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EMULATION OF SPACE MOTION SICKNESS (SMS) ON THE DYNAMIC ENVIRONMENT SIMULATOR CENTRIFUGE

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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Adaptation of the vestibular system, specifically, the otolith organs, to a non-terrestrial environment can result in space motion sickness-like symptoms when the human is re-introduced to the normal, 1G, terrestrial environment. This premise was investigated by exposing nine subjects to 90 minutes of sustained 2G acceleration in a human centrifuge and then observing and evaluating them at 1G. Five of the subjects developed slight SMS symptoms, three developed moderate, and one developed frank sickness. Postural instabilities in two of the most affected subjects were also observed using the Equitest System post exposure. Long duration exposure to a non-terrestrial G(2G) appears to be a potential means for developing SMS-like symptoms in a ground-based human centrifuge.

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PREFACE

This report documents a series of experiments conducted under Project/Task/Workunit ILIRBB16 entitled "Space Adaptation Syndrome Emulation on the Dynamic Environment Simulator". The research was conducted in the Combined Stress Branch (AL/CFBS), Biodynamics and Biocommunications Division, Crew Systems Directorate, Armstrong Laboratory, Wright-Patterson AFB, OH. The research was funded by a 1991 In-house Laboratory Idependent Research (ILIR) grant. Dr. William Albery was the Principal Investigator.

The authors wish to extend their appreciation to Mr. Thomas Hundt (Systems Research Laboratories, Inc.) for his timely response to a variety of programming needs and to Deepa Naishadham (Logicon Technical Services, Inc.) for her analysis efforts. Mr. Dick Crosbie is recognized for his original suggestion to investigate the SMS-like symptoms he observed in Carl Clark on the Navy's centrifuge over 30 years ago after Clark experienced 2G for 24 hours. It was Dick Crosbie who inspired this research on the centrifuge. Dr. Bill Chelen of the Air Force Institute of Technology (AFIT) is recognized for his collaboration on the original proposal, protocol, and test plan. In addition, the authors wish to acknowledge the contributions of the entire Systems Research Laboratories operations and maintenance crew including Mr. Steve Bolia, Mr. William Gruesbeck, Mr. Greg Bathgate, Mr. Marvin Roarke, and Mr. Donald McCollor. Finally, we thank Dr. Steve Popper, Dr. George Potor, Dr. Andrew Tong, SSgt Rudolf Cartwright, MSgt Robert Raymond, SSgt Mark Stevens, SSgt Jim Swinhart, and Mr. John Frazier, all of AL/CFBS, for their participation.

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INTRODUCTION

Space Motion Sickness (SMS) continues to be the operationally most significant biomedical problem during current Space Shuttle missions. Despite recent attempts to alleviate the occurrences, the condition continues to affect approximately two-thirds of all Shuttle crewmembers in some manner, with a great deal of variation in the extent and duration of the symptoms (Davis et al., 1988). Its impact is profound, as many mission objectives are often compromised or scheduled several days into the flight in order to reduce the influence of SMS on the effectiveness of the crew (Davis and Beck, 1990). There is yet no accurate way of predicting individual susceptibility or reliably preventing the variety of symptoms. It is believed that SMS will also be a problem for the crew of hypersonic vehicles such as the National Aerospace Plane (NASP), as they will be experiencing similar transitions from macro to microgravity.

Recent studies, some involving former Spacelab astronauts, have shown that prolonged exposure to hypergravity environments (greater than 1 G in either the x or z axes, i.e., chest-to-back or head-to toe) can result in symptoms resembling those of SMS when the individuals are re-exposed to earth-normal 1 Gz (Clark, 1960; Ockels, 1989; Bles et al., 1989, Ockels et al., 1990). It is believed that if the exposure is of sufficient duration, sensory and motor adaptation take place to a degree such that re-exposure to 1 Gz simulates the transition from 1 Gz to 0 Gz, or microgravity, and the symptoms associated with SMS can be elicited. If this is in fact the case, the potential exists for using long duration centrifugation as a platform from which to research the various theories surrounding the etiology of SMS and to provide a simulation and training opportunity as well as prophylaxis.

NASA Data Regarding SMS Incidence

In an attempt to quantify the incidence of SMS during Shuttle missions, NASA has conducted several surveys and compiled an extensive database to investigate the preponderance of SMS and its symptoms among Shuttle astronauts. Using a grading criterion developed at the Space Biological Research Institute at the Johnson Space Center, NASA categorizes the SMS symptomology experienced by individuals into one of four levels: severe, moderate, mild, or none, based on the number and severity of the symptoms encountered. Severe SMS is defined as the case in which there exists several symptoms of a relatively persistent nature. These include, but are not limited to, loss of appetite, malaise, lethargy, and a strong desire to keep the head very still. It also includes more than two episodes of emesis and significant performance decrement for up to 72 hours. Moderate levels of SMS are characterized by NASA as including those symptoms listed above with the addition of epigastric discomfort. Moderate SMS involves no more than two episodes of vomiting and minimal operational impact, with the symptoms resolving in less than 72 hours. Mild SMS is characterized by one or more of the aforementioned symptoms of a mild and transient nature and/or one episode of retching or vomiting, with no operational impact. Mild SMS is resolved in 36 to 48 hours. Finally, cases consisting of only a mild, transient headache or loss of appetite, or no symptoms at all are considered as asymptomatic. NASA researchers have found that through 34 missions (STS-1 through STS-34), 67% of Shuttle crewmembers experienced some degree of SMS during their first mission. Of those astronauts, 48% scored in the mild category, 34% scored moderate, and 17% experienced severe levels of SMS (Davis and Beck, 1990).

Since several Shuttle astronauts have participated in more than one Shuttle mission, reoccurrence of SMS symptoms within subjects has been examined. Since STS-26 (Challenger), 26 Shuttle crewmembers have been involved in subsequent missions. A total of twelve of these 26 crewmembers (46%) experienced SMS symptoms. Of these 26, 15 reported having no change in their symptomology, while nine felt their SMS experience had improved. Two reported having worse symptoms in subsequent missions. SMS incidence among "experienced" crew (those flying subsequent missions) was not statistically different from the incidence among first flight crewmembers (Davis and Beck, 1990).

NASA has also examined several biographical variables for differences in SMS occurrence. They have concluded that neither age nor sex co-vary in any way with the incidence of SMS. However, a significant difference ($p<.05$) was discovered among career and noncareer fliers. NASA defined career astronauts to be pilots or mission specialists who are NASA employees, trained at Johnson Space Center, and veterans of more than one flight. Noncareer astronauts are defined primarily as payload specialists and first time Shuttle fliers (Davis and Beck, 1990).

As yet, there is no reliable way to prevent SMS. Despite recent attempts to alleviate the condition, most notably, the use of a launch and entry suit, a "cure" remains at large. Drug treatment techniques, including oral and injected Scop/Dex and, more recently, Phenergan, both injected and suppository, have resulted in limited success, often only delaying the onset of the symptoms (Davis and Beck, 1990).

Background and Relevance

Prior attempts to predict or simulate an SMS experience using ground based simulators or parabolic flight have failed to reliably identify susceptible individuals or provide successful countermeasures (Parker and Parker, 1990; Lin and Reshke, 1987; Miller et al., 1969; Oman et al., 1984; Reshke et al., 1984).

Although there have been studies in which correlations between the incidence of motion sickness and selective predictors have been statistically significant (questionnaires, psychodynamic and personality traits, vestibular function tests, and the application of nauseogenic stimulation), they are of low magnitude and of little practical purpose in establishing predictive susceptibility or causality (Reshke et al., 1984). Additionally, although the symptoms are rather similar to earthbound motion sickness, no correlation has been found between individual susceptibility to motion sickness provocation tests on earth and susceptibility to SMS (Reshke, et al., 1984). Since SMS has proved to be so costly to Shuttle missions, often affecting astronauts for two to three days of a week long mission, fundamental research needs to continue. The absence of SMS simulation and training capabilities necessitates the investigation of alternative techniques for producing the experience of SMS, allowing for further research into the etiology of the condition and identifying reliable methods for its prevention.

There is intriguing evidence that prolonged application of a hypergravitational field and subsequent reintroduction to earth-normal 1 Gz produces symptoms very similar to those associated with SMS (Clark, 1960; Ockels, 1989; Bles et al., 1989; Ockels et al., 1990). Three Spacelab D-1 scientists were exposed to a one and one half hour 3 G centrifuge run in the supine position, resulting in a linear 3 G acceleration in the x-direction, that is, from chest-to-back. They used their space experience to evaluate their readaptation to earth-normal gravity and compared their observations with their SMS experience (Ockels et al., 1989). After the centrifuge runs, Ockels et al. report that the vestibular/visual system appeared to have been modified in a specific and repeatable manner. During the readaptation period, which took at least six hours, Ockels et al. discovered a striking similarity to the astronauts' experience with adaptation to weightlessness in space and the onset of SMS-like symptoms. Similarly, this phenomenon had been observed in one subject following a 24 hour centrifuge exposure of 2 Gz (Clark, 1960).

A BRIEF REVIEW OF DOMINANT THEORIES REGARDING THE ETIOLOGY OF SPACE MOTION SICKNESS

Sensory Conflict Theory

The most widely known theory of motion sickness (and SMS) is based on the concept of sensory conflict (Oman, 1982; Reason, 1978). In various forms, this theory of motion sickness has been prominent for decades, and recently has been extended to the phenomena of SMS (Daunton, 1982; Oman, 1982; Parker and Parker, 1990). Sensory conflict theory considers motion sickness to be a consequence of "incongruities" among the spatial senses, i.e., the organs of balance, the eyes, and the nonvestibular position senses of the joints, muscles, and tendons (McCormick and Sanders, 1982). This theory of motion (and space) sickness relies on expectations of past experience; various degrees of symptoms will exist if the incongruities among the senses are incompatible with those expectations.

Three forms of sensory conflict are believed to exist: input conflict, output conflict, and expectancy violation. Input conflict refers to conflict arising between sensory inputs, output conflict refers to conflict between nervous system afferents, and expectancy violation refers to conflict arising between afferents and expectations. Implicit in all these forms of conflict is the assumption that the sensory data are redundant regarding the state of the organism relative to the environment. Additionally, each of these theories necessarily entail some expectancy violation, as differences among sensory inputs (input conflict) and differences among sensory transfer characteristics (output conflict) can only "conflict" if one assumes some standard or privileged sensory modality (Stoffregen and Riccio, 1991).

The otolith tilt reinterpretation theory

The "tilt-translation reinterpretation" hypothesis (Young et al., 1984) and the "otolith tilt-translation reinterpretation" hypothesis (Parker et al., 1985) have been proposed as specific examples of the sensory conflict theory applied in the context of space motion sickness. This theory states that the misinterpretation of otolith signals leads to a conflict between motion and expected stimulation resulting in the onset of SMS symptoms. The origin of this misinterpretation is found when one considers that in a weightless environment, the otoliths are stimulated by translations of the head and not by tilts of the head, as is the case in a gravitational field. Thus, otolith signals generated by head rotations (shown to be nauseogenic in a weightless environment) are incompatible when compared to the information from other sensory modalities. Observations of astronauts in microgravity and immediate post-flight would indicate that an adaptation takes place such that a reinterpretation regarding these signals takes place (Griffin, 1990). Before and during this adaptation, astronauts receive conflicting information regarding their orientation and may be susceptible to SMS.

The otolith asymmetry theory

There is evidence that individual asymmetry of otolith function, as evidenced by asymmetric ocular counterrolling, has predictive value for motion sickness susceptibility during parabolic flight (Lackner et al., 1987; Diamond and Markham, 1988). This asymmetry, hypothesized by von Baumgarten and Thumler (1979) would provide a plausible explanation, due to the absence of a background gravitational force, for the illusions and sensory mismatch (Reason and Brand, 1975) of SMS.

The hypothesis of asymmetric otolith function was proposed earlier this century (von Bechterew, 1909) and revived some 70 years later (von Baumgarten and Thumler, 1979). The hypothesis is that in some individuals, the bilateral system of gravity receptors may have a long-standing, possibly congenital anatomical or physiological asymmetry between the two sides (Diamond and Markham, 1991). Such anatomical asymmetry has been clearly demonstrated in rat utricles (Ross, 1987; Ross, et al., 1986). In a certain number of humans, a similar imbalance may become very well compensated in the usual 1 G environment on earth, but when an individual is exposed to a novel, non-terrestrial environment, such as the hypogravity of spaceflight, the prior compensatory equilibrium may be disturbed. This hypothesized failure of compensation might be expected to cause unstable ocular torsion and be associated with the experience of SMS symptoms.

An Ecological Theory of Space Motion Sickness

An alternative theory regarding the etiology of SMS (and motion sickness in general) has its foundations in the ecological approach of J.J. Gibson (1966, 1986). The fundamental tenet of this approach espouses that the patterns of sensory stimulation (nauseogenic or otherwise) are not independent of the human-environment interaction but are determined by corresponding changes in the constraints operating on the control of action (Gibson 1966, 1986). That is, the behavior of the individual affects his relationship to the environment, and his relationship to the environment affects his behavior. The various perceptual systems collectively provide information regarding this relationship to the individual. Additionally, the Ecological Theory proposes that the control of action is influenced by the goals of the individual. Simply put, the Ecological Theory states that the goal-directed activity of an individual determines his relationship to the environment and information regarding that relationship is provided via complementary, multi-modal sensory stimulation (Gibson, 1966). This theory provides an alternative approach to studying not only space and motion sickness phenomena, but perception and action in general.

The foundation of applying this theory to space and motion sickness rests in determining the goals, and therefore, the behavior of the individual. It is assumed that a primary goal of any creature in any environment is to control its position and orientation (postural stability) with respect to that particular environment. This allows the accomplishment of secondary goals by optimizing the potential of the various sensory and motor systems. A broad range of situations exist over which the occurrence of motion sickness (or SMS) is related to factors that should influence postural stability: standing on a heaving ship, enjoying fairground rides, and accomplishing various tasks in weightlessness. This allows a logical link between motion sickness (and SMS) and postural stability. Thus, in the context of SMS, provocative situations may be characterized by novel demands on the control of action (posture) as well as by novel patterns of stimulation (Riccio and Stoffregen, 1991). The specific hypothesis is that humans become sick in situations in which they do not possess (or have not yet learned) strategies that are effective for the maintenance of postural stability, as is often the case in a weightless environment (Riccio and Stoffregen, 1991).

Motion sickness has been conspicuous in orbital flight, that is, weightlessness. In weightlessness the body is not subjected to externally imposed motions. This has led some researchers to question whether orbital symptoms reflect true motion sickness. It could be that orbital symptoms stem from postural instabilities, and therefore, do not reflect true motion sickness. It is also possible that the nauseogenic properties of weightlessness could be traced to the dynamics of the weightless state. In weightlessness, there are no sustained force relations between humans and surfaces, as there are in a gravitational field. This means that control of posture (and behavior in general) will be qualitatively different in weightlessness from what it is under terrestrial conditions. On earth, self-generated forces on body segments are resisted by the surface of support. In space, these same forces are not resisted. They tend to propagate the body until they are damped by muscle tension and/or joint viscosity. Because of this, postural movements that are stabilizing on earth are actually destabilizing in space. It is well known that in space even a simple head turn can result in motion of the entire body. For unadapted fliers, these body motions will be uncontrolled, or unstable. An immediate means for coping with this is simply to reduce the amount of motion which has been repeatedly observable in astronauts. Re-establishing the stability of motion will depend on the development of qualitatively different control strategies: the grossest example being that in weightlessness, body posture and orientation often is accomplished with the hands rather than the feet.

METHODS

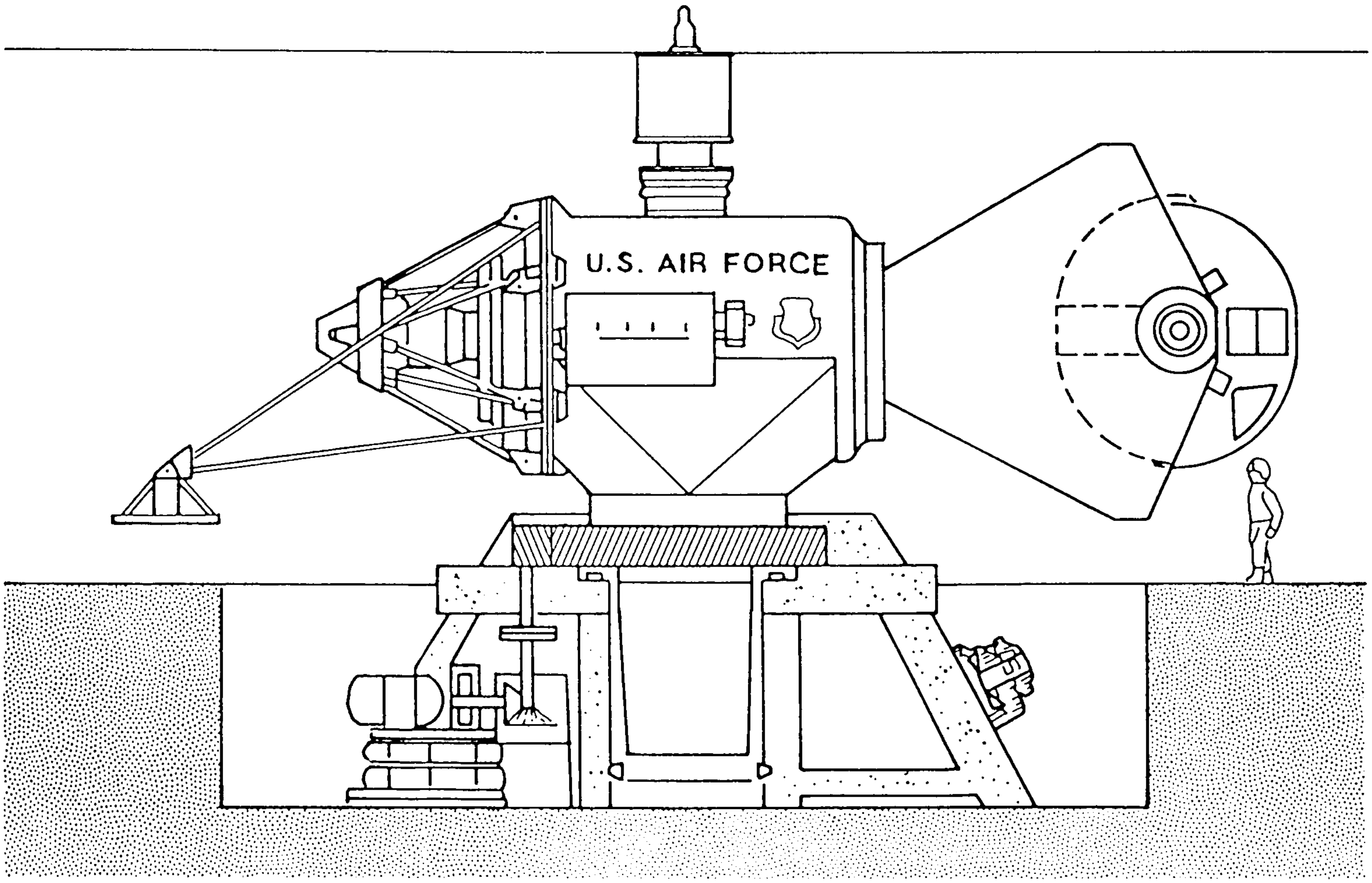
The primary hypothesis explored in this study was that centrifugation to an adequate level for a significant period of time should result in sufficient sensory-motor adaptation (otolith organs) such that reintroduction to earth-normal 1 Gz will simulate the transition from 1 Gz to weightlessness and result in the exhibition of SMS symptoms in human subjects. Several secondary hypotheses were investigated and reported in other papers. The secondary hypothesis examined in this paper is that the incidence of SMS is correlated with postural instabilities measured during readaptation to earth-normal 1 Gz implicating prolonged postural instability as a causal factor in the etiology of SMS. These hypotheses were investigated according to the following general method.

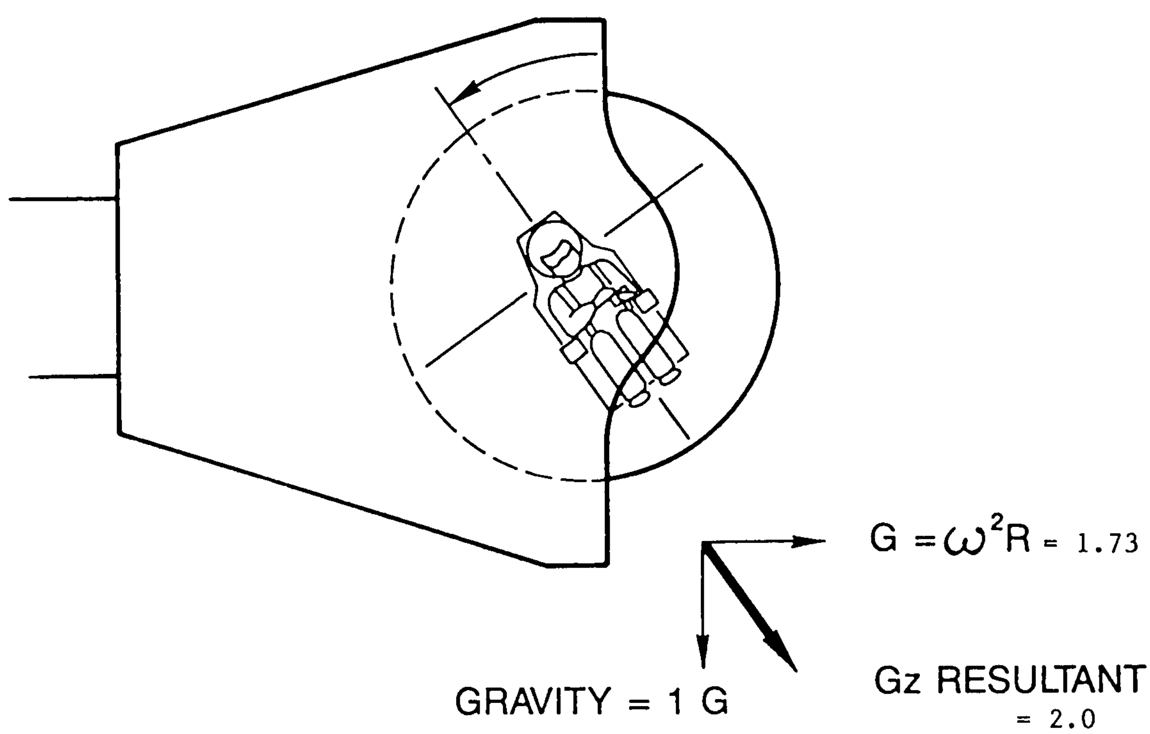
The subjects' involvement began with a postural stability assessment accomplished in advance of any centrifugation to establish normal, baseline performance in a variety of postural recovery and maintenance situations. These tests and the apparatus with which they were conducted will be described in detail below. Additionally, subjects completed a standardized motion sickness history questionnaire detailing any previous motion sickness experiences. Having displayed no postural control abnormalities and minimal predisposition to motion sickness, the subjects were then scheduled for two centrifugations separated by no less than one week. The first exposure addressed issues specific to the proposed National Aerospace Plane (NASP) flight profile and lasted 40 minutes. This research is detailed in a separate report (McCloskey et al., 1992). The second exposure was 90 minutes in duration. Subjects were instructed to sit as still as possible (to minimize potentially confounding Coriolis stimulation) and listen to music or view a movie of their choosing. Immediately after each of the centrifugations, the subjects were re-evaluated on the postural stability assessment apparatus and responded to a standardized motion sickness symptom checklist. Each subject then underwent a medical evaluation and was detained for observation until the attending physical determined they were fit for release. This resulted in three postural stability assessments: baseline, post 40 minutes, and post 90 minutes, to be compared with one another.

Equipment

The primary piece of equipment was the Dynamic Environment Simulator (DES), a three axes, 19 foot radius, man-rated centrifuge located at the Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio (Figure 1). The Gz was imposed by the rotation of the DES and "auto-vectoring" of the cab such that the resultant 2 G vector acted through the saggital plane of the subject seated in the cab (i.e., perpendicular to the floor of the cab). Subjects were seated in a F-16-like 30 degree tilt back seat and

• THE DYNAMIC ENVIRONMENT SIMULATOR (DES) CENTRIFUGE:





restrained with a five point harness. No additional G protection was required and communication was provided with a headset.

The second major piece of equipment used in this experiment was a NeuroCom EquiTest System, used to take the postural stability data (Figure 2). The EquiTest System consists of a dual force-plate capable of both forward and backward translations accomplished by servomotors. The servomotors are also capable of rotating the platform in the pitch axis, that is, toes up and toes down. Five force transducers under the forceplate measure vertical and horizontal forces produced by the subject's feet on the surface. Four of the five transducers are oriented so as to be sensitive to vertical forces. They are distributed in a square pattern and are identified as left front (lf), right front (rf), left rear (lr) and right rear (rr). Only one transducer collects shear (horizontal) force data and its location is between the two forceplates. The force data are collected and stored on a computer (an IBM 486 XT). Additionally, the system has a three-sided visual surround that can be sway referenced, thereby minimizing visual orientation cues. The platform can also be sway referenced, which minimizes sway information obtained from the ankle joint and associated musculature.

Subjects

The subjects in this study were all members of the Armstrong Laboratory Sustained Acceleration Panel. A total of eleven subjects (eight male, three female) participated in at least some portion of the experiment. Due to the limited availability of both the centrifuge and subjects, only six subjects (four male, two female) were able to complete both exposures. Of the remaining subjects, three males participated in the 90 minute run only and one male and one female each ran in the 40 minute condition only. Informed consent for this study was obtained from all 11 subjects. Nine subjects completed the 90 minute exposure.

Experimental Technique

The experimental technique employed in this study was a very simple before-after quasi-experimental design. A balanced, well controlled study with an appropriate number of subjects was not possible in the short time the centrifuge was available. Therefore, this work should be considered as a pilot study and occurred as follows. Subjects first performed in a baseline postural stability assessment at some time before the first centrifugation. Next, the subjects were subjected to a 2 Gz exposure for 40 minutes during which they accomplished NASP related tasks. Immediately following the exposure, the subjects were transported via wheelchair to the EquiTest System for post run postural stability evaluation. During transport, subjects reported their motion sickness symptoms as prompted from a questionnaire. All EquiTest evaluations were identical and proceeded as follows.

Neuro Com EquiTest System

Subjects stood on the forceplate encompassed by the visual surround (Figure 2). In one set of tests, the movement coordination tests, the forceplate was perturbed with known displacements and velocities and the ground reaction forces associated with recovery were recorded. These recordings were displayed with the appropriate biographical norms allowing an assessment of reflex recovery mechanisms. Reaction time, strength and symmetry of response, and adaptation scores were derived in the system software and displayed. Additionally, a strategy score, which reflects the relative amount of ankle and hip joint activity during recovery, was derived from the ground reaction forces and displayed.

In the second set of tests, the sensory organization tests, the subjects were instructed to stand as still as possible for approximately 20 seconds in a variety of conditions. These conditions were designed to minimize one or more orientation sensory modalities and measure the effect on postural stability. An equilibrium score as well as a strategy score, similar to the one calculated during the motor coordination tests, were calculated and displayed.

A minimum of one week necessarily passed between the first 40 minute centrifugation and the second exposure. The second exposure was also to 2 Gz but was 90 minutes in duration. Again, immediately following the exposure, the subject was wheeled to the EquiTest System for another post run postural stability assessment, which proceeded as described above.

Data Collection

The type of data collected was determined by both the primary and secondary objectives of the study: 1) Can long duration centrifugation and subsequent reintroduction to earth-normal 1 Gz simulate the transition to weightlessness and result in the symptoms associated with SMS?, and 2) Are there any postural effects (instabilities) that correlate with the incidence of these symptoms?

To answer the first question, several standardized questionnaires were administered. The first, a motion sickness history assessment, was used to determine an individual's predisposition to motion sickness (Appendix A). All the subjects used in this study were determined to be either minimally or moderately susceptible to motion sickness resulting from routine life events. The same questionnaire also detailed the severity and longevity of any previous motion sickness experience, to be used as a comparator in their post-centrifugation experience. As stated previously, no subject was exceptionally predisposed to motion sickness. In fact, most of the subjects used in this study were minimally susceptible.

Another questionnaire, the physiological status and symptom checklist, was administered prior to each of the two centrifugations (Appendix B). This survey assessed the subject's recent and current state of health to ensure that any post-centrifugation symptoms were not a result of some pre-existing condition. This questionnaire also contained a symptom checklist to be compared with the same symptom checklist administered immediately following the long duration G exposure. This allowed an assessment of any change in the condition of the participant.

Finally, the most relevant part of the physiological status and symptom checklist, the Graybiel Motion Sickness Scale, was administered immediately following each centrifugation (Appendix C). This scale, currently used by NASA, cataloged the number and severity of motion sickness symptoms allowing the assignment of an SMS experience score. These scores were then used to categorize a subject's SMS experience into one of several categories developed by Graybiel: slight malaise, moderate malaise B, moderate malaise A (A being more severe than B), severe malaise, and frank sickness.

These questionnaires determined whether or not long duration centrifugation could be used to simulate the evolution of SMS. The rest of the data collected were with respect to the secondary objective of the study: if this simulation was effective in eliciting SMS-like symptoms, was there any evidence of an accompanying postural condition that could possibly be associated with the incidence of the symptoms? Toward that end, the EquiTest System data were evaluated. The following describes those data taken from the EquiTest.

As stated earlier, the EquiTest force platform records ground reaction forces caused by postural recovery and maintenance via force transducers. Those signals are sent to the computer for conversion and processing. The EquiTest software, developed at NeuroCom International, Inc., carries out a variety of analyses based on a simplified yet suitable model of human posture. Details regarding this model and the calculation techniques which provide the scores on various postural stability measures can be found in the EquiTest User's Guide and will not be discussed in this report. Suffice it to say that the algorithms used are more than adequate at differentiating between healthy and impaired individuals. The various measures that these algorithms produce and their intended application, however, are described in the following paragraphs.

Recall that the EquiTest System performed two sets of tests; the motor coordination tests and the sensory organization tests. The motor coordination test set consisted of a series of perturbations (forceplate translations) and subsequent recordings of the forces on the platform associated with the subject's recovery.

There were six different types of perturbations accomplished by the forceplate: small, medium, and large forward translations, and small, medium, and large backward translations. The actual size (length) of the displacement was scaled to subject height to provide approximately the same size disturbance to each subject. The force recordings were 2.5 seconds long, beginning one half second before the translation, and continuing through the force-plate translation and recovery period. The measures derived from the force transducer signals and the human posture model reflected the characteristics of the recovery.

One measure provided by the motor coordination tests was response latency, which was calculated individually for both the right and left platform plates (right and left feet). A change in this measure after prolonged 2 Gz centrifugation might indicate that the proposed sensory-motor adaptation had taken place and that the responses to perturbations had been re-scaled to the balance dynamics associated with 2 Gz. One would expect, then, that upon reintroduction to 1 Gz, the response latencies would be inappropriately brief. This prediction is consistent with the hypothesis that prolonged postural instability is a causal factor in the etiology of SMS. Control behaviors such as this that are appropriate in a 2 Gz environment would be inappropriate in a 1 Gz environment and may lead to postural instabilities. If the proposed adaptation to 2 Gz persists, it is likely that the inappropriate behavior will continue during readaptation to 1 Gz, potentially leading to prolonged instabilities sufficient to produce SMS symptoms.

The other measure of potential interest provided by the motor coordination tests was a strategy score that reflected the relative amount of ankle and hip activity during recovery. Activity at these joints results in different ground reaction forces. Activity at the ankle joint exerts torque on the platform surface, whereas hip activity results in shear on the platform. The strategy score reflected the relative amounts of torque and shear forces exerted on the platform, and therefore, the relative amounts of activity at these joints. If one assumes that a hip strategy for balance is more robust in terms of recovery from a perturbation (as is widely accepted), one would expect more hip activity in demanding balance situations. Postural maintenance would be more difficult at 2 Gz than at 1 Gz simply due to the dynamics of balance associated with each of these environments. If sufficient sensory-motor adaptation had taken place during the 2 Gz exposure, one would expect to see more hip activity in response to perturbations immediately upon re-introduction to 1 Gz. Again, this is consistent with the proposed postural stability hypothesis regarding motion sickness. The strategies suitable for 2 Gz may be destabilizing at 1 Gz. If this condition persists for some time, it is predicted that the symptoms of SMS would ensue.

To parallel these concepts to the incidence of SMS, it can be said that control behaviors that are appropriate for orienting and balancing on earth are inappropriate in the weightless environment. Humans are accustomed (adapted) to the fact that, while in the earth's gravitational field, forces exerted on surfaces are resisted. These forces are used to maintain balance, locomote, and generally control position and orientation. In space, these same forces will tend to send one drifting through the capsule. Even something as simple as a head turn can result in torso counter rotation in the weightless environment. These unresisted forces can be destabilizing with respect to the desired position and orientation of an individual, and if prolonged, could result in the development of SMS symptoms. New strategies for controlling position and orientation in space are then discovered during adaptation to the weightless environment, the instabilities desist, and the symptoms disappear.

The remaining measures provided by the EquiTest System came out of the second set of tests, the sensory organization tests. The sensory organization test set consisted of several prolonged postural maintenance situations (20 seconds) under a variety of conditions. As detailed earlier, these various conditions were designed to minimize one or more orientation sensory modalities. Two measures were calculated in software and presented after each test condition: equilibrium and strategy. The equilibrium measure reflected the amount of postural sway during the 20 second test. The strategy score, as in the motor coordination tests, was a measure reflecting the relative amounts of activity at the ankle and hip joints. First, a baseline stability score was determined by instructing the subject to stand as still as possible with the eyes open and without any influence from the EquiTest System (perturbation or sway referencing). The same test was then accomplished with the eyes closed. Next, the platform was sway referenced, reducing the available amount of sensory information at the ankle joint, as the subject attempted to stand as quietly as possible, once with the eyes open and once with them closed. In the next test, the visual surround was sway referenced, minimizing the available visual information regarding postural stability. Finally, the last test had the subject with eyes open and both platform and visual surround sway referenced. An equilibrium and strategy score was calculated in the EquiTest software and displayed for each of these test conditions.

Predictions regarding postural stability in these tests are similar to those applied to the motor coordination tests. If sufficient sensory-motor adaptation had taken place during the long duration centrifugation, postural control behaviors would reflect a rescaling to the 2 Gz environment. Upon reintroduction to earth-normal 1 Gz, these behaviors would be inappropriate in the "new" environment and postural instabilities could possibly surface. One would expect, then, decreased performance in some or all of the postural maintenance tasks. Specifically, one could predict lower scores on the equilibrium metric and possibly lower scores on the strategy metric, reflecting an increase in hip joint activity.

RESULTS AND DISCUSSION

The results of primary importance are those that address the first priority of this study; can a long-duration, 2 Gz centrifugation and subsequent reintroduction to earth-normal 1 Gz adequately simulate the transition from 1 Gz to weightlessness and produce the symptoms of SMS? The measures that directly apply to this research goal are those obtained through the Symptom Checklist and the Graybiel Motion Sickness Scale. In the Symptom Checklist, subjects reported their symptoms both pre- and post-run as being either severe, moderate, slight, or none. Scoring was accomplished by assigning three points to a response of severe, two points for a moderate, and one point for slight. These were then totalled across subjects. Symptom Frequency Histograms were constructed from these responses for both pre- and post-run for comparison.

The Symptom Checklist revealed only a slight change in the condition of the seven subjects who participated in the 40 minute exposure (Figure 3). The symptom showing the largest increase was that of general discomfort, with a change in frequency of seven points. Interviews with the participants revealed that this was primarily due to the musculo-skeletal stresses endured and resulting back pain in the lumbar and cervical regions. Those symptoms displaying a moderate change (change in frequency between three and five points) included loss of appetite, increased appetite, confusion, and burping. Symptoms receiving only a slight increase in frequency (one or two points) were fullness in the head, blurred vision, visual illusions, faintness, yawning, and coughing.

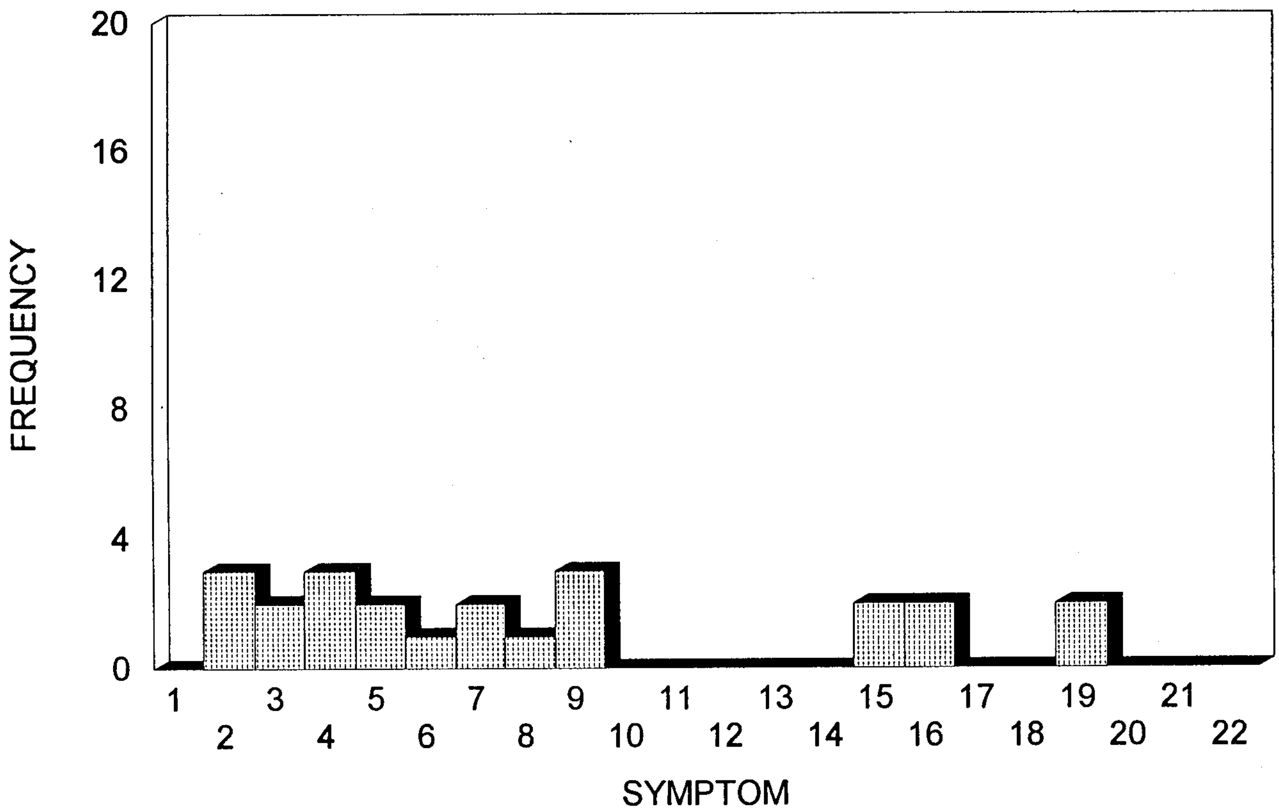
Although there appears to be a small change in symptomology following the 40 minute centrifugation, much of it can be attributed to one subject who probably experienced a great deal of Coriolis stimulation (Figure 4). This particular subject, one of the shortest in stature, had to lean forward often times in the seat while at G to accomplish the NASP related reaching tasks, thus translating the head and increasing the potential for Coriolis, or cross-coupled stimulation. This has been shown repeatedly to be highly nauseogenic.

Regarding the Graybiel Motion Sickness Scale, the results were similar. Post-run scores revealed that two subjects incurred no ill effects from the centrifugation at all. Two other subjects experienced only slight malaise while the categories of moderate malaise B and A contained one subject each (A being more severe than B). The experience of a headache in one subject and stomach awareness in the other disposed these subjects to these categories. Only one subject, the aforementioned "Coriolis subject", scored as experiencing frank sickness.

These results are in sharp contrast to those obtained from the

SMS SYMPTOM FREQUENCY HISTOGRAM

BEFORE 40 MIN. TRAINING RUN (NASP)

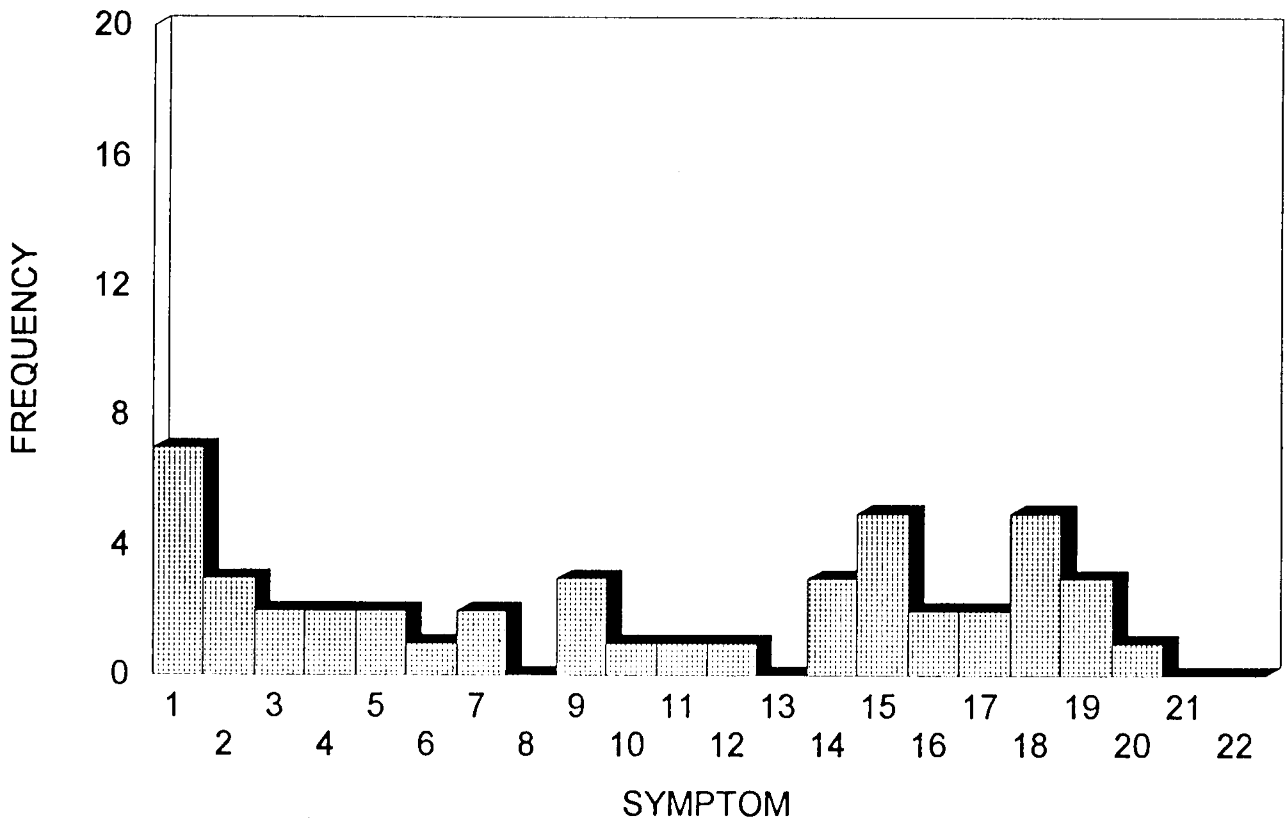


1 GENERAL DISCOMFORT
2 FATIGUE
3 BOREDOM
4 EYE STRAIN
5 DIFFICULTY FOCUSING
6 SALIVATION DECREASE
7 DIFFICULTY CONCENTRATING
8 MENTAL DEPRESSION
9 FULLNESS IN HEAD
10 BLURRED VISION
11 VISUAL ILLUSIONS
12 FAINTNESS
13 BREATHING AWARENESS
14 LOSS OF APPETITE
15 INCREASED APPETITE
16 DESIRE TO MOVE BOWELS
17 CONFUSION
18 BURPING
19 YAWNING
20 COUGHING
21 FLATULENCE
22 OTHER

FIGURE 4

SMS SYMPTOM FREQUENCY HISTOGRAM

AFTER 40 MIN. TRAINING RUN (NASP)



1 GENERAL DISCOMFORT
2 FATIGUE
3 BOREDOM
4 EYE STRAIN
5 DIFFICULTY FOCUSING
6 SALIVATION DECREASE
7 DIFFICULTY CONCENTRATING
8 MENTAL DEPRESSION
9 FULLNESS IN HEAD
10 BLURRED VISION
11 VISUAL ILLUSIONS
12 FAINTNESS
13 BREATHING AWARENESS
14 LOSS OF APPETITE
15 INCREASED APPETITE
16 DESIRE TO MOVE BOWELS
17 CONFUSION
18 BURPING
19 YAWNING
20 COUGHING
21 FLATULENCE
22 OTHER

nine subjects who participated in the 90 minute centrifugation (Figures 5,6). The Symptom Frequency Histograms for this condition revealed a large change in the occurrence of general discomfort (again, largely musculo-skeletal in nature), fatigue, boredom, salivation decrease, fullness in the head, increased appetite, burping, and yawning. Those symptoms experiencing a moderate increase included visual illusions, faintness, breathing awareness, and loss of appetite. Those symptoms displaying only a slight increase were mental depression, desire to move bowels and coughing. Unlike the 40 minute exposure, where one subject's experience skewed the data, these dramatic increases were found in several of the subjects.

The Graybiel Motion Sickness Scale revealed similar changes. All nine subjects experienced some ill effects of the long duration centrifugation and subsequent return to 1 Gz. Three subjects scored in the slight malaise category, three scored in the moderate malaise B category, and two in the moderate malaise A category. One subject was determined from the scale to be frankly sick.

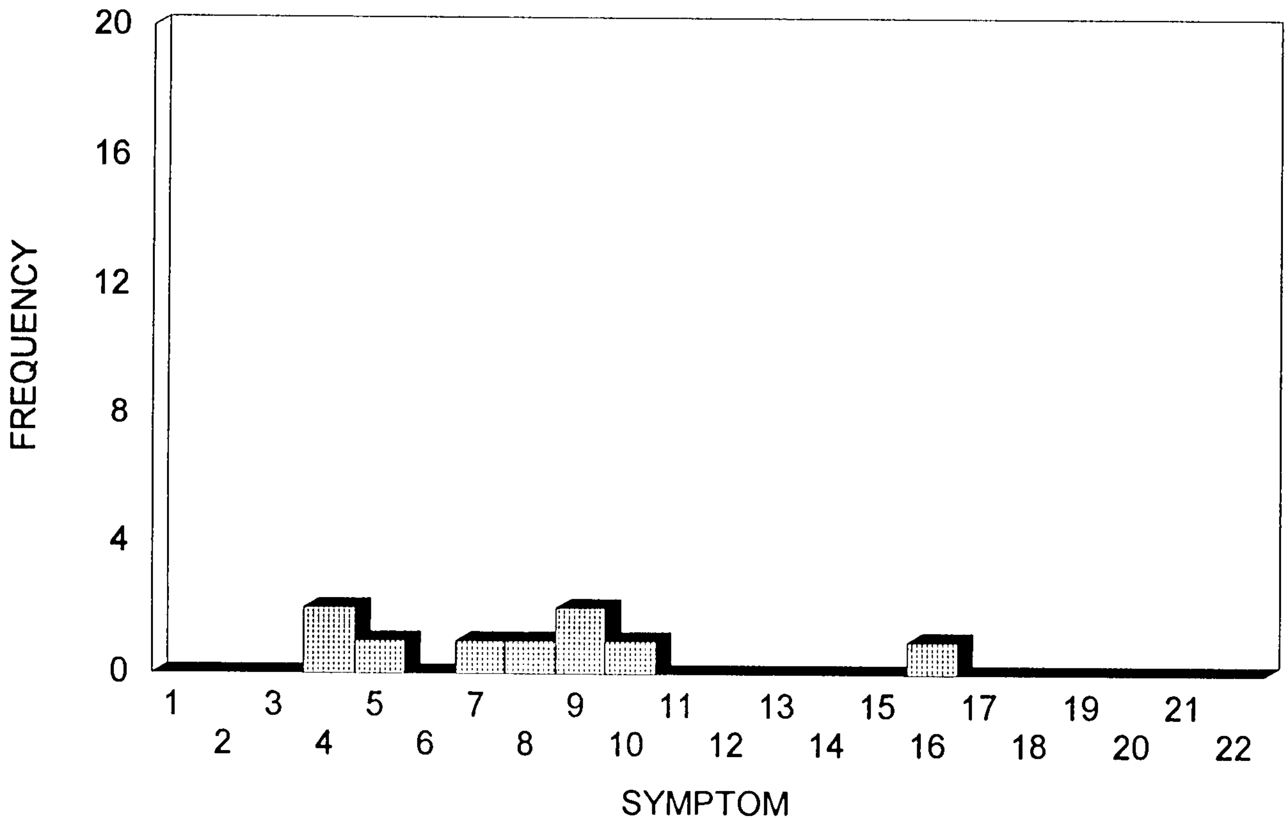
This would seem to indicate that of the two centrifugation conditions, the 90 minute exposure was more apt to produce the symptoms of SMS. Additionally, the profoundness of the increase in symptomology suggests that long duration 2 Gz centrifugation and return to 1 Gz is an adequate simulation of the transition to weightlessness and is capable of producing SMS-like symptoms. Regarding the secondary hypothesis, that postural effects coexist with the SMS experience, the EquiTest data proved somewhat revealing. T-tests were performed across subjects on the various EquiTest scores to compare baseline equilibrium and strategy with the postural performance after centrifugation.

In the motor coordination tests, those tests involving recovery from various sizes of perturbations, no real pattern of change was revealed, although several of the t-tests showed a statistically significant effect ($p<.05$). For the 40 minute exposure condition, the following EquiTest scores showed a statistically significant change.

- Small backward translation:
  - left leg latency of response (increase)
  - motor coordination strategy (increase, i.e., less hip activity)
- Medium backward translation:
  - left leg latency of response (increase)
  - right leg latency of response (increase)
  - motor coordination strategy (increase, i.e., less hip activity)
- Large backward translation:
  - motor coordination strategy (increase, i.e., less hip activity)

SMS SYMPTOM FREQUENCY HISTOGRAM

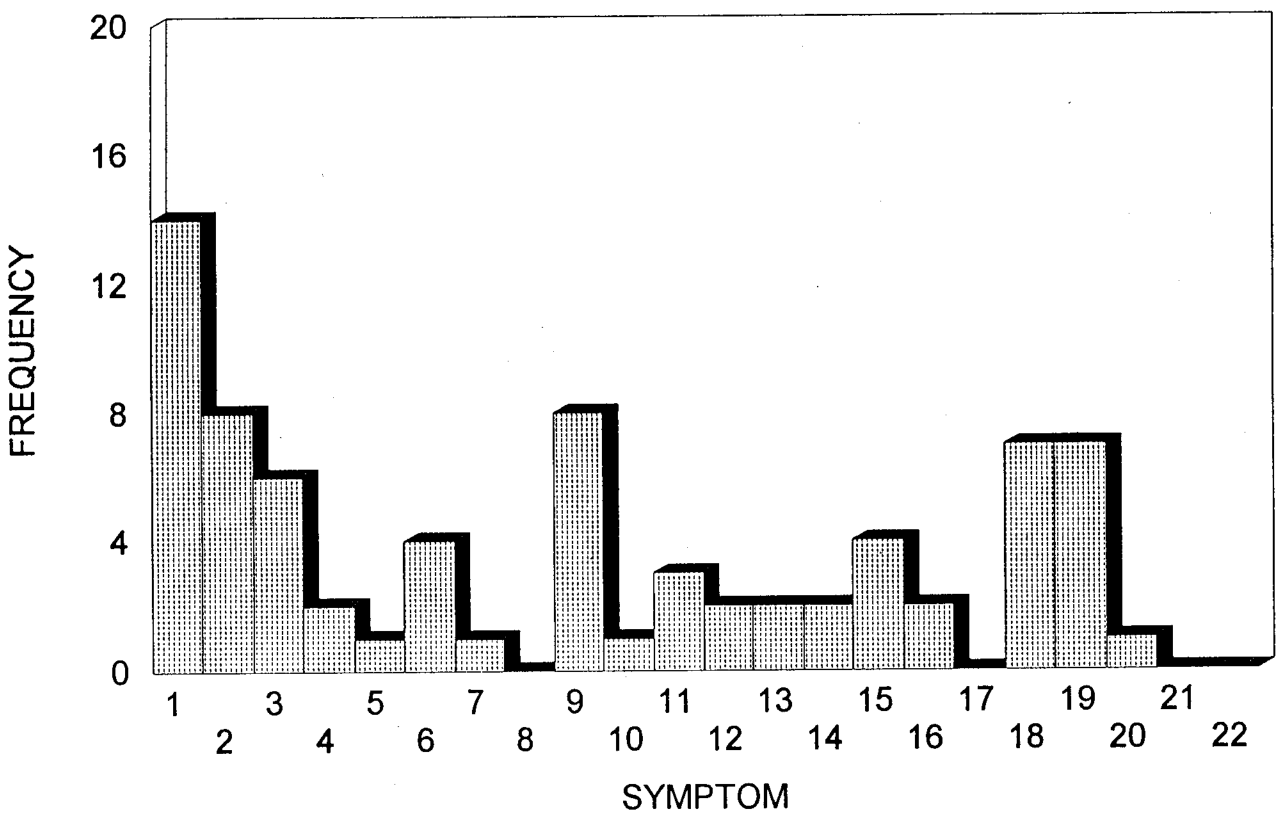
BEFORE 1.5 HR. RUN



1 GENERAL DISCOMFORT
2 FATIGUE
3 BOREDOM
4 EYE STRAIN
5 DIFFICULTY FOCUSING
6 SALIVATION DECREASE
7 DIFFICULTY CONCENTRATING
8 MENTAL DEPRESSION
9 FULLNESS IN HEAD
10 BLURRED VISION
11 VISUAL ILLUSIONS
12 FAINTNESS
13 BREATHING AWARENESS
14 LOSS OF APPETITE
15 INCREASED APPETITE
16 DESIRE TO MOVE BOWELS
17 CONFUSION
18 BURPING
19 YAWNING
20 COUGHING
21 FLATULENCE
22 OTHER

SMS SYMPTOM FREQUENCY HISTOGRAM

AFTER 1.5 HR. RUN



1 GENERAL DISCOMFORT
2 FATIGUE
3 BOREDOM
4 EYE STRAIN
5 DIFFICULTY FOCUSING
6 SALIVATION DECREASE
7 DIFFICULTY CONCENTRATING
8 MENTAL DEPRESSION
9 FULLNESS IN HEAD
10 BLURRED VISION
11 VISUAL ILLUSIONS
12 FAINTNESS
13 BREATHING AWARENESS
14 LOSS OF APPETITE
15 INCREASED APPETITE
16 DESIRE TO MOVE BOWELS
17 CONFUSION
18 BURPING
19 YAWNING
20 COUGHING
21 FLATULENCE
22 OTHER

Medium forward translation:
motor coordination strategy
(increase, i.e., less hip activity)

For the 90 minute exposure condition, the following EquiTest scores showed a statistically significant change ($p<.05$).

Medium backward translation:
right leg latency of response (increase)
motor coordination strategy
(increase, i.e., less hip activity)
Large backward translation:
right leg latency of response (increase)
motor coordination strategy
(increase, i.e., less hip activity)
Large forward translation:
motor coordination strategy
(increase, i.e., less hip activity)

The only interesting effect in the above data is the reduction in hip activity during recovery from a perturbation after a long duration exposure to 2 Gz. This is in direct conflict with the apriori prediction that hip activity would increase after centrifugation, presumably due to the "new" demands on the postural system warranted by the demanding postural dynamics associated with the 2 Gz environment. It is likely that this decrease in hip activity is a learning effect, exhibited in many subjects in many previous studies (Martin, 1990.) The fact is that the novelty of the translation conditions result in much more hip activity than is necessary when first encountered. Most subjects realize after their first couple of exposures to the translations that recovery can easily be accomplished with less vigorous movements; the translations are not that threatening and a simple ankle strategy is sufficient. Similarly, the increase in latency of response scores reflect this learning effect. Although these tests are useful in the clinical arena, they lack the sensitivity needed to distinguish changes in an otherwise healthy population.

The results of the sensory organization tests (standing as still as possible for 20 seconds in a variety of destabilizing conditions) were also somewhat interesting. The baseline and post-exposure scores for equilibrium and strategy provided by the EquiTest for these tests were also compared using t-tests. For the 40 minute exposure, neither the equilibrium nor the strategy score exhibited a statistically significant change ($p<.05$) between baseline performance and post-40 minute centrifugation. This is not surprising considering the fact that this condition resulted in little if any SMS symptomology.

The 90-minute centrifugation condition, however, resulted in one very interesting effect on the 20 second postural maintenance task. In the eyes closed condition, both the equilibrium and strategy scores post-exposure differed significantly ($p<.05$) from those obtained prior to the exposure. Subjects were less stable in this condition in which the dominant orientation modality had been eliminated. None of the other postural maintenance conditions enjoyed a similar significant change.

This finding prompted further investigation into the nature of this instability found in the post-90 minute evaluation. Fourier transforms (FFTs) were applied to the center of pressure traces collected from the platform during the 20 second postural maintenance tasks in an attempt to isolate any high frequency component in the postural sway data. This high frequency activity could indicate some postural instability. Power spectra were then constructed to reveal this high frequency activity. Four of the six 20 second postural maintenance conditions were investigated with the FFT: eyes open with no sway referencing of either the platform or the visual surround (a baseline condition, of sorts), eyes closed with no sway referencing (the condition revealing a statistically significant change), eyes open with visual surround sway referencing, and eyes open with both the platform and visual surround sway referencing. This was accomplished for each subject's baseline postural maintenance performance as well as their post-90 minute exposure performance.

Most subjects showed no change in the frequency distribution of their postural sway from baseline to post-exposure. For the most part, the power spectra revealed most of the postural sway to be occurring between zero and three Hertz, which is considered to be normal. Two subjects, however, exhibited additional peaks in their frequency distributions. One of these subjects was the "frankly sick" subject; the other suffered moderate malaise A (the more severe of the two).

For the subject suffering moderate malaise A, two separate high frequency peaks were found in the power spectra: one in the region of seven Hertz, the other in the region of thirteen Hertz. The thirteen Hertz peak most likely reflects some physiologic tremor (trembling) and is therefore somewhat uninteresting. The peak at seven Hertz, however, is well within the range of active control, and could reflect some self-imposed instability.

The subject experiencing frank sickness also displayed some high frequency behavior. One additional peak in the eight Hertz range was revealed in the power spectra. Again, this is within the limits of active control and could quite likely be a self-imposed instability. Unlike the above subject, this effect did not persist throughout all four tests, but was most evident in the first condition (eyes open with no sway referencing of either the platform or the visual surround), and gradually disappeared in the following tests. This "wash-out" could be due to the fact that the subject twice asked to sit down and recover during the postural maintenance portion of the data collection. This request was granted, possibly at the risk of losing the effect, as the subject was in obvious discomfort.

The most satisfying result of this study is with respect to the original goal: to determine whether long-duration, 2 Gz centrifugation and subsequent reintroduction to earth-normal 1 Gz adequately simulates the earth-bound to weightlessness transition as evidenced by the emergence of SMS-like symptoms. This was found to be the case for the 90-minute duration exposure. Secondarily, the identification of postural instabilities in two of the most sick subjects is also rewarding, as this is the first time such a relationship has been seen.

CONCLUSION

The results of this work confirm the findings of previous studies suggesting that long duration centrifugation and reintroduction to earth-normal 1 Gz produces the signs and symptoms associated with SMS. This invites the use of long duration centrifugation as a platform from which to study a variety of issues regarding SMS: chiefly, its etiology, prediction of susceptibility, and prevention strategies.

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Space/Motion Sickness (SMS) Questionnaire

Subject Panel ID No. ________
Date ____________________
Visit/Run __________________

Part I. Motion Sickness History (Administer any time before training run)

1. How often would you say you get airsick?
   Always ___ Frequently ___ Sometimes ___ Rarely ___ Never ___

2. How much experience have you had at sea aboard ships or boats?
   Much ___ Some ___ Very Little ___ None ___

3. How often would you say you get seasick?
   Always ___ Frequently ___ Sometimes ___ Rarely ___ Never ___

4. Have you ever been motion sick under any conditions other than those previously mentioned? No ___ Yes ___
   If "Yes", under what conditions? ____________________________________
   ____

5. In general, how succeptible to motion sickness do you feel you are?
   Extremely ___ Very ___ Moderately ___ Minimally ___ Not at all ___

6. Have you been nauseated for ANY reason in the past 8 weeks? No ___ Yes ___
   If "Yes", please explain. ____
   ____

7. When you were nauseated (for ANY reason, including the flu, alcohol, etc.), did you vomit:
   Easily ___ Only with difficulty ___ Retch and finally with great difficulty ___

8. If you vomited while experiencing motion sickness, did you:
   Feel better and remain so ___ Feel better temporarily, then vomit again ___ Feel better, but not vomit again ___ or, other (please specify) __________________

9. If you were in an experiment where 50% of the subjects get sick, what do you think your chances of getting sick would be?
Almost certainly would ___ Probably would ___ Probably would not ___ Almost certainly would not ___

10. Would you volunteer for an experiment where you knew that: (please answer all three)
50% of the subjects did get motion sick? Yes ___ No ___
75% of the subjects did get motion sick? Yes ___ No ___
85% of the subjects did get motion sick? Yes ___ No ___

11. Most people experience slight dizziness (not as a result of motion) 3 to 5 times a year. The past year, you have been dizzy:
more than this ___ the same as this ___ less than this ___ never ___

12. Have you ever had an ear illness or injury which was accompanied by dizziness and/or nausea? Yes ___ No ___

13. Have you ever experienced:

Inner ear infections	Yes ___	No ___	Date of onset ___________
Hearing problems	Yes ___	No ___	Date of onset ___________
Dizziness	Yes ___	No ___	Date of onset ___________

14. What were your usual eating habits during the last six months? (circle answers)
    a. Full meals _____ (number of regular meals per day)
    b. Snacking
    c. Combination of snacking and full meals

15. How much fluid do you regularly consume in one day? ____ (number of 12 oz. glasses)

16. If you have ever experienced sickness or discomfort from a simulator or the DES:
    a. What type of simulator was it? ______________________________
    b. What type of mission or maneuvers (profiles) ______________________
    c. What were the symptoms ______________________________
    d. How long did the symptoms last ______________________________
    e. Did you experience any symptoms that did not occur until some time after

your "flight"? If so, what were they and how long did they last? ________

____

f. If any symptoms went away, but then came back, describe the events surrounding their return. ____

____

g. What do you think caused the problems? ______________________

____

APPENDIX B

PHYSIOLOGICAL STATUS AND SYMPTOM CHECKLIST

Subject Panel ID No. ________

Date ____________________

Visit/Run __________________

Physiological Status and Symptom Checklist (Administer just before exposure. Also, administer Symptom Checklist just after exposure.)

1. Are you in your usual state of fitness? Yes ___ No ___
   If "No", why? ____

2. Have you been ill in the past week? Yes ___ No ___
   a. Nature of the illness (flu, cold, etc.) ________________________________
   b. Severity of the illness ____
   c. Length of the illness ____
   d. Major symptoms ____
   e. Are you fully recovered? Yes ___ No ___

3. How much alcohol have you consumed in the past 24 hrs?
   _____ beers; ______ ozs. wine; ______ ozs. liquor

4. Do you have a hangover now? Yes ___ No ___

5. Please indicate any medication you have used in the past 24 hours (aspirin, anti-histamines, etc.) ____

6. How many hours of sleep did you get last night? _____ hrs.

7. Please list any other factors regarding your present physical condition that may affect your DES experience today. __________________________________
   ____

APPENDIX C
Graybiel Motion Sickness Scale

Subject Panel ID No. ________

Date ________________

Visit/Run ________________

Symptom classifications: III=severe or marked II=moderate I=slight

1. Nausea Syndrome
   vomiting/retching ___ nausea II or III ___ nausea I ___ stomach discomfort ___
   stomach awareness ___

2. Skin color
   pallor III ___ pallor II ___ pallor I ___ flushing ___

3. Cold sweating
   level III ___ level II ___ level I ___

4. Increased salivation
   level III ___ level II ___ level I ___

5. Drowsiness
   level III ___ level II ___ level I ___

6. Headache Yes ___ No ___

7. Dizziness Yes ___ No ___

Category	Pathognomonic 16 points	Major 8 pts	Minor 4 pts	Minimal 2 pts	AQS* 1 pt
Nausea syndrome	Vomiting/retching	Nausea II,III	Nausea I	Epigastric Discomfort	Epigastric Awareness
Skin Color		Pallor III	Pallor II	Pallor I	Flushing
Cold Sweating		III	II	I	
Increased Salivation		III	II	I	
Drowsiness		III	II	I	
Pain					Headache
Central Nervous System					Dizziness: Eyes Closed ≥II Eyes Open III

Levels of Severity Identified by Total Points Scored

Frank Sickness (S)	Severe Malaise (M III)	Moderate Malaise A (M IIA)	Moderate Malaise B (M IIB)	Slight Malaise (M I)
≥ 16 points	8-15 points	5-7 points	3-4 points	1-2 points

*AQS = Additional qualifying symptoms. III = severe or marked, II = moderate, I = slight.

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