; the hydraulic actuators would move the base and the trainee's body so as to keep the trainee's head upright relative to gravity. Therefore, gravity signals from the otoliths would remain constant while visual and neck receptor feedback appropriate for the trainee's head and body motions would be provided by the apparatus.

In the Mode C apparatus, the trainee would be restrained on a one-degree-of-freedom moving base. Roll or pitch motion would be used to simulate an otolith receptor signal that would be elicited by translation in weightlessness, and the visual scene would translate with respect to the trainee. Therefore pitch or roll would be reinterpreted as translation by the trainee. This trainer derives from the OTTR model of sensory-motor adaptation to weightlessness.

In the Mode D trainer, the trainee would be restrained in a horizontal position and permitted to move his head only in a plane orthogonal to gravity (roll when supine and pitch when lying on side). The visual scene would be fixed with respect to the subject's body (only the subject's head moves); consequently, the visual feedback would be appropriate to the attempted head motion, as would the neck receptor and semicircular canal feedback. As with Modes A and B, the otolith signals would remain constant thereby achieving gravicceptor stabilization.

CONCLUSIONS

Relatively brief exposure to a stimulus rearrangement where a subject is moved passively in pitch and the visual surround translates with respect to him along his X body axis results in reduced vertical eye movement gain. This observation supports the view that apparatus and procedures can be developed to preadapt astronauts to the stimulus rearrangement associated with weightless spaceflight. Design concepts for four "part-task" preflight adaptation trainers have been developed.

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DISCUSSION

KUIPERS: Did astronauts who avoided head movements have prolonged adaptation time?

PARKER: The astronauts are aware that active head motions may result in disturbance. Nevertheless, their tasks require them to move about a good deal. What we see is people moving about fairly vigorously during the first few hours of flight, and then subsequently, as they begin to develop motion sickness, they remember, "I shouldn't have done that." Then they move around with the head almost fixed with respect to the body. Dr. Young might wish to comment on this.

YOUNG: I agree with that generalization, Don. Unfortunately, as yet we have been unable to limit or control the head movement activities in space missions. Consequently, a controlled, balanced, double-blind study of whether or not particular head movements are provocative has not been done as yet. We have the comments of the crew members who have been asked to make a sequence of stereotyped head movements, and as Dr. Parker said, they all have said that head movements tend to provoke motion sickness, and pitching head movements are the most serious. The point which all of us notice who've spent any time watching the live video of astronauts is that crew members who are suffering motion sickness symptoms (whether they tell us about them, at the time, or not) are very easy to recognise because they move about the space craft like a mummy, minimizing to the greatest extent possible not only head movements with respect to space but also head movements with respect to the body.

ROUND TABLE DISCUSSION

HOUK, MEETING CHAIRMAN: We have set up a mechanism to achieve some focus on information presented over the two technical days by having a round table discussion. It will only work if you, the audience, partipate and ask some of the questions I've overheard during breaks. Dr. Guedry is going to be our moderator, and he's accompanied by Drs. Casali, Kennedy, and Young of the United States, and Dr. Benson of the United Kingdom.

GUEDRY, MODERATOR: I've listed a series of points that seemed to me to be in need of more discussion. I'll read each point, give the panel members a chance to comment, and then we would like the audience to join in the discussion. Incidentally, the panel members have not had a chance to prepare their comments in advance. The points have been selected as the symposium progressed, and so the panel will be speaking extemporaneously. Point 1. A number of the symptoms that were described in various studies of simulator sickness are also common to many other conditions. For example, should a report of fatigue be recorded as a sign of simulator sickness, even though nausea, stomach awareness, or vomiting were never reported with this simulator? Alan, would you care to start?

BENSON: I'll begin mainly by saying that I think symptom ratings in terms of percentage come out rather too high if we include all the whole range of symptoms in post-exposure questionnaires, which include reports like fatigue, eye strain, and the like. Although these symptoms are associated with the exposure, they are not what I would call simulator sickness; i.e., patterns of symptoms which are associated with motion sickness. Bob Kennedy made the point in his overview speech that simulator sickness is really dealing with those signs and symptoms that are produced in the simulator, but not produced in real flight. Fatigue and postural instability have been included in the list of symptoms, but we don't really know in many cases the incidence of fatigue and postural instability following real flight.

KENNEDY: I'm probably not going to give answers - just more questions. For example, I'm not sure I know what should be done when a person has symptoms before they go in and no symptoms when they come out. (Additional comments by Kennedy were not clear in the audio-tape.) There is on record one simulator that was recorded by three different "experimenters." The first was a form sent out by the squadron to be filled out by all of the pilots after they had flown in simulators. Another was a form that was administered personally by the local flight surgeon who was himself a former helicopter pilot and had good relations with his squadron. Then there was a third survey conducted by the Navy - by the Naval Training Systems Center. The incidence in the first case was less than 12% as I recall. My recollection of the incidence, when the flight surgeon made the inquiries, was close to 80%. Incidence, as obtained from paper and pencil forms filled out by pilots as they came out, scored according to a criterion of "Did you have it when you came out?" and "Did you have it when you came in?", and subtraction of the second from the first was about 48%. So there are many ways to look at this problem, none of which is without some difficulty and without some shortcomings. (Kennedy was prepared to amplify his remarks with slides, but to conserve time for other speakers, the chairman intervened.)

CASALI: Let me just make one comment from an experimental standpoint rather than a survey standpoint because I think our perceptions are somewhat biased. We started with a simulator in our laboratory which is known not to induce symptoms, and we have data on that from about 1500 subjects. Our approach has been to progressively degrade different dynamic variables in that simulator and compare degraded conditions against control conditions. We then use measures, some of which are subjective, some of which are instrumented (that I discussed in my talk) and look for significant changes between the control conditions and the different degraded conditions and draw some conclusions. We still have the danger that Dr. Benson has alluded to - we don't know what happens in the actual vehicle to many of those measures. We have found our approach to be fairly useful from the standpoint of getting a statistical basis for our conclusions and also for developing predictive models.

GUEDRY: Does anyone from the audience have comments you would like to make on this point?

BILLINGS: In speaking of some of the physiological adaptations in space flight - and particularly of space motion sickness - I think we are gradually moving toward conceiving of this as a physiological rather than pathological response to a radically altered environment. I've been made progressively more uncomfortable here by the term, simulator sickness, for what to me sounds very much like a physiological adaptive response to some imperfections, inadequacies, insufficiencies, if you will, in our motion-based simulators. I think it's been mentioned already this week that perhaps one should consider the occurrence of these symptoms as indications of design defects in the simulator as, in fact, was done with one or two of the very early helicopter simulators. Whether it was simulator sickness or engineering sickness, everybody got it. I'm having increasing difficulty coming to grips with the concept that this is a sickness - a disease - as opposed to a physiological adaptation, i.e., an appropriate response of a normal individual to an abnormal environment. I don't know whether that's any help or not, but it's perhaps a slightly different way of thinking about the problem.

GOWER: I would agree with what Dr. Billings said, if we're to hang a title on what we are saying in terms of responses being abnormal or normal to an abnormal situation. Regardless of the name tag, if the end result is reduced performance or any other type of adverse effect, then it is a problem, regardless of what we call it. Whether we call it simulator-induced syndrome or simulator sickness or whatever, it still must be treated and continue to be studied. I would be more concerned with Dr. Guedry's second point for discussion. Is what we see in the simulator different from what we see in the aircraft? Furthermore, how long does the effect persist after the stimulator exposure, and what safety factors are involved with it?

FRANK: I agree with Dr. Billings in the sense that simulator sickness is not an illness but a natural reaction to sensory rearrangement. I agree with Dr. Billings in the sense that simulator sickness really means that the simulator is sick. (Dan Weintraub was the first to point this out, and he recommended the use of "simulator-induced syndrome.") However, there's an advantage to the term, simulator sickness, because as Dr. Gillingham has said, simulator sickness like motion sickness and seasickness is really an orientation sickness, if you will. Labeling something either as seasickness or motion sickness or carsickness or airsickness or simulator sickness serves to define the stimulus conditions under which that rearrangement took place. For this reason, the phrase, simulator-induced sickness, is of some benefit. It doesn't give you the specifics but at least it tells you the effects occurred in a simulator as opposed to a ship at sea or a hovercraft or whatever.

DOPPELT: I don't want to carry on the discussion ad libidum, but I would like to add also to Dr. Billings' comments and to some of the initial speakers. The name may have relevance perceptually to the operators in the field, but certainly we must have some reasonable taxonomy available so that one can approach the experiments and the results of those experiments in as rational a fashion as possible. As we have reviewed effects for the last two days, it's very hard to come to grips with what is simulator-induced in terms of the symptom or what is simulator-reproduced in terms of flight. Unless we get to the point of trying to understand these differences, as has been pointed out, we then indeed do a lot of lumping. The effects that have been described as lumped are obviously eye strain and fatigue. Anybody knows that when you design and develop a simulator, you try to cram as much training as you can in the shortest period of time. Ergo, you're going to induce some level of fatigue or eye strain which would be made worse, or better, depending upon the specific design of the system, the pressure on the crew, the schedule that's imposed, etc.; and that indeed may be a simulator-induced symptom, but it may be a positive one because it may replicate flight-induced fatigue. So I hope (from the operational R&D field) that we get to some sort of taxonomic understanding that allows us to categorize the research in a way that it can be better understood as it relates to both the design of the simulator for the purposes of relating to the flight employment and as well as to the physiological implications to individuals participating that may not relate to the air environment itself. I would propose that if we're to use the word, simulator-induced -- then perhaps we should also consider using "simulator-reproduced," which is really what you're after in certain of the symptoms. The word, sickness, I think, is a difficult one for us conceptually because I also believe that pathology is not involved, and I don't think air crew really feel it is proper to be called sick in simulator environments.

GUEDRY: We must move on to the next point which has already been alluded to by several participants including General Doppelt and Dr. Benson: Are effects during and after simulated flight also present after real flight? If so, then this may be one sign that the simulation is good. It would conceivably have some impact on down-time. In other words, if the simulator effects match effects during and after real flight, then there would appear to be no reason for down-times following simulated flight to exceed down-times after real flight. Certainly pilots fly more than one hop a day at times. I bring this in so that we will move on to other points before our time expires. However, there were several hands up so we will accept a few more comments.

LANDOLT: I want to advance the premise that the simulation-induced sickness in the papers presented here appears to be less a worry for the flight physician than it is a convenient means for exploring the conflict resolution hypothesis for motion sickness. I know with airsickness, which is a serious problem, that we can bring back 80% of the air crew with good drug therapy and autogenic procedures. Seasickness is a problem also, but the only time that I perceive that simulator-induced seasickness is a real problem is with helmet-mounted devices. I think that the real strength of the problems that we encounter here with simulator-induced sickness is that they are leading us to explore and resolve many of the different proprioceptive-visual-vestibular interactions that are inherent in conflict resolution.

YOUNG: Dr. Landolt's comments about the potential for the greater problem of simulator sickness with helmet-mounted devices is, I believe, correct. Inherently they should not necessarily produce adaptation sickness, as Dr. Billings refers to it. But they have the potential, when engineering is not done correctly, of creating greater sensory mismatch and consequently the potential for creating conditions that typically lead to motion sickness. I don't think a priori they are more dangerous, but they do have that potential, particularly as we develop head-slaved and later eye-slaved area-of-interest displays. The potential for temporal as well as spatial mismatches is a very severe one. And while I have the microphone, Mr. Chairman, let me just continue with "what's in a word." Certainly Dr. Billings is correct in that we should not be led into thinking that simulator sickness is a pathological condition. You (Dr. Billings) will recall, since you mentioned space sickness, that NASA has attempted to include space sickness under a rubric of what it called space adaptation syndrome, partly because sickness is bad and adaptation is good - and so maybe we could get people to admit that they had adapted even if they didn't get sick. However, Major Gower's point cannot be overlooked, viz., regardless of what you call it, if it interferes with training, it's bad. And to follow up LCDR Frank's comments about whether simulator sickness means that you get sick in the simulator, or the simulator is sick, I think that there is yet another risk and that is the danger of being sick of the simulator.

KENNEDY: There is some indication that people minimize their head movements in simulators to avoid some of the conditions of simulator sickness. If one does this in a simulator which is designed to have a wide field of view for the operator who should be making lots of head movements in combat, you may be teaching him habits that will be disadvantageous in combat as a result of his "adaptation" to the simulator. So I would agree with Dr. Landolt in a general way, but I think there are some occasions where adaptation in the simulator can bring on bad consequences.

BENSON: This is really one of the critical matters, isn't it? We know that the nervous system is highly plastic and we can adapt to the sensory rearrangement, whether severe or mild, of a particular simulator. Now you've mentioned adaptation in a behavioral sense as well, modifying motor activity, and here the question is whether exposure to the simulator is going to have a negative effect on subsequent exposure to real flight. It's that which I think is one of the crucial questions to which we should try to find answers.

CASALI: From a different research standpoint, we are concerned in our laboratory with sickness being a threat to the validity of our research simulator. We're concerned with the research results coming from the simulator, the behavioral data being influenced by sickness and also by inadequacies of the vehicle model or inadequacies of how cues are presented, i.e., invalid data which do not correlate with data from the actual vehicle. So not only is simulator sickness a problem from the training standpoint, but it's a problem from a research standpoint where we may only have a single person in a simulator one time, and there is no opportunity to adapt except within the course of that one run. In this context it is a threat to validity in transferring our results say, to vehicle handling characteristics.

PRICE: Before we get away from symptoms, I want to make a point. While there are many somewhat vague symptoms and perhaps common symptoms, a major concern in the operational community is the after-effect illusions. My concern is not only the distribution of various effects, but what is the time distribution? What is the time distribution after one simulator flight? After two? After a sustained period of simulator flight like for a week or ten days? This is relevant to saving travel money and/or putting simulators in too many locations. I think that's a real operational concern, and I'd hate to see us focus all of our time on more common effects that may be less significant.

KENNEDY: Based on a combination of some of the data that you people (U.S. Army personnel) collected and that we collected, out of 750 cases of people who were questioned about after-effects, about half had effects that outlasted the stimulus. This brings us down to about 300. Of the 300, about 40% said that they had effects that lasted more than an hour - or slightly more than 100 - and out of those about 30 had effects that lasted more than 6 hours. That's the first cut at the data that I mentioned. So in terms of effects that outlast the stimulus, by self-report, there were 30 out of 700 - maybe 5% - who said they had effects that are presumed to last 6 hours.

BENSON: Bob, do we ask the same question of people after real flight?

KENNEDY: No.

PRICE: We also had a group that flew (I believe that Major Gower reported) for a sustained period, yet we did not follow them long enough to assess the time distribution of symptoms, and that's what concerns me.

GUEDRY: I don't think we're going to answer your question any better than it's already been answered. Unless someone else wants to comment, we'll go on to the next point. It has been very common to say that it is the experienced pilot who is disturbed by simulator handling characteristics and simulator sickness, whereas the novice tends to be less disturbed. In this meeting we've had several papers that seemed to find little difference between the experienced pilot and the novice. May we consider this as the next point for discussion.

VIOLETTE: (In French) Technical difficulties prevented translation of tape recording.

YOUNG: The only comment I would make is that the experienced pilot has a certain expectation of sensory input, as you said, both motion and visual sensory input. When those are not met, that causes a more serious problem vis-a-vis the sensory conflict theory for the experienced pilot with his well-developed prediction than for the novice pilot with his lack of well-developed prediction. This is consistent with the older simulator sickness data going back to Miller and Goodson. Now finding that the novice pilots are also having difficulties may be related to the notion of knowing essentially what commands to apply in the simulator. The inexperienced pilot may, as you say, be producing rather more irregular and less tolerable acceleration than would the experienced pilot who is controlling the simulator in a manner closer to his control of the aircraft and therefore flying a smoother flight.

McCAULEY: I'd also like to comment that in Dr. Magee's paper, with the Canadian experiments, I think that using the term, novice, may not be quite correct. As I recall, the flight hour average of that group was about 1500 hours. Is that correct? So they were new to that particular aircraft, the C-130, but still I wouldn't call them novices.

BENSON: And again in the series that Chappelow reported, they were hardly homogenous groups of experienced and inexperienced pilots, and very few of them had experience in that particular kind of aircraft. So his data are not directly relevant to the classical concepts of effects of current experience in the aircraft. Certainly anecdotal experience from driving simulators which were taken around the country in the U.K. do fit with the classical concepts. It was the police driving instructors who came out pale and sweaty, whereas relatively young people who'd not done much driving had minimal symptoms. There is evidence in other situations where experienced people are at higher risk.

GUEDRY: To summarize, you feel that the novice-versus-experienced pilot difference does hold up, but perhaps I have referred to groups as being comprised of novices who were really not novices. Also, the novice may generate more provocative motions than the experienced pilot. Finally, some motion conditions are inherently provocative, and in such conditions true novices would be subject to motion sickness.

MAGEE: Some of the early work was based on the fact that instructors seemed more susceptible than the students, but they didn't have their hands on controls so that there was an active/passive distinction. They were off-axis in viewing perhaps, and maybe they were older and there were many confounding variables that entered in. I don't think that any real clear statements can be made at this point on the role of flight experience because there are so many other factors, such as instructors being more willing to report symptoms.

YOUNG: Of the other variables that you mentioned, I believe they go generally in the direction of supporting the notion that the experienced driver or pilot will be more susceptible. The original studies - the original reports from helicopter simulator sickness studies going back to the late 1950's were always with a pilot with his hands on the controls, i.e., an instructor flying the simulator as opposed to observing; otherwise, of course, the situation would be very different. Age, as we well know, tends to decrease our susceptibility to motion sickness in general (that's one of the good things about aging), so I doubt that age would be a factor in favor of increased susceptibility for instructor pilots.

KENNEDY: Except, age is likely to make you less perceptible and flexible and adaptable, and to the extent that that could play a role in how well you adapt to the simulator, age could work against you.

YOUNG: Were you not the same age as I, Dr. Kennedy, I would disagree with you strongly.

TECHNICAL EVALUATOR: Here it should be noted that differences in ages of various groups mentioned in this symposium were not very great, and "elderly" groups were not a consideration.

KENNEDY: There are two other issues: First, there are at least three sets of data that haven't been mentioned, one that was done several years ago for the Naval Training Systems Center - where there were experienced pilots that did have increased incidence, and then there are two other data sets that I had slides on and didn't get to show, where more experienced pilots tended to have slightly more incidence. Perhaps more important is a measurement issue. Virtually all of the distributions of flight times tend to be skewed and non-normal, where the mean and median do not exactly coincide. For this reason, ordinary statistics are difficult to use. Secondly, the criterion variable is almost always some kind of difference score or cumulative score. The criterion tends to have a restriction in range even with a 7-point scale where averages are running something like 2 or 3 or 1.

GUEDRY: I think we'll move on, and let's skip the fourth point and go to the fifth. There was a statement made by Dr. Mooij......

VIOLETTE: (In French) Translation not available due to technical difficulty with the tape recordings.

GUEDRY: I'll ask Dr. Young to answer because he is fluent in French and I was unable to hear the translator.

YOUNG: Briefly, the question refers to the fact that in making a turn - somebody running around a turn leans into the turn before he gets the vestibular stimulation. There is a lovely picture that many of you know by Dr. Fukuda of the bus driver and the bus passenger taken in Japan. You see the bus driver (or ticket taker) leaning into the turn and all the bus passengers leaning out away from the turn. Clearly the prediction of acceleration allows the experienced operator to set in a motor program to overcome responses prior to the sensory signals which the passengers are relying upon. I think that that applies precisely to an aspect of motion sickness, namely that the active person, the pilot in control, is unlikely to get sick whereas the passenger is likely to get sick. (Technical Evaluator: Reference to Fukuda is: Fukuda, T. Postural behavior and motion sickness. Acta Otolaryngol. (Stockholm), 1976, 81:237-241.)

GUEDRY: We are very near our closing time and only have time for one more point for consideration. Several speakers have suggested that as the fidelity of visual displays of the outside scene increases, simulator sickness increases. Are there comments from the panel or audience on this point?

BILLINGS: One very brief comment: Let us not confuse the size of our visual display systems with the fidelity of our visual systems. You know, the brighter they get, the worse they get. I think there will come some point at which we may well find some responses to certain distortions in these very rich, if not faithful, visual scenes; but what we've been talking about here, I believe, is the angular size of these visual images, not the fidelity of them.

KENNEDY: I think that the comment could be made more correct if one were to say in our quest for fidelity, as we get closer and closer to physical fidelity, the differences between inputs from different sensory systems may take on increasing importance. So I don't think that it is simply a fidelity issue, but as we get closer to fidelity, we may have tighter tolerances between two or more sensory systems.

YOUNG: By fidelity, I think most of us think of spatial fidelity, resolution, field of view, color, number of lines, etc., but we also should not forget temporal fidelity. Now in the presentations of Frank and Casali, they talk about asynchrony. I think that we must be very careful in considering the data which tell us about maximum asynchrony between motion and visual cues from the point of view of minimising symptoms of sickness. We should not neglect the total transport delay between controlled element movement and the movement of both the visual and the control motion. It does not take very much in terms of increased transport delay, of the order of 100 to 120 milliseconds, to convert a possibly stable vehicle to a marginally stable or unstable vehicle. Certainly from the point of view of fidelity in training, we would be doing a great disservice if, in an attempt to solve the simulator sickness problem, we ended up with control laws in the computer which made the simulator non-useful for training. I have been in a simulator which, through the addition of one more equation and one more equation, had transport delays approaching half a second, and it clearly was not flyable. So I don't think we want to be led into that trap on the delay side.

GUEDRY: It's time for closing. I have asked Larry to provide a summary of our round table discussion.

YOUNG: It's certainly difficult for me to try to summarize the summary. Let me only point out that the areas of simulator sickness are areas of legitimate concern. The notion that this is a malady, something pathological, or abnormal behavior, I think, has been thoroughly discredited, and I believe that the side discussion, which we can call "What's in a Name?" was useful in bringing out those points. The question of whether or not simulator sickness exists and is a threat to adequate simulation, again I think, has been thoroughly disposed of. It's real - you may quibble about the numbers, but there's no question that it poses a threat and is of concern not only in a military community but in the commercial community as well. In terms of a theoretical basis for it, all that I've heard tells us that it is consistent with the sensorimotor conflict theory, which is now generally deemed to underlie most kinds of motion sickness. The issues of what does one do, some of the kinds of things that I know Dr. Kennedy (I was privileged to serve on his panels down in Pensacola) has dealt with - what does one do to fix the system? I think there are still a number of important areas that have been and will continue to be explored. My feeling is that the greatest area for fruitful research at the moment is in the operational area; and that is, given the current situation concerning hardware, what does one do in terms of simulator utilization, appropriate curriculum design, and scheduling to maximize the return and minimize the risk?

GUEDRY: A comment that I should have made to close the Round Table Discussion, I will make now in my role as Technical Evaluator. I thank the Panel members, Drs. Benson, Casali, Kennedy, and Young for their willingness to serve as panelists without opportunity for advance preparation. They did an excellent job. I also thank the audience for their thoughtful contributions and vigorous participation.

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14. Abstract

These proceedings include seventeen papers, ensuing discussions of the papers, and a Round Table Discussion from the Symposium sponsored by the AGARD Aerospace Medical Panel, held in Brussels, Belgium, on September 28 to October 2, 1987.

The frequency of reports of undesirable effects associated with simulator training has increased as simulator usage has increased to offset the higher costs and risks of conducting training in the complex modern aircraft. Review of current and anticipated future trends in simulator design features suggests that additional problems will arise if research on the etiology of simulator-induced motion sickness and other unwanted simulator effects is insufficient to counteract problems before they arise. The objective of this symposium was to examine simulator-induced effects, their operational implications, and their etiology in order to develop ideas for reducing undesired effects. The papers in this symposium address present and anticipated trends in simulator design, a theoretical viewpoint underlying many of the studies of simulator effects, characteristics of simulators associated with undesired effects, surveys of simulator-induced effects, models for the design and evaluation of simulators, and perceptual and neurophysiological functions fundamental to the understanding of simulation. These papers and the accompanying discussion provide a summary of information obtained in recent years on simulation, and guidelines for direction of future research. Keywords'

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