

MICROGRAVITY VESTIBULAR INVESTIGATIONS
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Our perception of how we are oriented in space is dependent on the interaction of virtually every sensory system. For example, to move about in our environment we integrate inputs in our brain from visual, haptic (kinesthetic, proprioceptive, and cutaneous), auditory systems, and labyrinths. In addition to this multimodal system for orientation, our expectations about the direction and speed of our chosen movement are also important. Changes in our environment and the way we interact with the new stimuli will result in a different interpretation by the nervous system of the incoming sensory information. We will adapt to the change in appropriate ways. Because our orientation system is adaptable and complex, it is often difficult to trace a response or change in behavior to any one source of information in this synergistic orientation system. However, with a carefully designed investigation, it is possible to measure signals at the appropriate level of response (both electrophysiological and perceptual) and determine the effect that stimulus rearrangement has on our sense of orientation. The environment of orbital flight represents the stimulus arrangement that is our immediate concern. The Microgravity Vestibular Investigations (MVI) represent a group of experiments designed to investigate the effects of orbital flight and a return to Earth on our orientation system.

All of our tests are based on a fundamental chain of ideas. In orbit, the absence of an effective gravity vector in the "freefall" environment of the orbiting craft creates the requirement for adaptive changes in sensorimotor and perceptual systems that on Earth subserve the voluntary and reflexive control of eye, head, and body motion relative to the Earth. Interactions between the vestibular, visual, and proprioceptor systems are necessary for these control functions. Adaptive change in the motion control functions of these sensorimotor systems provokes motion sickness. Space sickness is a particular form of motion sickness. A functional vestibular system is apparently necessary for motion sickness. Therefore, measures of perceptual and sensorimotor reactions to stimuli involving interactions between vestibular, visual, and proprioceptive systems at selected times before, during, and after space flight will provide measures of changes that are an integral part (part and parcel) of the adaptive process.

The favorable consequences to the astronaut of the adaptive changes are improved efficiency and abatement of sickness associated with head and body movement during the orbital mission. The price for these improvements on orbit is maladaptive perceptual and sensorimotor reactions *during return to Earth and during readaptation to Earth*. The threats posed by maladaptive perceptual and sensorimotor reactions are at least as great as those posed by the discomfort of space motion sickness. Advancement of knowledge of mechanisms of adaptation to "environmental" change in the acceleration field is of profound importance to all NASA

mission, present and future. Any future knowledge gained in neurophysiological mechanisms of the adaptive process will achieve holistic functional significance only when tied to solid facts on the perceptual and sensorimotor reactions to measured stimulation of the orientation sensors before, during, and after orbital missions. The Microgravity Vestibular Investigations project is an effort to provide these fundamental facts.

Premise

The basic premise of this investigation rests on four points:

1. There is a normal synergy or interaction in the vestibular system between activity arising in the semicircular canals, the otolith organs, the visual system, the somatosensory system, and probably other sensory systems. Through coordination of the many inputs, the sensation of movement and accuracy of compensatory responses to various states of motion is maintained. Integration of this sensory information may begin at the receptor level (i.e., in canal/otolith interaction) but most probably occurs mainly within the central nervous system.

2. Otolith input is altered during spaceflight. The phasic component of the otolith signal in response to linear acceleration during translation persists, but the static component is probably absent. Therefore, spontaneous activity from the otolith organs associated with signaling position in a gravitational field must be modified as a new set point is established.

3. Adaptation will occur in microgravity with corresponding modifications of sensory and motor reflexes until new and appropriate response patterns are established.

4. In the immediate postflight period, responses will reflect the nature and degree of the inflight adaptation.

Based on these four points, an inclusive hypothesis would suggest a modification of the normal synergy that exists to coordinate canal, otolith, proprioceptive, and other sensory input. This modification will be reflected in the compensatory eye movements and perceptual reports elicited by angular acceleration when that acceleration is either self-imposed or passively experienced on a rotator.

Vestibular Function

If a cat is dropped upside down, it will land right side up on all fours. If a new newborn infant is tilted backward, its eyes will roll downward so that its gaze remains fixed. If the reader shakes his head from side to side as he reads this overview, the print nonetheless stands still. Each of these effects represents a compensation for a disturbance to balance or orientation, and each is controlled in part by the sensory apparatus in the vestibule of the inner ear. While these responses are a part of our everyday lives, they are basically reflexive in nature and are seldom called to our attention. The vestibular system functions to stabilize gaze and ensure clear vision during head movements. Because head movements can be fast, the visual system, encumbered

by relatively slow retinal processing cannot act rapidly enough to produce compensatory eye movements that would maintain images steady on the retina. The vestibulo-ocular reflex (VOR), which depends upon the motion sensors of the labyrinthine semicircular canals and otolith receptors, produces promptly generated slow-phase eye movements that compensate for head rotation. Thus, a horizontal rotation of the head to the right produces an equal eye movement in the orbit to the left so that the sum movement (eye in space or gaze) does not change and the image of the world does not move on the retina. The VOR is not capable of maintaining an image on the retina during sustained rotation; therefore, there is a need for alternative means of image stabilization to supplement the fading vestibular response. The optokinetic system serves this function by taking over and maintaining compensatory slow-phase eye movements during sustained rotation when the labyrinthine signal declines.

EXPERIMENT DESCRIPTIONS

MVI is comprised of seven different experiments conducted on the IML-1 payload crewmembers. The experiments require the MVI Rotating Chair to provide stimulus in the subject's Yaw, Pitch or Roll planes. The experiments and the axes tested for each are:

Suppression of the Vestibulo-Ocular Reflex:	Yaw & Pitch
Semicircular Canal Dynamics:	Yaw, Pitch & Roll
Visual-Vestibular Interaction:	Yaw & Pitch
Per-Rotatory and Post-Rotatory Nystagmus:	Yaw, Pitch & Roll
Optokinetic Responses:	Yaw & Pitch
Sensory Perception Reporting:	Yaw, Pitch & Roll
Preflight and Postflight Testing:	Yaw, Pitch & Roll
	Dynamic Posture Test
	Positional Nystagmus

SUPPRESSION OF THE VESTIBULO-OCULAR REFLEX

Keeping the visual image of an object still while moving the head is critical for reading, for tasks requiring eye-hand coordination and possibly, for avoiding motion sickness. All the MVI experiments converge on answering questions of how processing of vestibular information

about head movements is affected by orbital flight, and this experiment's unique contribution is to study this in a particular visual context.

If the head is rotated and the eyes don't turn relative to the head, the visual image will sweep across the whole retina. This visual sweep and the vestibular signal from the rotation both elicit reflexes (the optokinetic reflex (OKR) and the VOR, respectively) driving the eyes opposite to the head movement. This keeps the eyes stationary relative to space and to the visual background. The OKR and the VOR are field-stabilizing reflexes. The eyes can also fixate on a small object of interest that is moving relative to the fixed background and follow it without moving the head (pursuit response), but in doing so optokinetic stimulation in the opposite direction is generated. For this experiment, the background is darkened to prevent optokinetic stimulation and a small target is fixed relative to the head as the subject is rotated. This situation allows us to study how the pursuit responses suppress the VOR.

There is evidence that vestibular processing is affected by transitions between a terrestrial gravito-inertial force background and the micro-gravito-inertial force environment of orbital flight. Thus, interactions between pursuit and vestibular eye movements may be altered during space shuttle missions. Deficits in visual and visuo-motor performance may occur, and their time course and extent may correlate with the occurrence of symptoms of space motion sickness.

Background

1. What is the evidence that the VOR and pursuit interact?

When we look at a moving object we usually do it by moving both the head and eyes. The process of turning the head in the direction of the object produces a vestibular stimulus which activates the VOR, holding the gaze stationary in space. It is unclear what cancels the VOR.

There are several possibilities for what the cancelling signal is. It could be the signal that drives pursuit eye movements, it could be a copy of the vestibular signal with the opposite sign gated by pursuit information, or it could be feedback from the neck. Evidence from lesions in humans and from the similarity between visual suppression of the VOR and visual pursuit suggests that the pursuit signal is the cancellation signal. For example, Halmagyi and Gresty (1979) have shown that patients with lesions that degrade pursuit also have deficits in the ability to cancel the VOR. In normal humans (Barnes, et al., 1978; Barnes, 1983) and monkeys (Lisberger and Fuchs, 1978), the ability to suppress the VOR diminishes at higher frequencies where the pursuit system also breaks down.

2. How do the VOR and pursuit contribute to suppression?

The VOR and visual pursuit interact during visual suppression of the VOR in ways that are predictable from their individual characteristics. Quantitative models covering the

behavior of each system and of the interaction between them will be presented in the next science orientation training tour.

The VOR is frequency dependent. The gain is higher and the phase angle between eye and head movements is smaller at higher frequencies. The pursuit system is also frequency dependent, its gain being lower and phase angle larger at higher frequencies. Figure 2 shows that when VOR gain (ratio of eye to head movement in the dark) is higher there is less suppression (the ratio of eye to head movement is higher when there is a head-fixed target).

When the gain of pursuit errors is large, suppression is poor (the relation of eye to head movement is large when there is a head-fixed target). Visual performance suffers when suppression is not achieved. The ability to read letters presented in an expected location - straight ahead of the head - is degraded at high frequencies of head oscillation, paralleling breakdown of suppression at high frequencies.

3. What affects the normal frequency dependence of suppression?

Anything that affects the VOR, pursuit, or the mechanism of interacting can affect visual suppression of the VOR. Consumption of alcohol interferes with the ability to pursue moving objects, and this manifests itself as a degradation in the ability to suppress. The effect of alcohol on pursuit and on suppression cuts across a range of frequencies. Blurred vision and decrements in visual recognition also occur.

Patients with peripheral vestibular injuries have impaired VOR function and impaired visual suppression of the VOR. These patients can stabilize their gaze fairly well during oscillation in full room illumination, but in the dark, the VOR and suppression are worse than in normals because the eye and head movements are out of phase.

Changes in the VOR that can affect suppression are not limited to changes in gain and phase. Some mechanisms subserving the VOR can affect the three dimensional organization of the VOR. Peterson, Baker and Wickland (1987) have exposed cats to conditions where oscillation of the head in yaw is coupled to vertical optokinetic stimulation. This brings about an adapted state of the VOR in which yaw head movements in the dark elicit pitch eye movements.

We have reason to believe the astronauts will experience a small degradation in visual suppression of the VOR upon insertion into orbit. There is no reason to expect the dynamics of pursuit to change as a function of gravito-inertial force level, but there is reason to suspect that the dynamics of the VOR will. Data from parabolic flight experiments (DiZio and Lackner, 1988), observations made before and after orbital flight (Oman and Kulbaski, 1988), and studies of cross coupling of optokinetic after-nystagmus (Raphan and Cohen, 1988) all point to a decrease in the time constant of decay of post-rotatory nystagmus after a transition from 1 g to 0 g in orbital flight. There is also ample evidence of an interaction between angular and linear acceleration in the VOR on Earth (cf. Benson, 1974 for a review).

Applying these data from the time domain to the frequency domain (assuming linearity) suggests that responses to low frequency oscillation will be altered initially in 0 g relative to 1 g. At 0.05 Hz, there should be an increase in the usual phase lead of the VOR and a small decrease in gain. It is clear that fixation suppression does not work by simple suppression of the VOR, so gravito-inertial force dependent changes in the VOR at low frequencies will probably produce gravito-inertial force dependent changes in suppression at low frequencies. Thus, a quantitative comparison of phase and gain of the visually suppressed and unsuppressed VOR at low frequencies is the most important potential contribution for this experiment.

Methods

This experiment will be conducted in both pitch and yaw axes. In pitch, oscillation will occur at two frequencies (0.05 and 1.25 Hz, each with 40/s peak velocity), and two visual conditions (in total darkness and with a head fixed target). In yaw, pseudorandom rotation (see Semicircular Canal Dynamics below) will be performed during both darkness and head-fixed target conditions. These conditions are shown schematically in Figure 3.

The main objective of data analysis will be to compare the velocity of eye movements and head movements. Head velocity is recorded and stored directly by monitoring chair velocity. Eye velocity must be derived from the eye position signals. Eye and head velocity will both be subjected to time series analysis and will be compared in terms of gain and phase. Difference in phase and gain across frequencies, visual conditions and rotation axes as a function of orbital flight will provide the evidence needed to test the hypotheses listed below.

Expected Results

1. There will be an increase in phase lead and a small reduction in gain of the VOR at low frequencies early in orbital flight relative to preflight.
2. The ability to fixate a head-fixed visual target during rotation will decrease at low but not high frequencies early in orbital flight relative to preflight. That is, the percent suppression will decrease.
3. Changes for the vertical VOR and for vertical suppression will be qualitatively similar but smaller.
4. It is unclear whether the VOR will return to its normal behavior during a space shuttle mission, but whether or not the VOR returns to normal during an extended period of exposure to weightlessness, visual suppression will return to normal. If the VOR does not return to normal and suppression does, it can be inferred that the pursuit system, or the way pursuit cancels the VOR, has changed.

5. There may be a correlation between the time course of adaptation of the VOR or suppression of the VOR and the severity of motion sickness symptoms inflight.

6. If adaptation of the VOR and its suppression occur after the initial inflight changes, there will be after-effects postflight.

References

Barnes GR, Benson AJ, Prior ARJ (1978). Visual-vestibular interaction in the control of eye movements. *Aviat Space Environ Med*, 4:558-564.

Barnes GR (1981). Visual-vestibular interaction in the coordination of eye and head movements. In: Fuchs & Becker (eds), *Progress in Oculomotor Research*, New York, Elsevier, 299-308.

Barnes GR (1984). The effects of ethyl alcohol on visual pursuit and suppression of the vestibulo-ocular reflex. In: J Stahle (ed), *The Vestibular System. Fundamental and Clinical Observations*. Almqvist & Wiksell, Uppsala, 161-166.

Benson AJ. Modification of the response to angular accelerations by linear accelerations. In: HH Kornhuber (ed), *Handbook of Sensory Physiology*, Vol. 6, Part II. Springer-Verlag, Berlin, 281-320.

DiZio P, Lackner JR (1988). The effects of gravito-inertial force level and head movements on post-rotational nystagmus and illusory after-rotation. *Exp Brain Research*, 70:485-495.

Halmagyi GM, Curthoys IS (1987). Human compensatory slow eye movements in the absence of vestibular function. In: MD Graham & SL Kemink (eds), *The Vestibular System. Neurophysiologic and Clinical Research*. Raven, New York, 471-479.

Halmagyi GM, Gresty MS (1979). Clinical signs of visual-vestibular interaction. *J Neurol Neurosurg Psychiatry*, 42:934-939.

Lisberger SG, Fuchs AF (1978). Role of primate flocculus during rapid behavioral modification of vestibulo-ocular reflex. I. Purkinje cell activity during visually guided horizontal smooth-pursuit eye movements and passive head rotation. *J Neurophysiol*, 41:733-763.

Oman CM, Kulbaski MI. Space flight affects the 1 g post-rotatory vestibulo-ocular reflex. Paper presented at The Barany Society Symposium on Representation of Three Dimensional Space in the Vestibular, Oculomotor, and Visual Systems. Bologna, Italy, June 3, 1987.

Peterson BW, Baker JR, Wickland C (1987). Spatial properties of the vestibulo-ocular reflex before and after labyrinthine lesions. In: MD Graham & JL Kemink (eds), *The Vestibular System. Neurophysiologic and Clinical Research*. Raven, New York, 455-461.

Raphan T, Cohen B (1988). Organization principles of velocity storage in three dimensions: the effect of gravity on cross-coupling of optokinetic after-nystagmus. In: B Cohen and V Henn (eds), Representation of Three Dimensional Space in the Vestibular, Oculomotor and Visual Systems, New York Academy of Sciences, New York.

Wall C, Black FO (1984). Intersubject variability in VOR response to 0.005-1.0 Hz sinusoidal rotations. In: J Stahle (ed), The Vestibular System. Fundamental and Clinical Observations. Almqvist & Wiksell, Uppsala, 194-198.

SEMICIRCULAR CANAL DYNAMICS

The general premise for the MVI set of experiments is that all systems of the body will attempt to adapt to weightlessness in a way that will optimize performance in the new environment. This will occur in posture and the control of eye movements with corresponding modification of sensory and motor reflexes until new and appropriate response patterns are established. It is expected that the weighting of canal and otolith inputs to the system will change with time inflight and will be reflected in eye position responses. The pseudorandom rotation tests in this experiment are designed to measure the weighting of the canal inputs to control of direction of gaze. As discussed above, pseudorandom stimuli will be used in Yaw in darkness and with a head fixed target. This stimulus will also be used in Roll and in Pitch (as an alternate inflight procedure).

Background

Two major mathematical tools utilized by engineers and scientists to analyze dynamic systems are time domain methods represented by differential and difference equations and frequency domain methods represented by transform calculus.

The basic view of a gain-phase system analysis is illustrated in Figure 4. The features tend to be much the same for biological system with changes occurring in the shape of the curves.

The use of frequency domain analysis in engineering from electric circuits to mechanical devices and on to complex systems of components is pervasive. When feedback control is considered, the tool is used to predict the behavior of an open loop system after the control loop is closed. In biology, the method has been extensively used when system performance must be quantified and characterized completely. Human operator performance, particularly under conditions when the human operator is part of a larger system is sometimes quantified using frequency domain analysis. That way, the operator can be embedded into the overall analysis of system performance.

Sensory systems which bring the external world to consciousness, such as the visual system and the auditory system, have been subjected to forms of frequency analysis. An example in the visual system is the determination of the light modulation frequency at which rapid variations in light magnitude can no longer be observed. The auditory system utilizes frequency domain analysis to reduce complex sound to their components. Its nature, therefore, makes it a prime candidate for frequency domain analysis. Indeed this system may have the longest history in this field

Why Use this Analytical Tool?

The vestibular system contributes to two major control systems, the Vestibular Ocular Reflex (VOR) and the postural control system. The MVI experiments utilize these systems as windows into changes occurring in the nervous system as a result of extended exposure to weightlessness. The evidence is clear that frequency domain tools will deliver the information required from the investigations. We have had experience with the tools and there are ample reports in the literature to support these methods.

The VOR is a complex control system having a number of inputs and several tasks to perform toward the organism's function. The overall dynamics of the VOR can be broken down by stage. That is, the end organ, the several involved processing centers of the Central Nervous System (CNS), and the eye in its orbit.

Physical Dynamics

Cupular Movement - The fluid filled semicircular canal with its cupular obstruction can be characterized by an analysis of its physics at several levels of detail. The most intuitive is a underdamped second order differential equation having the characteristics of inertia (fluid mass), restoring force (cupular elasticity) and viscosity (fluid shear on the wall of the canal).

Eye Movements - The and the eye in its socket and there are dynamics which arise from the interactions of neural structures.

Neural Dynamics

The nervous system communicates over distances greater than a few hundred microns by discrete events called action potentials which are propagated undistorted using the metabolic energy of the brain. The view of the nervous system generally held by neurophysiologists engaged in research on control systems within the body is that signals being passed from place to place on neural pathways are encoded by rate of discharge. There are numerous details under this statement but the approximation is good to the first order. These discrete event signals interact and are modified near cell bodies in ways analogous to the changes which occur to electronic signals are modified in electronic systems by summing, filtering and re-routing. Thus

new dynamics are imposed by waystations of the nervous systems which do not have obvious physical substrates such as mass, friction, and potential energy storage. Moreover, large changes in this signal processing capability can occur as a result of the needs of the organism. Some of the dynamical components of the VOR nervous circuit are as follows:

First Order Fibers - Goldberg and Fernandez (1971; Fernandez et al., 1972) have recorded responses of first order vestibular neurons to various motion stimuli. Approximately, the observed dynamics reflect the displacement of the cupula within the semicircular canals for the rotation detection system and displacement of the otoconia with respect to the otolithic membrane in the linear motion detection system. As will be enumerated later, this detection reflects velocity of angular motion and acceleration in the otolithic system.

Integration - The fact that the first-order fibers deliver velocity information to the CNS and the major task of the eye movement system is to maintain positional stability, requires an integration of the velocity signal so that the ocular muscles will be driven by the proper signal. It is generally accepted that this integration is accomplished by neural circuits located in the brainstem.

Velocity Storage - For the angular motion system, the observed time constants for horizontal eye movements did not match the time constants observed in the above first-order fiber system. This discrepancy could not be accounted for in any other location than in the CNS. Further, the horizontal eye movement system has been observed to "forget" its motion state and come under control of another system. An example of the conditions for this is a change in the plane of rotation for the head. A simple dynamical system which could accomplish this is pole zero pair on the real axis which cancels out the original time constant of the canal system and establishes a longer time constant in its place. Since any such system must have internal memory states, it is convenient to provide these memory states with the facility to forget upon command from an outside influence. Thus, a single neural network provides the means to explain two experimental observations.

Choice of the Stimulus Signal

The enumeration below is a list of characteristics which are desirable in a stimulation signal.

Covers the frequency range - It is an imperative that the stimulus contain energy across the entire spectrum being considered for analysis. Energy outside the band of interest is wasted. When particular discrete frequencies are of interest, it is best to concentrate energy at those frequencies.

Use complex signals - Signals such as sinusoids allow a subject to anticipate the motion. Often this is desired but when the primitive portions of the system are the objects of the analysis,

the anticipation effect is confounding. Signals which change themselves at random or at least are too complex to be anticipated remove this effect.

Persistently exciting - It is better to pack as much energy into the stimulus as possible within certain limitations. It is important as well to have the energy of the signal spread over all the time allotted for the signal rather than being delivered in short intervals. This reduces the dynamic range of the excitation for the same total energy and therefore helps keep the signal within the linear range of the system under analysis.

Control start-up transients - A signal with large derivatives or even discontinuities any time in its duration introduces transients which may push the system outside its linear region of operation and therefore disturb the frequency analysis. Smooth start up is an important factor in this and when the stimulus is periodic, the end of the period should be continuous with the beginning.

Avoid interaction among frequency components - One of the tenants of linear systems theory is that different frequency components do not interact. In living systems, however, it is inevitable that harmonics and other interproducts will arise. A signal which avoids this or at least makes it detectable is desired.

The stimulus chosen for this experiment is the sum-of-sines pseudorandom periodic stimulus. It is closely related to the pseudorandom noise stimulus first used by O'Leary and Honrubia (1975) to identify neurophysiological systems. It satisfies the needs expressed above with few compromises. It is made up of a number of sine waves which may or may not be harmonically related. The stimulus we have chosen has components which are all harmonics of a fundamental which is missing from the series. Generally the phases of the components are random with respect to each other but some are chosen to meet the start-up smoothness criteria.

Complex - Above all, the sum-of-sines stimulus appears to the subject to be random. He will not be aware from cycle-to-cycle where in the stimulus he is and will not be able to anticipate the state of the chair motion more than a few hundred milliseconds ahead.

Initial conditions controlled - At the start of the stimulus, the chair will be at rest and will have zero acceleration. This condition provides for both a smooth start and stop and allows a seamless transition between periods.

Periodic - The signal is periodic, which carries with it the advantage that time to frequency conversion is most easily done utilizing discrete-time to discrete-frequency algorithms (FFT).

Relative Primes - The harmonics chosen are relative primes. This means that nonlinearities which generate harmonics and cross terms will not lay over each other and can therefore be measured and separated in the frequency domain from the principle components of

the response. The actual values of the primes chosen are based on an equal logarithmic frequency model.

Can be packed - Through the generation of several series all meeting the above criteria, special ones can be chosen which pack the most amount of energy into the smallest excursion. This helps keep the equipment in its proper operating range and also optimizes the persistently exciting requirement.

Methods

As illustrated in Figure 6, semicircular canal dynamics is studied in Yaw, Roll and Pitch planes using the pseudorandom stimulus described above. The data analysis will involve first deriving time domain data and then frequency domain data.

Eye velocity - A signal processing step is executed on the eye movement signal to remove the fast phase component of eye movement, leaving a slow phase which can be differenced to produce a sampled slow-phase velocity signal.

Accumulated eye position - By extrapolating the eye velocity signal over the fast phase components, an estimate is obtained of what the eye position would have been if the fast phase components had not reset the eye position.

Ocular Counterroll - With current technology, the only method of analysis for rotation of the eye in the X axis is by analysis of a video or photographic image of the eye. The MVI ground based equipment includes a device to convert video to eye movement data. As it stands, the method is very computer intensive and cannot be run in real time.

After the derived time domain data from above has been verified it will be converted to frequency domain information. The values of frequency which will be analyzed are locations of the signal energy, namely the harmonics of the fundamental which are in the sum-of-sines signal. These will be the records and charts from which the final conclusions of the research will be derived.

Gain and Phase vs. frequency - After the chair data and the eye movement data are converted to common units and transformed separately to the frequency domain, the transformed eye movement data will be divided by the transformed chair data. The result will be a complex sequence. Gain is derived from the complex series by taking the magnitude of each complex number, and phase is derived by taking the inverse tangent of each number.

Expected Results

Our expectation is that the VOR gain and phase as derived from the transfer function analysis will be modified, and these modifications are of central origin. Of particular interest will be the time course of the changes. It is expected that the changes from the baseline will take 3 to 6 days and recovery after landing will take somewhat less. In addition, the two axes which are commonly influenced by otolith inputs (Pitch and Roll) may be altered more than the Yaw axis which, in normal posture, operates independently of the otolithic system.

References:

Cohen, B., The Vestibulo-Ocular Reflex Arc, In *The Handbook of Sensory Physiology* Vol VI/1 H.H. Kornhuber (ed) pp 476-540, 1974.

Fernandez, C., J. M. Goldberg, and W. K. Abend, Response to Static Tilts of Peripheral Neurons Innervating Otolith Organs of the Squirrel Monkey, *J. Neurophysiol.* Vol. XXXV, #4, 1972.

Goldberg, J. M. and C. Fernandez, Physiology of Peripheral Neurons Innervating Semicircular Canals of the Squirrel Monkey. I. Resting Discharge and Response to Constant Angular Accelerations, *J. Neurophysiol.* Vol. XXXIV, #4, 1971.

Luenberger, David G. *Introduction to Dynamic Systems- Theory, Models & Applications-* Wiley, 1979.

O'Leary D. P. and V. Honrubia, On-Line Identification of Sensory Systems Using Pseudorandom Binary Noise Perturbations, *Biophysical Journal*, Vol 15, pp. 505-532, 1975.

Robinson, D. A., The Systems approach to the Oculomotor System, *Vision Research*, Vol. 26, pp. 91-99, 1986.

VISUAL-VESTIBULAR INTERACTION

This study will investigate the extent to which sinusoidal angular motion could modulate slow phase velocity of nystagmus elicited by optokinetic stimulus at constant velocity. Rotation in yaw combined with horizontal optokinetic nystagmus, and rotation in pitch combined with vertical optokinetic nystagmus will be investigated with two oscillations frequencies and one velocity of optokinetic stimulus. Rotation in darkness and optokinetic stimulus presented with the rotator in static position will be used as controls.

Background

In recent years, the interaction of optokinetic and vestibular stimuli on the slow-phase velocity (SPV) of nystagmus (Koenig, et al., 1978; Barnes, et al., 1978; Guedry, et al., 1978; Buizza, et al., 1980) and on the perception of body motion (Zacharias, 1977; Dichgans and Brandt, 1978) has gained increasing interest. The resulting research work has improved our understanding of how man compensates for a sensory deficit: there is no receptor signaling constant angular or linear body velocity. The adequate inputs to the semicircular canals are angular accelerations; and to the otoliths, linear accelerations. With vestibular stimuli of high frequency (sinusoidal stimulation above 0.1 Hz) this deficit is compensated for by the inertia of the cupula which integrates the acceleration to a velocity signal of the head in space (Fernandez and Goldberg, 1971). With lower frequencies of vestibular stimulation, the activity of an additional central integrator, presumably located in the vestibular nuclei storing the neuronal activity from the peripheral nerve, elicits a vestibulo-ocular reflex (VOR) in phase with head velocity (Buettner, et al., 1978).

In spite of its integrative properties, the vestibular system is not able to provide an adequate velocity signal during motion with constant angular velocity. In the presence of visual cues, this can be compensated for by the visual system. When the whole visual surround moves with uniform velocity, a sensation of self-motion is induced (circular vection) (Brandt, et al., 1973). The neurophysiological basis for this perception is a convergence of visual inputs on the premotor structures of the vestibular system (Henn, et al., 1974; Waespe and Henn, 1977).

Features common to VOR and optokinetic after-nystagmus (OKAN), as well as recordings from vestibular neurons during OKAN, indicate that the convergence of the two inputs has to be located at or prior to the level of the central integrator in the vestibular nuclei mentioned above (Raphan, et al., 1977, 1979). Thus OKAN and the prolongation of the peripheral time constant to that of the VOR could be accomplished by the same integrator.

Interaction of vestibular and optokinetic nystagmus under natural conditions was first demonstrated by Maurer (1935), who showed that optokinetic stimulation reduces post-rotatory nystagmus. Thus additional optokinetic stimulation results in a better correspondence of stimulus velocity and SPV of nystagmus than pure vestibular stimulation. Quantitative measurements of interaction lead to contradictory assumptions on how the outputs of the vestibular and optokinetic system are combined to yield a common SPV output. Allum, et al. (1976) suggested a variable gain in both the vestibular and the optokinetic system before their summation. Linear interaction was proposed by Robinson (1977) on the basis of the data from Waespe and Henn (1977) which suggested a switching between the vestibular and optokinetic input. Recently, Koenig, et al. (1978) found rather accurate linear interaction when the vestibular and optokinetic stimuli added. But when the vestibular stimulus was opposite to the optokinetic, SPV of the OKN was reduced more strongly than was expected on the basis of linear interaction. These data were used as the basis of a model of nonlinear interaction by Schmid, et al. (1980).

The basic advantage of the present experiment is that we use sinusoidal oscillations instead of a velocity step for the vestibular stimulus, combined with a unidirectional optokinetic stimulus. This makes it possible to measure, within the limited time frame imposed by the constraints of experimentation in space, the interaction when both stimuli are of same or opposite directions. In general, on ground, there is a very good correspondence of the SPV observed with pure optokinetic stimulation and the change in SPV by the additional vestibular stimulus (Koenig and Diehggs, 1982). Thus, the optokinetic reflexes, predominantly the pursuit system, modulate SPV in the same way during combined visual vestibular stimulation as during pure optokinetic stimulation. When the vestibular and optokinetic stimuli add, the retinal image motion helps to decrease the SPV (or to suppress the VOR) so that the eye velocity never exceeds the optokinetic stimulus velocity. When the two stimuli are in opposite directions, a fully compensatory SPV depends on the respective gain of both vestibular and pursuit systems.

Methods

Visual-vestibular interaction will be evaluated using the Helmet-mounted Optokinetic Stimulus (OKS) Module during sinusoidal oscillation. This module provides a moving visual field (black/red checkered pattern) which may be oriented to turn right to left, left to right, up to down, or down to up.

The OKN field direction will move horizontally (left to right or right to left) with the head in the yaw orientation and vertically (up to down or down to up) for the pitch head position. Data will be collected at 0.2 Hz and 0.8 Hz (same frequencies as SPE/SASE FO-2) for both yaw and pitch orientations. The peak velocity of both the optokinetic stimulation and rotator oscillation will be 40 deg/sec.

Figure 7 illustrates these conditions. The data analysis will essentially be the same as described above for the VOR suppression experiments.

Expected Results

1. Major changes should occur for visual vestibular interaction about pitch axis when compared to yaw axis because the synergy between canals and otoliths will be disrupted in free fall;

2. Adaptive changes should occur throughout the flight during visual vestibular interaction about pitch axis when both stimuli will be in the same direction. At the beginning of the flight SPV should be greater than the optokinetic stimulus velocity and the visual pattern should then appear moving in the opposite direction of its actual displacement. Then SPV should be fully compensatory given the development of the visual suppression of nystagmus throughout the flight.

3. The storage mechanism eliciting after-nystagmus will change its charge to a considerable extent in such as long intervals as 25 seconds. So, it should also be discharged at the end of the optokinetic stimulus, and the SPV during the following pure vestibular stimulation should change accordingly. It will be interesting to compare this effect throughout the adaptive process to the microgravity environment.

4. In addition, previous data on OKN and VOR in earlier space flights suggest that a direction-specific (downward) change in the SPV should occur during visual vestibular interaction in the vertical plane in a weightless environment. Indeed, previous studies have indicated that the asymmetry between upward and downward OKN is reversed during the first three days of spaceflight, and parabolic flight as well (Clment, et al., 1986; Clment and Berthoz, 1988). The beating field of vertical OKN and the vertical OKAN time constant are also affected. Then, changes in the vertical VOR as a function of angular acceleration and optokinetic stimulus are expected to occur in the direction of the observed reversal of OKN during orbital flight. It has been hypothesized that the suppression, during free-fall, of the antigravity tonic influence exerted by the otoliths, which tends to raise the body and to rotate upward the eyeball (upward drive) in order to compensate for the downward pull of gravity, would then facilitate eye movements directed downwards. Such an asymmetry should be exemplified during the visual vestibular interaction protocol.

References

- Allum JHJ, Graf W, Dichgans J, Schmidt CL (1976) Visual-vestibular interactions in the vestibular nuclei of the goldfish. *Exp Brain Res* 26: 463-485
- Barnes GR, Benson AJ, Prior ARJ (1978) Visual vestibular interaction in the control of eye movement. *Aviat Space Environ med* 49: 557-564
- Brandt Th, Dichgans J, Koenig E (1973) Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Exp Brain Res* 16: 476-491
- Buettner UW, Buettner U, Henn V (1978) Transfer characteristics of neurons in vestibular nuclei of the alert monkey. *J Neurophysiol* 41: 1614-1628
- Buizza A, Leger A, Droulez J, Berthoz A, Schmid R (1980) Influence of otolithic stimulation by horizontal linear acceleration on optokinetic nystagmus and visual motion perception. *Exp Brain Res* 39: 165-176
- Clment G, Vieville T, Lestienne F, Berthoz A (1986) Adaptive modifications of gain asymmetry and beating field of vertical optokinetic nystagmus in microgravity. *Neurosci Lett* 63: 271-274
- Clment G, Berthoz A (1988) Vestibulo-ocular reflex and optokinetic nystagmus in microgravity. *Adv Oto-Rhino-Laryng* 42, Karger, Basel (in press)

Dichgans J, Brandt Th (1978) Visual vestibular interaction: effects on self-motion perception and in postural control. In: Held R, Leibowitz H, Teuber HL (eds) Perception. Springer, Berlin Heidelberg New York (Handbook of sensory physiology, vol 8, pp 755-804)

Fernandez C, Goldberg JM (1971) Physiology of peripheral neurons innervating semicircular canals of the squirrel monkey. II. Response to sinusoidal stimulation and the dynamics of the peripheral vestibular system. J Neurophysiol 34: 661-675

Guedry FE, Lentz JM, Jell RM (1978) Visual vestibular interaction: influence of peripheral vision on suppression of the vestibular ocular reflex and visual acuity. WASA, NAMRL 1246

Henn V, Young LR, Finley C (1974) Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. Brain Res 71: 144-149

Koenig E, Allum JHJ, Dichgans J (1978) Visual-vestibular interaction upon nystagmus slow phase velocity in man. Acta Oto-Laryngol 85: 397-410-

Koenig E, Dichgans J (1982) Iner interaction of vestibular and optokinetic nystagmus. In: Roucoux A, Crommelinck M (eds) Physiological and pathological aspects of eye movements. Junk Publishers, The Hague Boston London, pp 271-280

Maurer OH (1935) Some neglected factors which influence the duration of post-rotational nystagmus. Acta Oto-Laryngol 22: 1-23

Raphan T, Cohen B, Matsuo V (1977) A velocity-storage mechanism responsible for optokinetic nystagmus, optokinetic after-nystagmus and vestibular nystagmus. Dev Neurosci 1: 37-47

Raphan T, Matsuo V, Cohen B (1979) Velocity storage in the vestibulo-ocular reflex arc. Exp Brain Res 35: 229-248

Robinson DA (1977) Linear addition of optokinetic and vestibular signals in the vestibular nucleus. Exp Brain Res 30: 447-450

Schmid R, Buizza A, Zambarbieri D (1980) A non-linear model for visual-vestibular interaction during body rotation in man. Biol Cybernetics 36: 143-151

Waespe W, Henn V (1977) Neuronal activity in the vestibular nuclei of the alert monkey during vestibular and optokinetic stimulation. Exp Brain Res 27: 523-538

Zacharias GL (1977) Motion sensation dependence on visual and vestibular cues. Ph. D. Thesis. MIT, Cambridge

OPTOKINETIC RESPONSES

As mentioned above, the vestibulo-ocular reflex is a mechanism for moving the eyes in response to movements of the head. The vestibular system in combination with the visual and proprioceptive systems maintains an approximate fixed gaze in space as we move about in the environment. This tends to keep images fixed on the retina so that we may see clearly. If we are to fully understand how space travel affects our ability to compensate for head movements, we must first have a fundamental understanding of the quantitative dynamical aspects of the VOR and how it interacts with other systems to implement compensation for motion. Over the last 12 years, considerable insight about the detailed dynamics of the VOR has come from modelling the VOR as a dynamical system and identifying a process in the central vestibular system which is responsible for "integrating" vestibular, visual, and proprioceptive information to generate compensatory eye movements. This process has been labelled a velocity storage integrator.

Background

When the head is rotated in the dark, slow phase eye velocity increases immediately to compensate for the rotation and then decays to zero as the rotation continues, called per-rotatory nystagmus. When the rotation is stopped, there is a reversal of slow phase eye velocity (post-rotatory nystagmus) into the anticomensatory direction which decays to zero with the same time course as the compensatory response during the rotation. An interesting observation is that the time course of the decaying velocity is generally two or three times as long as the change in activity seen in peripheral units in the eighth nerve. This indicated that some central storage mechanism was responsible for lengthening the time course of the response.

Another phenomenon having similar characteristics which also indicated that some central storage mechanism was responsible for generating the slow phase compensatory eye movements is observed after optokinetic stimulation. This is called optokinetic after-nystagmus (OKAN). When an optokinetic drum is rotated about a subject's yaw axis, the eyes follow the drum. When the lights are extinguished, the compensatory eye movements do not disappear immediately but continue, decaying with a time course similar to that of compensatory eye velocity during rotation. What is interesting is the fact that during OKN eye velocity builds up to a steady state value, while during rotation in dark eye velocity decays. In addition, the eye velocity during the OKAN is oppositely directed to that of the anticomensatory eye velocity when the subject is stopped after rotation. This indicates that the visual and vestibular systems complement each other during rotation in light and that the anticomensatory after-responses cancel each other when rotation is stopped. When the two are combined, one gets the appropriate compensatory response. When a subject is rotated in light, there is compensation throughout the period of rotation. When the subject is stopped, there is no anticomensatory response.

In summary, the vestibulo-ocular reflex responds with a gain close to one in the monkey, and has a time constant of about 12 to 15 seconds mainly attributed to velocity storage. Velocity storage is also activated by the visual system by full field optokinetic stimulation.

A key insight about the properties of the VOR which has been gained over the past decade has been the idea that the storage properties associated with both vestibulo-ocular compensation and optokinetic following are both mediated by a common mechanism that we have called the velocity storage integrator. The properties of the velocity storage integrator are such that it is capable of storing velocity information up to some saturation level and then it declines with increasing stimulus velocity.

While the studies on velocity storage for rotations about a vertical axis have elucidated the dynamical aspects of the VOR, the full functional significance of velocity storage in coordinating postural stability is only recently coming to light. An important discovery in the last few years has been the realization that velocity storage has a three dimensional structure and the profound effect that gravity has on the storage properties.

The model of visual-vestibular interaction about a vertical axis is shown in Figure 8A and forms the basis for the generalization to three dimensions. Vestibular nystagmus is generated by head velocity signal r_h , which through the cupula dynamics generates the signal r_v , that appears in semicircular canal afferents in the vestibular nerve. This information activates the integrator, as well as projecting around it, to form a component of the eye velocity command signal in the vestibular nuclei V_n . The time constant of the integrator is equal to $1/\omega_0$. OKN is initiated by the velocity signal r_o generated by movement of the visual surround. From this signal is subtracted head velocity and eye velocity, whose sum is gaze velocity. This generates the retinal slip signal e . The slip signal can be extinguished by light switch L or transmitted centrally to two elements. One is the direct pathway that is responsible for rapid changes in eye velocity. It has been omitted so as to concentrate on those signals that converge onto the integrator and the vestibular nuclei. The second is a nonlinear function whose output activates the velocity storage integrator (visual coupling to the integrator). The suppression switch S in the model is utilized to discharge or 'dump' the integrator rapidly during visual or tilt suppression.

The three dimensional extension of the model is shown in Figure 8B. Head and surround velocity are transformed into canal based coordinates. T_{can} is the transformation from head to canal coordinates and D_{can} is the dynamic three dimensional transformation of the canals. T_{oto} and D_{oto} are the transformations that convert linear acceleration or changes in the position of the head with regard to gravity into the velocity command signals that drive the integrator during such motions as pitching while rotating (Raphan, et al., 1983) or off-vertical axis rotation (OVAR) (Raphan and Cohen, 1981; Cohen, et al., 1983). The canal excitation vector r_c , is dynamically transformed into a signal, r_v , representing the eight nerve canal excitation vector. The visual signal is also converted into canal coordinates by T_{can} to generate a central representation of retinal slip in canal coordinates e . Both r_v and e activate a multidimensional representation of velocity storage which combines with the direct vestibular pathway to generate eye velocity in canal coordinates. This representation of eye velocity is transformed back into

head coordinates by the transformation T_{can-1} to generate eye velocity in head coordinates which can combine with head and surround velocity. The three dimensional structure of the direct optokinetic pathway has been left out in order to concentrate on those parameters which couple to the velocity storage integrator.

The state of the integrator is the three dimensional vector x and is presumably encoded in the second order lateral, posterior and anterior canal oriented neurons in the vestibular nuclei. The vector e is the retinal slip, $n(e)$ is a nonlinear matrix operator on the central representation of retinal slip, G_0 is the coupling matrix from the eighth nerve to the integrator and H_0 is the matrix representing the dynamics associated with the integrator.

Gravity has a profound effect on the mathematical structure of the velocity storage integrator. When subjects are on their sides and receive optokinetic stimulation about their vertical axis, the velocity storage integrator is activated in such a way so as to produce optokinetic after-nystagmus which has a vertical component. The oblique optokinetic after-nystagmus that develops is more closely aligned with the spatial vertical. Some of the interesting aspects of the dynamics of this "cross-coupled" response are the following:

1. The time constant of the horizontal component is somewhat shortened.
2. The buildup and decay of the slow phase velocity in for the vertical component of nystagmus is asymmetrical and is consistent with the asymmetries and the dynamic properties of velocity storage when rotations are about the subjects' pitch axis with the subjects on their sides.

When subjects are upright receiving vertical optokinetic stimulation in the upward direction, the velocity storage integrator is activated in such a manner so as to produce OKAN which has a small time constant and little activation. When the head is tilted 90 deg., the level of OKAN is increased and the time constant is bigger. For vertical optokinetic stimulation in the downward direction, a similar change in the characteristics of the velocity storage integrator is observed. There is an increased level of OKAN with a longer time constant. There is also an asymmetry between upward and downward slow phase velocity. The upward slow phase velocity is stronger and has a longer time constant. Recently we have discovered that the asymmetry is modified by tilting the animal more than 90 deg, i.e., into the southern hemisphere, i.e., head down. This indicates that the asymmetries as well may be a function of gravity.

In summary, we have reviewed the dynamical behavior of the VOR and the optokinetic reflex and shown that both activate a central vestibular process called the velocity storage integrator. We have also shown that velocity storage has a three dimensional structure that is modified by gravity. The effects of the modification are changes in time constants and activation levels of horizontal and vertical compensatory eye velocity for different orientations of the head with regard to gravity. Humans also have velocity storage although it is weaker than storage in monkeys.

Methods

Horizontal and vertical optokinetic responses are recorded in the Yaw and Pitch orientations, respectively. As Figure 9 illustrates, this experiment will also be conducted with the crewmembers free-floating out of the Rotating Chair. Due to crew-time constraints, the free-floating portion of this experiment will be conducted only later in the flight on two of the four MVI subjects. While free-floating, oblique (30) optokinetic stimulation will be used in addition to horizontal and vertical. As an alternate procedure, the optokinetic responses will also be recorded while the crewmembers tilt their heads laterally to one side. For each optokinetic stimulus run, three speeds are presented in succession (20, 60 and 40/sec) for 15 sec each in one direction, and then OKAN is recorded in darkness for 15 sec. The same stimulus is then presented in the opposite direction (i.e., 15 sec of 20/sec, 15 sec of 60 /sec, 15 sec of 40/sec, 15 sec of darkness).

Expected Results

The purpose of the MVI optokinetic experiments during the upcoming flight is to obtain information on the time constant of the velocity storage integrator in the absence of gravity when it is activated to produce horizontal and vertical OKAN. Some of the questions which we hope to answer are:

1. What is the relationship between the time constants of the velocity storage integrator before, during and after insertion into microgravity for horizontal and vertical nystagmus?
2. To what extent are the time constants in the various planes equalized in microgravity?
3. How will asymmetries in vertical storage be affected by space travel?
4. What is the time course of adaptation of the various time constants?
5. What effect does head tilt have on the optokinetic responses inflight?

References

Cohen B., Helwig D., Raphan T.: Baclofen and velocity storage: A model of the effects of the drug on the vestibulo-ocular reflex in the Rhesus monkey., *J. Physiol. (Lond.)*, 393:703-725, 1987.

Cohen B., Henn V., Raphan T., Dennett D.: Velocity storage, nystagmus, and visual-vestibular interactions in humans. *Annals of the New York Academy of Sciences*, New York, Vol. 374, pp. 421-433, 1981.

Cohen B., Matsuo V., Raphan T.: Quantitative analysis of the velocity characteristics of optokinetic nystagmus and optokinetic after-nystagmus. *J. Physiol. (Lond.)* 270: 321-344 (1977).

Cohen B., Raphan T., Waespe W.: Floccular and Nodular control of the vestibuloocular reflex. In: *The Vestibular System: Neurophysiologic and Clinical Research*, (Malcolm D. Graham & John L. Kemink, eds.), Raven Press, New York, 1988.

Cohen B., Suzuki J.I., Raphan T.: Role of the otolith organs in generation of horizontal nystagmus: Effects of selective labyrinthine lesions. *Brain Res.* 276: 159-164, 1983.

Raphan T., Cohen B.: Multidimensional modelling of the vestibulo-ocular reflex. In: *Adaptive Processes in Visual and Oculomotor Systems*. (eds. E. Keller & D. Zee). Pergamon Press, Holland 1986.

Raphan T., Cohen B.: Organizational principles of velocity storage in three dimensions: The effect of gravity on cross-coupling of optokinetic after-nystagmus (OKAN). In: *The Representation of Three Dimensional Space in the Vestibular, Oculomotor and Visual Systems*, Ann. N.Y. Academy of Science (eds. B. Cohen & V. Henn), 545:74-92, 1988.

Raphan T., Cohen B.: The role of the integrator in modelling the visual-vestibular interaction. In: *Models of Oculomotor Behavior and Control* (ed. B. L. Zuber). CRC Press, West Palm Beach, Fla., pp. 91-109, 1981.

Raphan T., Cohen B.: Velocity storage and the ocular response to multidimensional vestibular stimuli. In: Berthoz, A. and Melvill-Jones, G. (eds.), *Reviews in Oculomotor Research*, Elsevier North Holland, pp. 123-143, 1985.

Raphan T., Cohen B., Suzuki J.I., Henn V.: Nystagmus generated by sinusoidal pitch while rotating. *Brain Res.* 276: 165-172, 1983.

Raphan T., Matsuo V., Cohen B.: Velocity storage in the vestibular-ocular reflex arc (VOR). *Exp. Brain Res.* 35:229-248 (1979).

Raphan T., Schnabolk C.: Modelling slow phase velocity generation during off-vertical axis rotation (OVAR). In: *The Representation of Three Dimensional Space in the Vestibular, Oculomotor and Visual Systems*, Ann. N.Y. Academy of Science (eds. B. Cohen & V. Henn), 545:29-50, 1988.

Sturm D., Raphan T.: Modelling the three dimensional structure of velocity storage in the vestibulo-ocular reflex. *Proc. 14th Bioengineering Conf. (IEEE)*, 1988.

Waespe W., Cohen B., Raphan T.: Dynamic modification of the vestibulo-ocular reflex by the nodulus and uvula. *Science* 228: 199-202, 1985.

Waespe W., Cohen B., Raphan T.: Effects of flocculectomy on vestibular and optokinetic nystagmus and unit activity in the vestibular nuclei. *Adv-Oto-Rhino-Laryng.* 30: 226-229, 1983.

Waespe W., Cohen B., Raphan T.: Role of the flocculus and paraflocculus in optokinetic nystagmus and visual-vestibular interactions: Effects of lesions, *Exp. Brain Res.* 50:9-33, 1983.

PER-ROTATORY AND POST-ROTATORY NYSTAGMUS

This experiment is designed to test, with one minute long constant angular velocity rotation, the per-rotatory and post-rotatory nystagmus slow phase velocity decay profile dynamics in Yaw, Pitch, and Roll. These angular acceleration impulses are used to examine indirect VOR pathway responses which were described in the Optokinetic Responses section above.

Background

When a human subject is rotated about an earth vertical axis for an extended period, nystagmus slow phase velocity decays from its initial value in quasi-exponential fashion with an apparent time constant on the order of 12 seconds. After several minutes of rotation, nystagmus disappears, and the subject is no longer aware of his rotation. If the rotation is then suddenly stopped, the subject immediately feels that he is rotating in the opposite direction, and exhibits the well-known phenomenon of post-rotatory nystagmus (PRN). The nystagmus beats in the opposite direction to that seen during the original turning period (the "per rotatory period"). The nystagmus slow phase velocity is initially equal to approximately 60 percent of the previous rotation rate, and then decays with an apparent time constant in a manner similar to the per rotatory response. This "impulse response" test paradigm is of particular utility in quantifying the characteristics of the human VOR, since the response dynamics are approximately linear (e.g., doubling the input doubles the response; responses can be predicted assuming superposition in time). Once the impulse response of the VOR is known for a given axis, if the VOR dynamics are linear, it is theoretically possible to predict the time course of nystagmus for any arbitrary input.

The per- and post-decay of nystagmus was for many years attributed solely to the semicircular canal cupula-endolymph dynamics, which are relatively linear, and believed independent of *g*. However, more recent experiments in animals have shown that the cupula-endolymph dynamics (as manifest in semicircular canal afferent neuron responses) have a shorter time constant (5-6 sec; Goldberg and Fernandez, 1971) than that manifest in PRN (Cohen, et al., 1977; Waespe et al., 1983). Investigators have postulated the existence of two parallel pathways from the vestibular periphery to the eye velocity input centers of the

oculomotor nuclei: one, the so called "direct VOR pathway", carries the 5-6 sec time constant semicircular canal afferent information. The second, an "indirect" pathway, passes through a "velocity storage" center with somewhat slower (approx 15-20 sec) dynamics, and which effectively integrates canal, otolith, optokinetic, and haptic inputs, and provides a second, augmenting oculomotor input which prolongs the PRN response, lengthening the "apparent time constant" of nystagmus decay. The PRN response decline - traditionally characterized by a single decaying exponential - is now seen as consisting of the sum of at least two decaying exponential terms. Although the anatomical site of the velocity storage mechanism has not yet been determined, the dynamics of the indirect pathway have been deduced using both vestibular and optokinetic inputs in the yaw and pitch axes. There is some evidence in animals that velocity storage mechanisms in the pitch axis have a longer time constant for pitch forward than for pitch back. Little is yet known concerning human velocity storage in roll. The yaw indirect velocity storage pathways in the human appear to saturate at relatively modest nystagmus slow phase velocities. Mathematical models for cupula/endolymph dynamics, afferent neuron transduction and encoding, direct VOR pathway and indirect VOR pathway velocity storage have been developed, and will be reviewed in the course of experiment training. It is clear that the traditional view of the human VOR as a "reflex" which exhibits linear system dynamics is correct only in a qualitative sense. Nonlinear models are required to accurately predict the time course of responses in many cases.

It is now thought that gravity dependent effects on angular VOR responses may be mediated via indirect VOR pathway mechanisms. Experiments have shown that the dynamics of post-rotatory nystagmus in animals and man is dependent on the orientation of the subject with respect to gravity. Khilov (1929) first demonstrated that the duration of PRN following a stopping stimulus was dependent upon the orientation of the head to gravity in the post-rotational period. The phenomenon was, e.g., confirmed by Koella (1947) in rabbits, and in humans by Correia and Guedry (1964), and also by Benson and Bodin (1966), who showed that if the body is kept in an erect position, the slow phase decays quasi-exponentially with a time constant of 10-12 seconds. However, if the subject's head is tilted in pitch or roll by 90 deg during this period of post-rotatory nystagmus, the magnitude of the slow phase is rapidly decreased, and time course of decay decreases as if the "apparent time constant" of decay had been reduced. If the head is then subsequently raised to the erect position, nystagmus strength and time constant are once again increased, although not to the level they would have had if the head tilt had not taken place. This phenomenon - sometimes termed "nystagmus dumping"- has been assumed to be mediated by the otolith organs, although the exact mechanism is subject to some debate. Possibly a "dump" of the putative integrator in the system takes place, triggered by a conflict between angular velocity storage integrator output (signalling, in effect, "I'm rotating about a horizontal axis") and gravireceptor information (signalling "no I'm not!").

There have been occasional anecdotal reports of oscillopsia (apparent motion of the seen world upon active head movement) from shuttle astronauts in flight. However, oscillopsia has not regularly been reported by participants in parabolic flight. Many have speculated that a change in VOR gain or time constants might be a contributing factor in the etiology of space motion sickness. Quantitative parabolic flight experiments using sinusoidal stimuli have

generally shown no consistent changes in medium frequency VOR gain (Jackson and Sears, 1966; Vesterhage, et al., 1984). Experiments by DiZio, et al. (1987, 1989) have demonstrated that the apparent time constant of PRN in yaw and pitch is shortened during (but not after) acute exposure to weightlessness. Space shuttle experiments conducted to date using active head movements and sinusoidal stimuli generally support the view that there is no consistent change in gain in the yaw axis (Thornton, et al., 1985, STS-6-8; Watt, et al., 1985, STS 41-G), although one experimenter (Clement, et al., 1985) has observed a decreased gain early in the mission. Yaw axis post-rotatory nystagmus was monitored inflight in one crewmember on the SL-1 mission using a hand spun rotating chair; results indicate no change in gain and are suggestive of a shortened time constant in flight, but are not statistically conclusive. The nystagmus dumping phenomenon appeared present in flight, suggesting that the dumping phenomenon can be triggered by processes related to the active head movement, rather than by gravity per se.

Comparison of pre and postflight PRN among four Spacelab-1 and five D-1 astronauts (Oman and Kulbaski, 1988; Oman and Weigl, 1989) have shown a residual shortening of the apparent time constant during the first several days after return from week long flights, but no consistent change in the magnitude of the initial peak slow phase velocity response (see Figure 10). The effects were thus qualitatively similar to those observed by DiZio, et al in parabolic flight. Responses gradually returned to preflight norms during the first postflight week. Oman, et al. have speculated that as a consequence of the altered gravireceptive input in weightlessness, the CNS may reduce the vestibular component driving central velocity storage in favor of visual inputs. Confirmation of this hypothesis awaits the results of further PRN testing both on orbit and pre/postflight, and data on changes in the visually dependent response of the velocity storage system from simultaneous experiments on human optokinetic after-nystagmus.

Methods

As illustrated in Figure 11, time constants will be tested in the clockwise and counterclockwise directions, and in three axes - Yaw, Pitch, and Roll. The constant velocity per-rotatory period will be 60 sec in duration at a velocity of $120^\circ/\text{sec}$. These values were chosen to match those used in previous SL-1 and D-1 experiments. Acceleration and deceleration will be set at $120^\circ/\text{sec}^2$.

Horizontal, vertical, and torsional eye position data will be analyzed using software which includes routines for calibration, semi-automated detection and removal of nystagmus fast phases, and calculation of the time course of nystagmus slow phase velocity for each run. Data from individual runs will be ensemble averaged by crewmember, session, and rotation direction and examined for changes. At least two different approaches will be used for making "same or different" statistical comparisons. One approach involves fitting the slow phase velocity time series (either individual runs or ensemble averages) with a multi-parameter model for the VOR so as to parameterize the data. Computed parametric data will then be analyzed using traditional statistical methods (e.g., ANOVA, using SYSTAT). A second approach (Oman and Kulbaski, 1988) involves computing a chi square parameter for the sum of the squared differences between

two ensemble averaged time series, each normalized based on pooled variance estimate computed for each point in time. This method allows us to assess whether there is a statistically significant difference between any two mean SPV profiles (e.g., comparing preflight vs. inflight) without having to "force fit" any particular mathematical model to the time series data in order to parameterize it.

Expected Results

This protocol will be utilized to investigate the hypothesis that adaptation to weightlessness influences the dynamics of the "indirect" VOR pathway through the "velocity storage" system. Responses of this same pathway are also simultaneously under investigation using optokinetic stimulation (see above). We hypothesize that any g dependent changes in velocity storage pathway time constants or storage asymmetries will also be manifest in optokinetic responses.

References:

- Benson A.J. and Bodin M.A. (1966) *Aerospace Medicine* 37:889.
- Cohen B., Matsuo V. and Raphan T. (1977) Quantitative analysis of the velocity characteristics of optokinetic nystagmus and optokinetic after nystagmus. *J. Physiol. Lond* 270: 321-344
- Correia M. and Guedry F.E. (1964) US Naval School of Aviation Medicine Report NAV SAM 905, Pensacola, FL.
- DiZio P., Lackner J. and Evanoff J. (1987) The influence of gravito-inertial force level on oculomotor and perceptual responses to sudden stop stimulation. *Aviation, Space, Envir. Med.* 58: Suppl. A.
- Goldberg J.M. and Fernandez C. (1971) Physiology of peripheral neurons innervating semicircular canals of the squirrel monkey. *J. Neurophysiol.* 34:635-684
- Khilov K.L. (1929) *Zh. ughn. nos. gorlov. Bolezn.* 6:289-299.
- Koella W. (1947) *Helv. Physiol. Pharmacol. Acta* 5:154-168.
- Oman C.M. and Kulbaski M. (1988) Spaceflight affects the 1-g postrotatory vestibulo-ocular reflex. *Adv. Oto-Rhino-Laryng.* 42: 5-8
- Oman C.M. and Weigl H. (1989) Postflight vestibuloocular reflex changes in Space Shuttle Spacelab D-1 crew. Abstract: 1989 meeting of the Aerospace Medical Association, May 7-11, Washington, DC

Raphan T. and Cohen B. (1988) Organizational principles of velocity storage in three dimensions. *Ann. NY Acad. Sci.* 545:74-92

Waespe W., Cohen B. and Raphan T. (1983) Role of the flocculus and paraflocculus in optokinetic nystagmus and visual vestibular interactions: effects of lesions. *Exp. Brain Res* 90:9-33

SENSORY PERCEPTION REPORTING

The vestibular system operates as a silent partner with other senses improving the efficiency of control of goal-directed head and body movement relative to the earth. Vestibular sensations do not reach conscious awareness as we skillfully move about. Vestibular sensations achieve conscious awareness only when they are "disorderly" in relation to concomitant information from other senses that participate in the voluntary control of head and body motion. The "dizziness" that accompanies vestibular disorders is usually poorly described because the perceptual event is characterized by the confusion and disturbance that comes from mixed signals among the various senses involved in the control of motion. Under the controlled conditions of MVI the crewmembers will be asked to report with this experiment whether their perceptions of particular motions in orbit are (1) different than they were on Earth and (2) are more (or less) confusing (or disturbing) than they were on Earth. This experiment is also designed to describe, quantify, and record any changes in symptoms of motion sickness which may occur during the flight. Although none of the features of this experiment are intended to induce motion sickness symptoms, the coincident occurrence of motion sickness and the nature and degree of symptoms are very important to the interpretation of data collected during the performance of the other MVI experiments. In addition, the use of any anti-motion sickness medication will be very important to the investigators in interpreting their data.

Background

Orientation illusions have been studied in parabolic and orbital flight. These studies indicate that when static visual cues to self orientation are "wrongly" interpreted by the brain, illusory perceptions of self-orientation with respect to the vehicle result. Attempts have been made to define the perceptual "rules" which the brain uses to identify objects and surfaces and to infer self-orientation. Reports from the crews of the D-1 and Spacelab-1 missions indicate that, when the identity of the subjective "floor" changes, it generally becomes that cabin surface which is closest to being beneath the observer's feet and parallel to the left/right head visual axis. Similarly, if an observer floated very close to a cabin surface with his body parallel to it, there was a tendency to perceive the surface as a subjective wall (even if it were actually a ceiling or floor). In other cases, a change in gaze angle or scene content was sufficient to trigger a change in subjective orientation. For example, if the observer simply viewed another person who was floating nearly horizontal or inverted with respect to the actual cabin floor, and if other visual

cues were ambiguous, the observer often suddenly felt that he himself was tilted and that the wall or ceiling of the vehicle closest to being in the direction of the seen person's feet was perceived as the subjective floor. Orientation illusions can often occur spontaneously in zero-g, but are also subject to volitional control. ("If I decide that I want to make the true floor a ceiling, suddenly it is.")

Another illusory phenomenon which occurs in parabolic and orbital flight is the Inversion Illusion - a feeling of somehow being continuously upside down while in weightless flight. Some crew members have been able to reverse or diminish the illusion by pulling themselves down into a seat. Another reported that he could reduce the paradoxical sensation only by looking at the reflection of his own face in a shaving mirror.

Other sensory perceptual distortions which have been observed by space crews during and/or after orbital flight include, among others, paradoxical motion,vection, and altered awareness of limb position. Some crewmembers have described, when during a deep knee bend with their feet affixed to the orbiter floor, a sensation of the floor coming up to meet them rather than their body lowering to the floor. Perceptions of the wall seemingly moving toward the observer rather than the observer's body moving toward the wall as he bent forward have also been reported.

The various illusory phenomena experienced in parabolic and orbital flight, both from the scientific objective of seeking to understand the integration and underlying mechanisms of the neurosensory system, as well as from the operational need to fully understand, and prevent if possible, the symptoms of space motion sickness, are important experiences to study and quantify.

Space motion sickness has been the most clinically significant phenomenon occurring during the first few days of space flight on the space shuttle. Symptoms of motion sickness in space were first reported by Soviet Cosmonaut Titov in 1961. During the United States Mercury and Gemini programs, no instances of space motion sickness were reported. However, during the Apollo program, 35 percent of crewmembers reported symptoms and during the three Skylab flights, 60 percent of the astronauts were affected by symptoms of motion sickness. We believe that this emergence of motion sickness symptoms was due to the ability of the crewmembers to move about within the spacecraft in the larger Apollo and Skylab vehicles, while during the Mercury and Gemini flights, very little movement was possible due to the confined quarters within these vehicles. The space shuttle has a relatively spacious flight deck and middeck, permitting crewmembers considerable freedom for head and body movements. When the Spacelab is flown in the payload bay, the room for movement is increased even more. Consequently, there is ample opportunity for visual and motion stimulation to occur.

Of the 85 crewmembers whose first space flight occurred during the first 24 shuttle flights, 67 percent reported some symptoms of motion sickness during the first 2 to 4 days. Their motion sickness experience included one or more of the following symptoms: headache, malaise, drowsiness, disequilibrium, lethargy, anorexia, stomach awareness, nausea, and

vomiting. Of these 67 percent with symptoms of space motion sickness, 26 (46%) were classified as mild, 20 (35%) were moderate, and 11 (19%) were severe. Although there is great individual variation, investigation of the motion sickness experienced during the shuttle flights has shown two "typical" patterns of symptom development. In the first pattern there is unmistakable and rapid onset of symptoms with, in an occasional case, an episode of vomiting occurring as early as 15 minutes after launch. Individuals with this pattern may have several episodes of vomiting, often without precedent nausea. They are likely to experience other symptoms as well with both gastrointestinal and central nervous system manifestations. In the second pattern of onset there is a more gradual development of symptoms often starting with a mild headache, anorexia and lethargy. These individuals may go on to vomiting, but usually not until the latter part of the first day in orbit. The type of symptom onset does not, however, seem to be predictive of either the overall severity or duration of symptoms. In both cases, movement of the head and/or body and unusual visual orientations are provocative and kept at a minimum by the affected crewmember. Movements in the pitch plane seem to be especially uncomfortable for some crewmembers. In addition, visual cues associated with being off-vertical with respect to the interior of the vehicle can be provocative and are avoided by the astronauts affected with motion sickness. In a few cases, no symptoms are experienced during the first day of flight, but then develop on the second flight day. Also, a few crewmembers who took an anti-motion sickness medication (Scop-Dex) during the first one or two days of flight did not develop any symptoms until after they stopped the medication.

A number of theories have been advanced to explain the cause of motion sickness. None has been successful, however, in fully explaining the underlying mechanisms involved in the development of motion sickness symptoms. The one factor which is a prerequisite for motion sickness to occur is an intact vestibular system coupled with the presence of real or apparent motion of the head and/or body. Thus the investigation of each of the hypotheses of this experiment is expected to shed some light on the underlying mechanisms which reach clinical expression in the experience of motion sickness, visual orientation illusions, and other sensory distortions.

Methods

Implementation of this experiment will require crewmembers to utilize a standardized Sensory Perception Questionnaire as a checklist for inflight reporting of any illusions or symptoms. The questionnaire has been assembled from previous questionnaires (ground-based, DSO-401, DSO-459, Spacelab 1, and D-1). There are three reporting timeframes for this experiment. (1) It is vital that the reporting of sensations, illusions, and symptoms be accomplished concurrently with the other MVI experiments inflight by means of a microcassette voice recorder. Dynamic changes in motion sickness symptomology will be recorded by describing specific symptoms and by using a subjective self rating of overall discomfort assigned a numerical score from 0 to 20 (1 being no symptoms, 20 being emesis). (2) The second reporting timeframe will be performed at the end of each test session and will allow the crewmember to reflect on comparisons across different runs and chair orientations. (3) The third

report will be recorded at the end of each shift, and the crewmembers will record motion sickness symptomology using both a checklist (Figure 12) and a timeline chart describing the timecourse of any symptoms using the 0-20 discomfort rating score (Figure 13).

PREFLIGHT AND POSTFLIGHT TESTING

The main objective of the preflight baseline data collection is to obtain normal one-g responses from each payload subject. These responses will serve as baseline criteria from which all in-flight adaptation and postflight readaptation will be evaluated. These tests involve nominal and alternate in-flight test objectives as well as the other pre/postflight functional objectives. The preflight sessions are performed at 130, 68, 30 and 15 days prior to launch.

In addition, the Launch-130 day session will be used as a control study to duplicate the early postflight test schedule (including other IML-1 experiment objectives) in order to identify what individual responses, if any, might change as a function of interactions across the different BDC tests or as a function of the repeated testing.

The postflight readaptation testing occurs on landing day within 1-2 hours, and is repeated on 1, 2, 5 and 7 days after the landing. In addition to the Pitch, Yaw and Roll experiments which are also performed inflight, the preflight and postflight testing includes testing for Positional Nystagmus and on a Dynamic Posture Platform.

POSITIONAL NYSTAGMUS TEST

The purpose of the positional nystagmus test is to determine whether or not a nystagmus results from a change in head or body position.

Depending upon the conditions of the test (eyes open, eyes closed, visual fixation, etc.), a positional nystagmus has been reported in as many as 50% of putatively normal subjects. This study is designed to determine the incidence of positional nystagmus in flight crews and relate these findings to other vestibular test results.

Background

The incidence and prevalence of positional nystagmus in the normal population has never been determined. Studies of so-called "normal" populations have been highly selected, and report an incidence of positional nystagmus ranging from about 25-50%.

Positional nystagmus associated with vestibular disturbances, on the other hand, can be as high as 100% in patients with benign paroxysmal positional nystagmus and vertigo, to a variable percentage in patients in various stages of compensation from unilateral or asymmetric bilateral

vestibular disturbances. There does not appear to be a consistent relationship defined between patients with a positional nystagmus and motion sickness.

Methods

This test will consist of horizontal and vertical EOG recordings, approximately 30 seconds in duration, obtained with the crewmember in each of the following positions: (1) upright, seated; (2) supine; (3) supine with head turned to the right; (4) supine with head turned to the left; (5) supine with head and neck extended over the edge of the examining table; (6) body and head turned to the right side with neck supported; and (7) body and head turned to the left side with neck supported. EOG responses will be recorded in each position with the crewmember's eyes open and closed in the dark. No visual targets will be provided, and tapping patterns will be employed as attention tasks (peak alertness is required). The test session will also include the Dix-Hallpike maneuver (1951), which consists of a rapid backward motion to a head-hanging and turned position.

Expected Results

Under normal circumstances, the vestibular system (both semicircular canals and otolith systems) responds only to angular and linear accelerations, respectively. The presence of a nystagmus in 1 g would suggest that the VOR is attempting to correct for an abnormal or inaccurately detected head acceleration.

DYNAMIC POSTURE TEST

The Dynamic Posture Test will be performed as a pre- and postflight study to determine the ability of subjects exposed to microgravity to interact visual, vestibular and proprioceptive sensory orientation references for control of upright stance before and after exposure to 0 g.

Postural instability on return to 1 g has been a consistent result of sustained exposure to microgravity. This study addresses the sensorimotor adaptive changes associated with control of upright posture upon return to earth following space flight.

Background

In a terrestrial environment, the vestibulo-spinal systems are organized to control center of force produced by the effects of gravity acceleration on the body center of mass over the foot supports when standing. When a human is introduced to 0 g, the forces acting upon the body center of mass change from primarily those produced by gravity to forces on the body resulting from active and passive body movements. Maintenance of head, body and eye stability under the two circumstances would require very different motor programs. Reprogramming of body

movements in space to maintain clear vision or to minimize center of mass movements would require disregarding otolith input references normally used as a reference to vertical. Upon re-entry to 1 g, re-establishment of preflight reflexes would be required in order to re-adapt to Earth vertical references provided by otolith responses to gravity.

The types of movements required to maintain distribution of the center of force over the feet during standing in normal subjects requires rotation around the ankle joints on a fixed surface, and hip movements if standing on a rail. In space, the hip movements would be the only body axial movement pattern which would be potentially effective in controlling body center of force. Consequently, upon return to Earth the subjects must switch from a "hip" synergy to an "ankle" synergy as they re-adapt to an Earth environment.

Methods

The Dynamic Posture Test is currently being used on Extended Duration Orbiter missions under a Detailed Secondary Objective (DSO 605). This test utilizes a modified posture platform (Equitest; Portland, OR) which consists of two sets of automated test procedures: movement coordination tests and sensory organization tests. During the movement coordination tests the platform will be suddenly translated forward or backward (by about 3 inches) or suddenly rotated toes-up or toes-down (by about 10 degrees) to perturb the subject's upright stance. The reflex responses to each of these sudden perturbations is monitored and recorded for a 2.5 second period. For the sensory organization tests, movements of the footplate or the visual surround or both will be referenced to the subjects postural sway and the responses for each sensory test will be recorded for 20 second periods.

In addition to the postural sway of the subject, the muscle activity from the legs will be measured using conventional electromyographic (EMG) techniques. The same electroding procedures described above for the EOG electrodes will be used for EMG as well, except that the electrode sites may be shaved if necessary to achieve acceptable electrode impedance. A safety harness is worn by the subject during this test and an operator's footswitch must be depressed throughout the test for it to be operational.

Expected Results

In one-G environments, the vestibulo-spinal systems are organized to control body center of mass over a support surface while resisting 1 g. In 0 g, these control systems must be reorganized to control inertial movements of the body center of mass.

EQUIPMENT DESCRIPTION

Figure 14 contains an experiment block diagram to define the MVI flight equipment and their interfaces. Below is a description of the main equipment components.

Experiment Control and Data Interface (ECDI)

The ECDI is a programmable microcomputer-based control center for the MVI experiment. The ECDI performs the following functions:

(1) acquisition of analog experiment sensor data (5 channels at 128 Hz and 8 channels at 32 Hz);

(2) data formatting and transmission over the Spacelab High Rate Multiplexor (HRM) and Closed Circuit Television (CCTV) systems;

(3) experiment stimulus hardware control via analog and/or digital means;

(4) experiment operation management via real time data displays and custom designed software.

Rotator

The experiment unique Rotator has been designed to mount and operate in the center aisle of the Spacelab. Operational safety requires a 32 inch sweep radius from the center axis of rotation. The Rotator is programmed to provide three types of velocity profiles (pseudorandom, step, and sinusoid).

Chair

A chair has been designed for MVI to improve the capability to accommodate all subject positions and restraint requirements. The subject's head is repositioned with respect to the axis of rotation by removing the entire chair from the rotator base and resecuring the chair to a different attachment point on a different side (i.e., no lateral head tilts are required). A trunnion design has been developed which will allow a secure attachment point to the rotator base but will also allow the operator to quickly change the subject/chair position. This chair repositioning method allows for subject rotation in the yaw, pitch and roll planes. The design requires that the subject's body be centered over the axis of rotation in the pitch and roll configurations, which means the head is slightly off-center resulting in eccentric rotation.

The Helmet Restraint Device attaches to the rotating chair and is used to fix the position of the subject's head relative to the rotational axes of the rotator by locking the helmet into a fixed position. The HRD has a quick-release attachment point to the top of the Helmet for subject ingress and egress. To accommodate subjects of various sizes, the HRD can be adjusted up and down along the chair frame by releasing two locking pins. Once adjusted to a comfortable position for the subject, the HRD is locked into place by engaging the HRD locking pins in indexing holes in the chair frame.

Helmet Interface Box (HIB)

The Helmet Interface Box mounts on the MVI rotator/chair assembly and provides:

- (1) the interface and controlling circuitry for devices used on the MVI Helmet.
- (2) data communication circuitry for transmitting experiment sensor data to the ECDI and digital command signals from the ECDI.

The HIB contains the LSLE Electro-oculographic Signal Conditioners, which are lightweight, miniaturized, battery operated electronic systems capable of detecting and amplifying the EOG potentials generated by the human eye. Each unit has two amplifier channels such that both left-right (horizontal) and up-down (vertical) eye positions are detected.

Helmet Assembly and Modules

The MVI subject will wear a lightweight Helmet Assembly which provides for:

- (1) interchangeable mounting of visual stimulus modules and a video recording module;
- (2) hard mounting of head acceleration sensors;
- (3) total restraint of the subject's head relative to the rotational axes.

Throughout the many experiments, the helmet can be used in free head movements or constrained in the Helmet Restraint Device on the chair.

The Helmet contains earphones for communication from the operator and auditory stimulus cues (e.g., an oscillating tone or white noise). Two visors on the Helmet move independently and have a bayonet mount for the three different Helmet Modules.

The Camera Module contains a miniature CCD video camera and an infrared illumination source which are positioned with respect to the subject's eye to record eye movements. The illumination intensity of the IR source is by computer control from the ECDI.

The LED Module houses an array of five LEDs used for eye movement calibrations. The center LED is also used as a fixation target during some portions of the MVI experiment. Digital command signals from the ECDI control the timing and sequence of the LEDs.

The Monocular Optokinetic Stimulus (OKS) Module contains a variable speed/direction DC motor-driven checkerboard pattern to provide a moving visual display in front of the eye. The pattern can be reoriented by 90 deg to alternate between horizontal and vertical planes with respect to the subject. The speed, direction (CW or CCW) and pattern illumination are controlled by software in the ECDI.

INFLIGHT PROCEDURE DESCRIPTION

The MVI rotator experiments have been grouped for timeline efficiency into three timeline models or Functional Objectives, or FOs (Pitch, Yaw and Roll). The Pitch FO includes all of the previously described protocols that require pitch rotation. Similarly, FO-2 Yaw and FO-4 Roll test the subject in the yaw and roll orientations. In FO-3 OKAN, the subject is free-floating out of the chair with a visual stimulus provided by the OKS module connected to the MVI helmet. In addition to these timeline models, FO-5 SPR involves the subject's monitoring of sensory perceptions. Other FOs have been developed for experiment setup and system testing, subject preparation, subject/operator handover, and experiment stowage.

MVI is timed to be performed by all four payload crewmembers on the Pitch, Yaw and SPR procedures. The Roll is only scheduled to be performed by one crewmember, and OKAN by two crewmembers. The goal is to obtain early, mid and late measurements of the Pitch and Yaw procedures to define the inflight adaption time course and correlate this with the postflight readaptation time constants as well. Figure 15 illustrates when the measurements occur relative to the hypothesized adaptation curves. Due to crew time constraints, the Roll and OKAN measurements are limited to the steady-state late mission part of the adaptation curves.

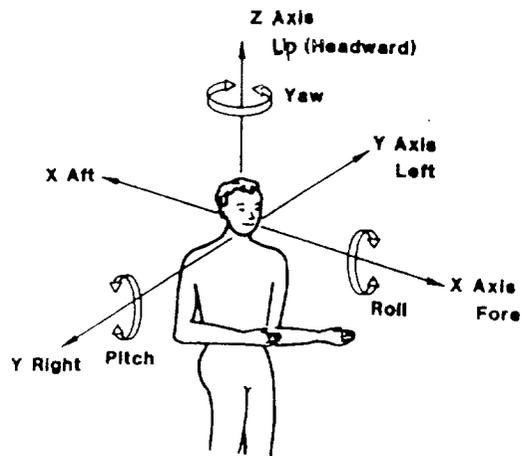


Figure 1. Illustration of Rotational Axis Frame of Reference.

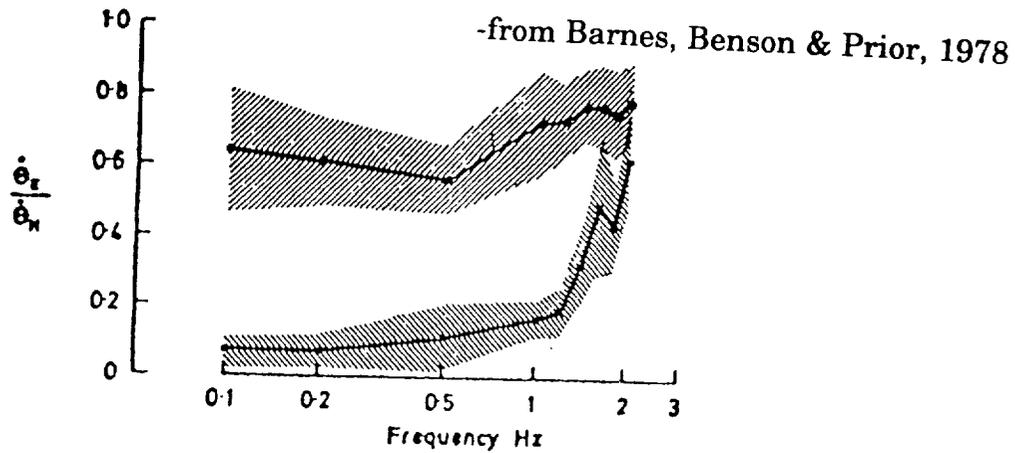
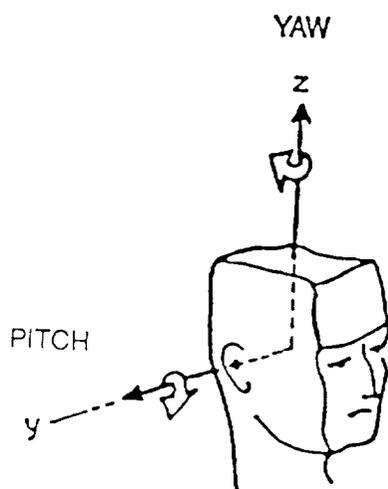
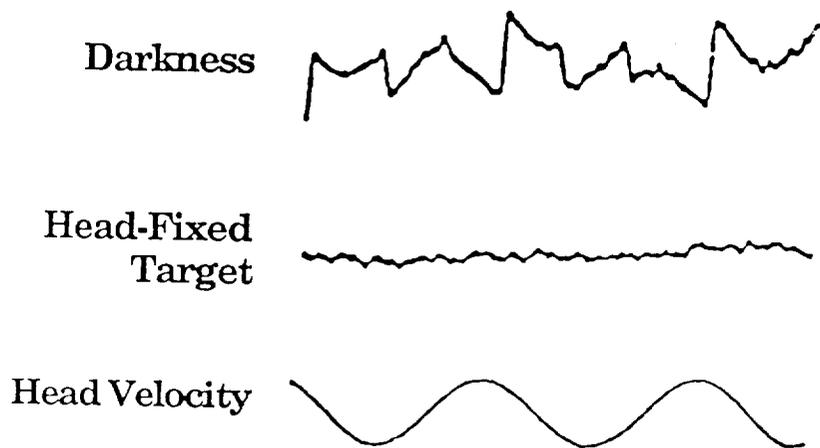


Figure 2. Comparison of the VOR and visual suppression of the VOR in humans. The upper curve shows the ratio of eye velocity relative to the head velocity (VOR gain) in the dark. The lower curve represents the same ratio when a head fixed target is present.

ROTATIONAL AXES



EYE MOVEMENT RESPONSES



STIMULUS CONDITIONS

Visual Conditions	Pitch Rotation	Yaw Rotation
Darkness	Sinusoids (0.05 & 1.25 Hz)	Sinusoids (0.05 & 1.25 Hz) Pseudorandom (0.02 - 1.39 Hz)
Head-Fixed Target	Sinusoids (0.05 & 1.25 Hz)	Pseudorandom (0.02 - 1.39 Hz)

Figure 3. VOR Suppression Experiment Protocol.

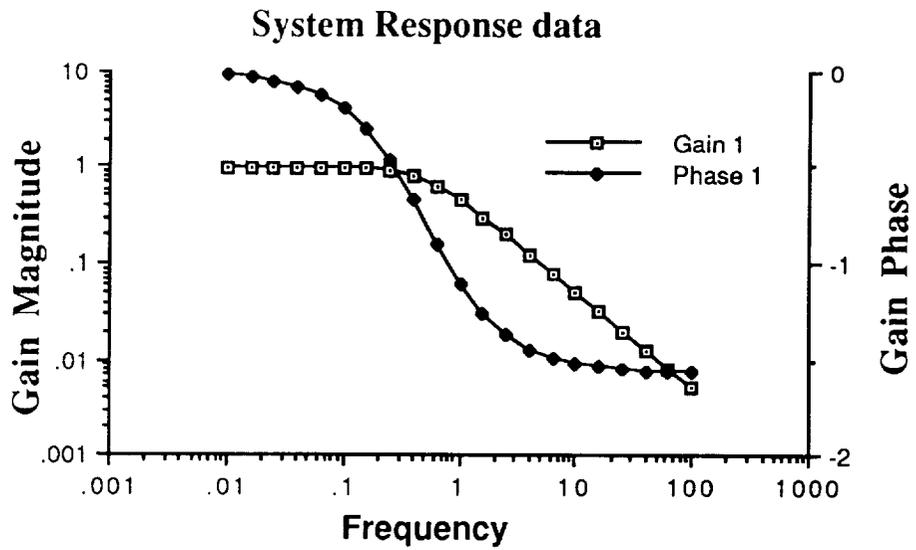


Figure 4. View of a gain-phase system analysis.

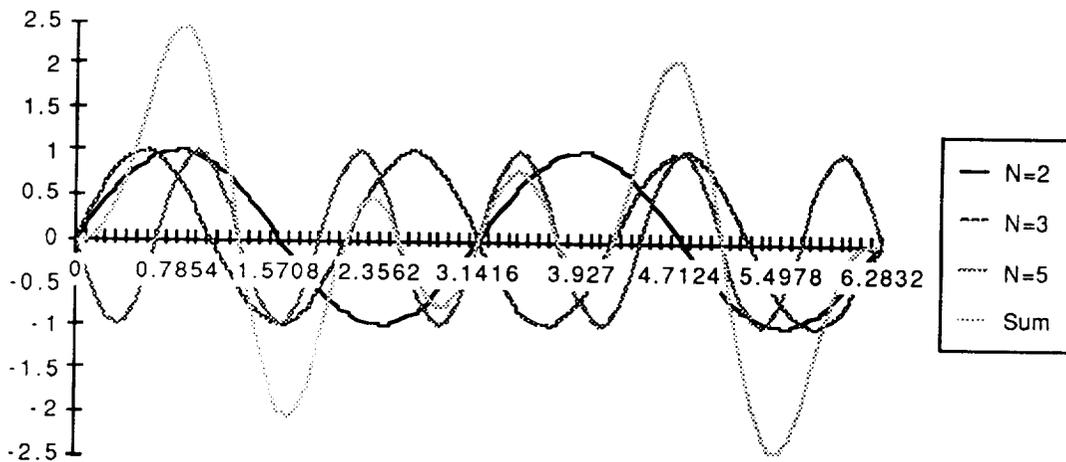


Figure 5. Illustration of a Sum-of-Sines Plot.

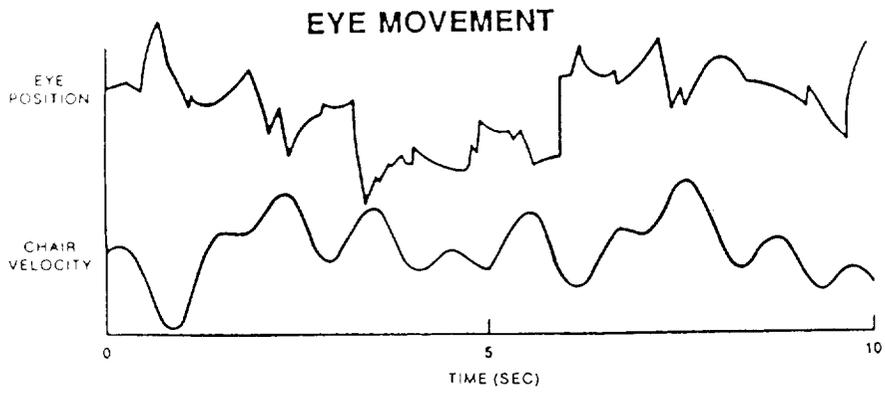
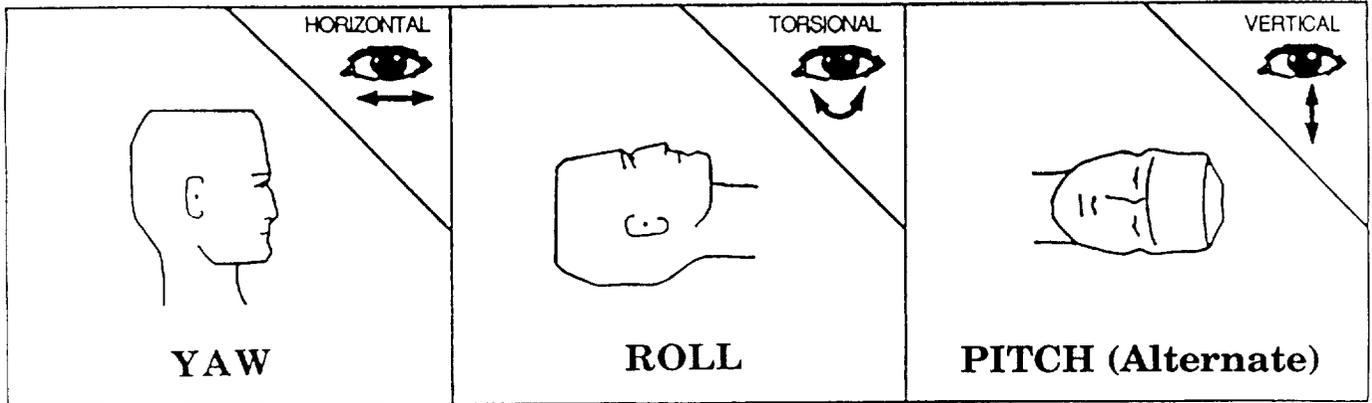
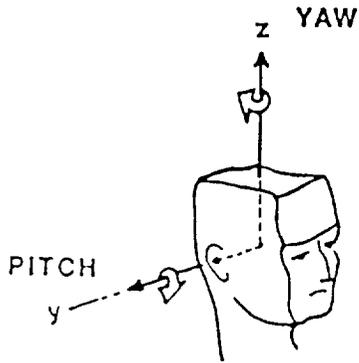


Figure 6. Semicircular Canal Dynamic Experiment Protocol.

ROTATIONAL AXES



STIMULUS CONDITIONS

Optokinetic Stimulus	Rotator Profile
± 40 °/sec	Static
OFF	Sinusoid (0.2 & 0.8 Hz)
± 40 °/sec	Sinusoid (0.2 & 0.8 Hz)

EYE MOVEMENT RESPONSES

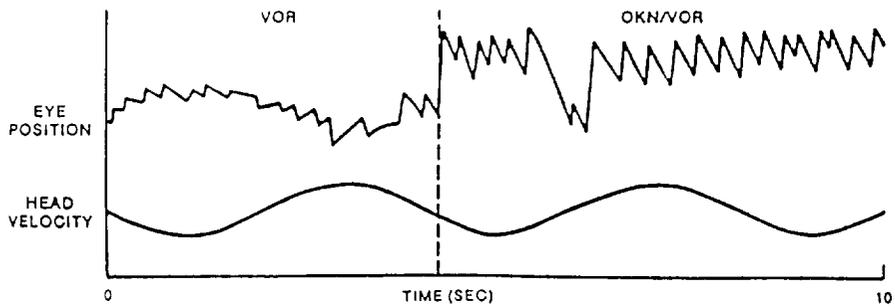
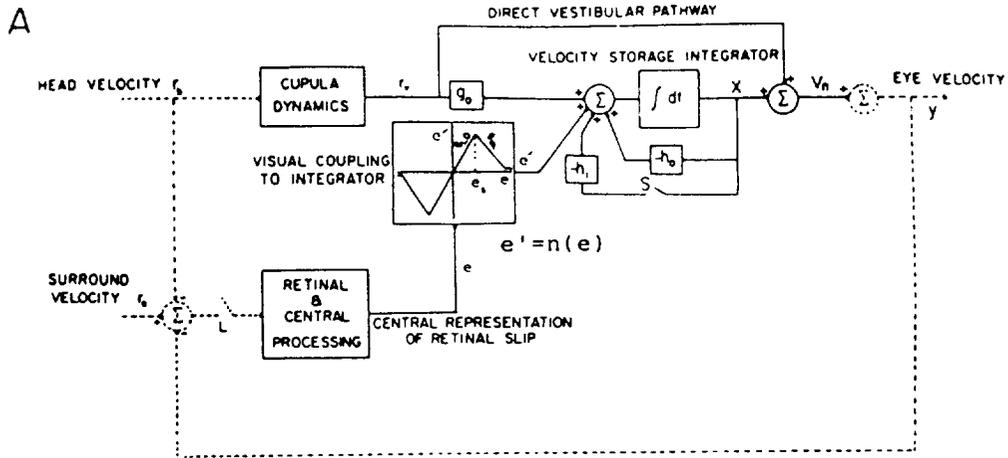
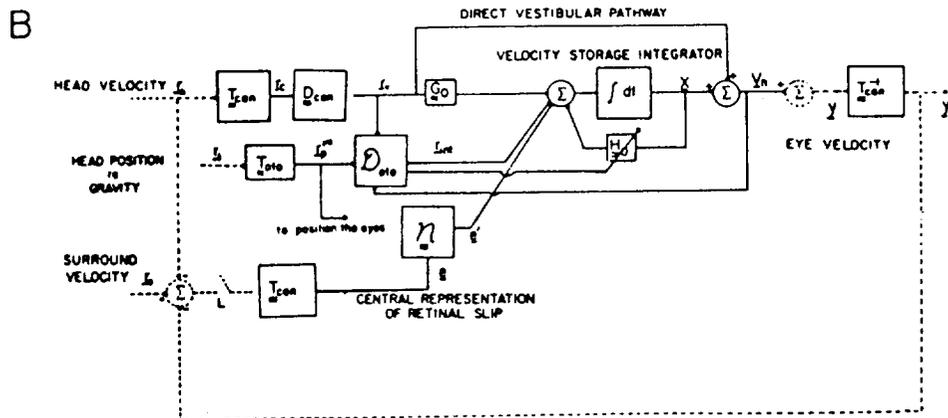


Figure 7. VOR Suppression Experiment Protocol.

ONE-DIMENSIONAL



THREE-DIMENSIONAL



(From Raphan & Cohen: Velocity Storage, 1988)

Figure 8. Velocity Storage Models.

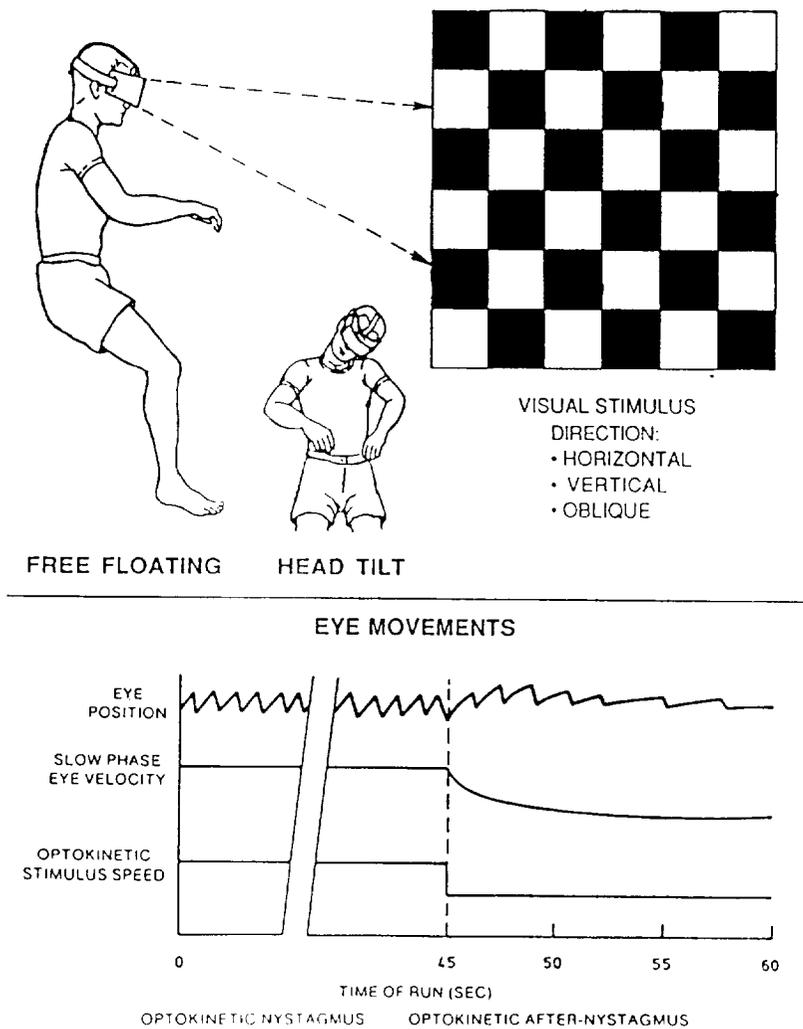


Figure 9. Optokinetic Responses Experiment Protocol.

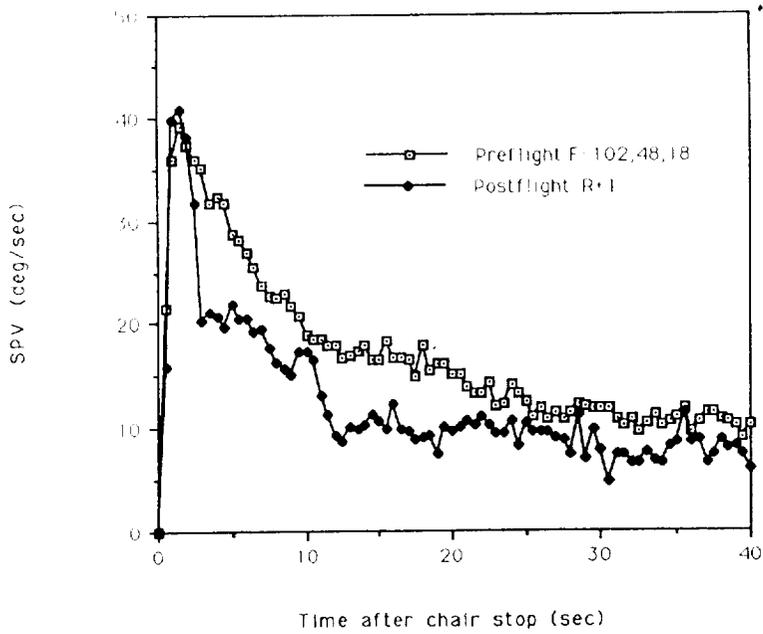


Figure 10. Preflight vs Postflight PRN Responses.

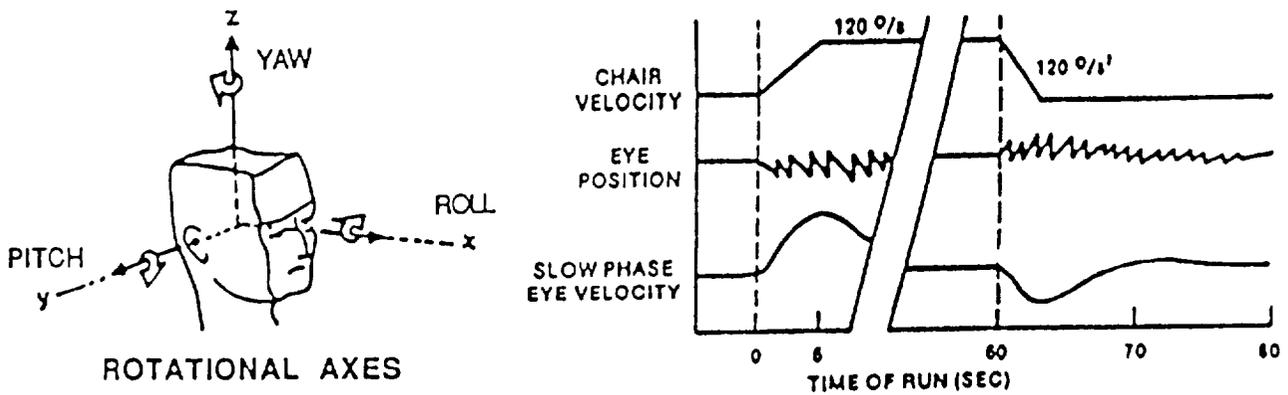


Figure 11. PRN Experiment Protocol.

DIRECTIONS: √ = symptoms you have experienced any time during the shift
 + = symptoms you have at the present time

MET time of reports (D/HH MM)

Sweat (slight) "mild clammy feeling"									
Sweat (moderate) "small beads of sweat"									
Sweat (intense) "profuse whole body"									
Pallor (slight) "limited to mouth, earlobes"									
Pallor (moderate) "involves face, torso"									
Pallor (intense) "white as a ghost, ashen"									
Subject warmth									
Flushing									
Dry lips/mouth									
Salivation (moderate) "swallowing more frequently"									
Salivation (intense) "copious amounts"									
Yawning									
Puffy face/stuffed nose									
Distorted smell/taste									
Back pain									
Lethargy									
Headache (slight) "intermittent, mild"									
Headache (moderate) "persistent"									
Headache (intense) "incapacitating"									
Dizziness (lightheadedness or vertigo)									
Disorientation									
Drowsiness (slight) "decr. mental alertness"									
Drowsiness (moderate) "feel like falling asleep"									
Drowsiness (intense) "literaly falling asleep"									
Apathy									
Concentration impaired									
Appetite loss									
Belching									
Epigastric awareness - intermittent, mild sensation (not uncomfortable)									
Epigastric discomfort - persistent and uncomfortable									
Nausea (slight), more intense and unpleasant									
Nausea (mod), feel like "reaching for the bag"									
Nausea (intense)									
Vomiting									
Sudden vomit									
MS medication effective									
Feeling Fine									

Figures 12. MVI Daily Motion Sickness Symptom Checklist.

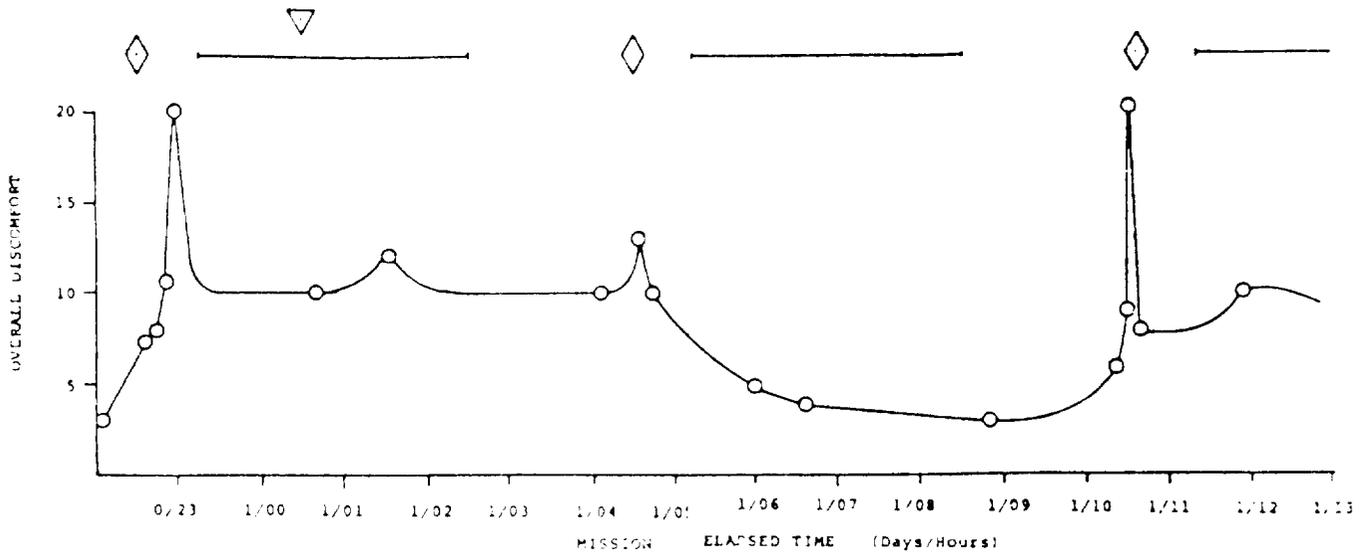


Figure 13. Subjective Comfort vs. Time for Subject B, Spacelab 1, Second day of orbit (Oman, et al., 1984).

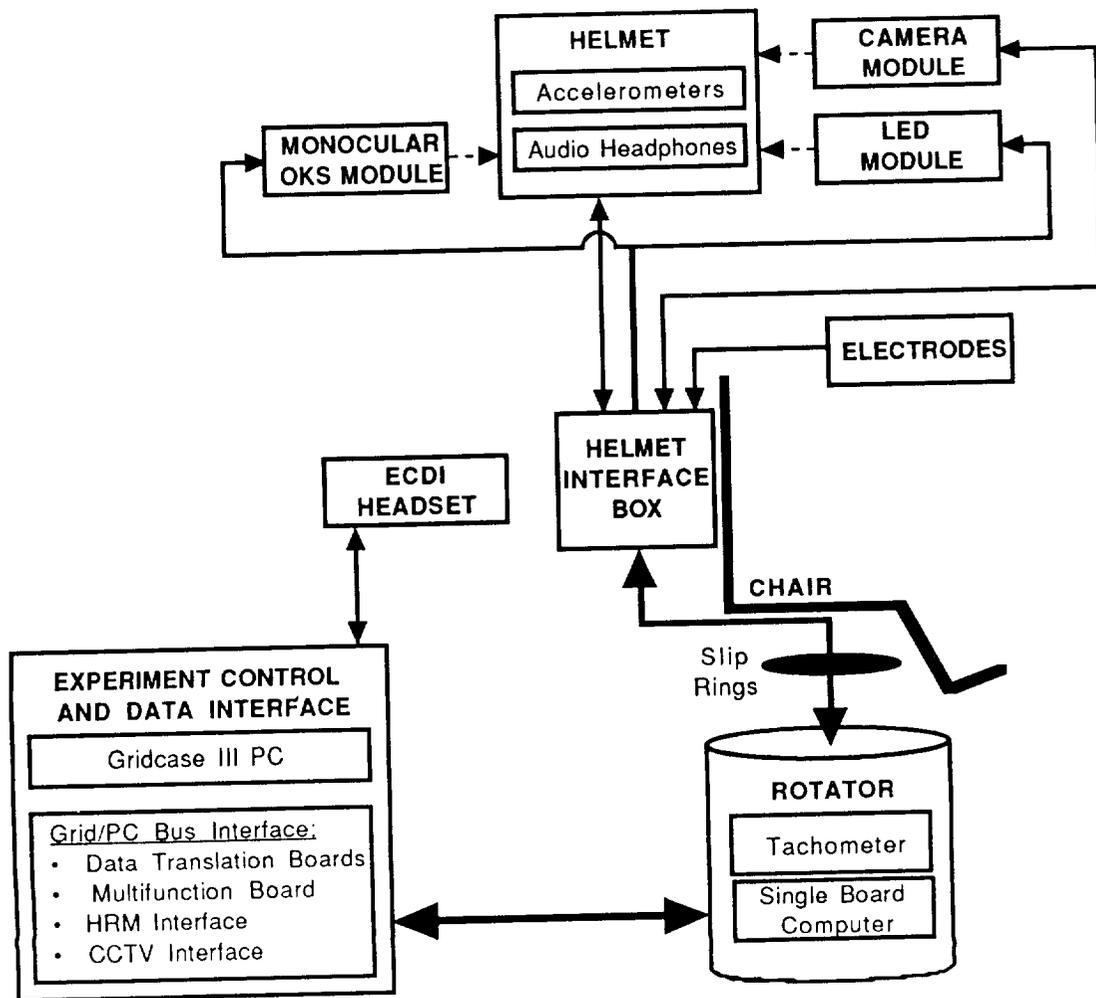


Figure 14. MVI Flight Hardware Block Diagram.

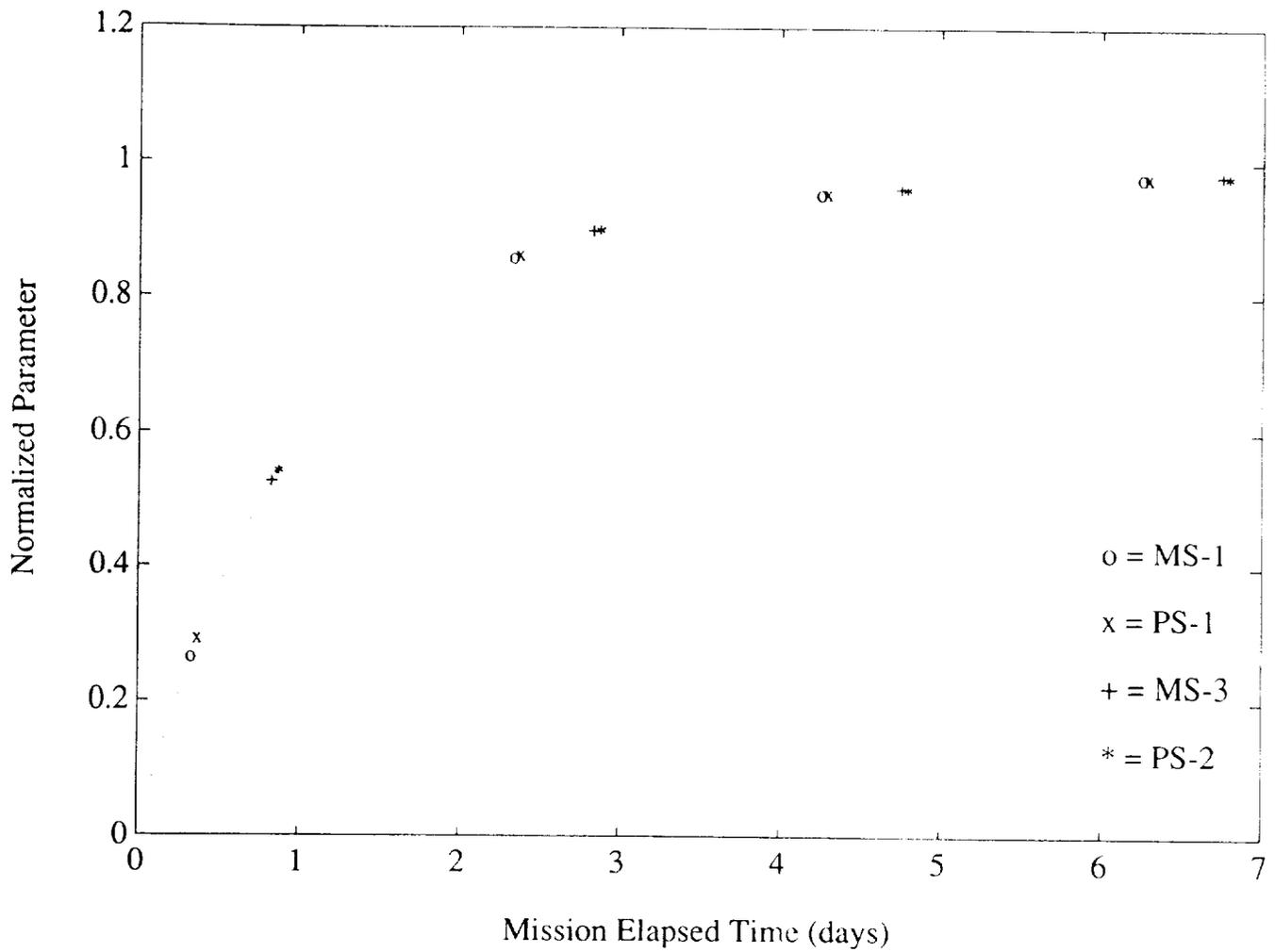


Figure 15. MVI Measurements in Pitch Relative to Theoretical Response Adaptation Curves.