Artificial Gravity:
Adaptation of the Vestibulo-Ocular Reflex to Head Movements During Short-Radius Centrifugation

by

Kathleen Helen Sienko

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Signature of Author: _____
Department of Aeronautics and Astronautics
May 19, 2000

Certified by: _____
Laurence R. Young, Sc.D.
Apollo Program Professor of Astronautics
Thesis Supervisor

Accepted by: _____
Professor Nesbitt Haygood
Chairman, Committee for Graduate Students

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Abstract

Short-radius centrifugation is currently being pursued as a potential countermeasure to long-duration space flight. Short-radius centrifugation requires relatively high angular velocities (on the order of 30 rpm) to create centripetal accelerations on the order of 1 g. Unfortunately, out-of-plane head movements during centrifugation induce inappropriate vestibulo-ocular reflexes, debilitating motion sickness symptoms, and illusory tilt sensations due to conflicting visual and vestibular signals. Practical use of an intermittent short-radius centrifuge as a countermeasure requires that crewmembers be capable of rapidly adapting to the unexpected semicircular canal inputs with minimal side- or post-effects. Furthermore, adaptation not only has to be achieved, it also has to be appropriate for the environment (stationary, rotating, 1 g, or 0 g).

The purpose of this research was to investigate humans' ability to attain and maintain adaptation to rotating environments. Subjects participated in a series of pre-/per-/and post-rotation data collection sessions consisting of both eye reflex recordings during head movements, a subjective battery of tests, and autonomic measurements. Eight subjects were tested on three days (D=1, 2, 8). Eye movements were measured in response to out-of-plane head movements during rotation at 23 rpm on-board the MIT short-radius centrifuge (r=2 m). Slow phase eye velocity (SPV) was reconstructed from filtered and de-saccaded eye movement data. The significant main effect of day and pre-/post-adaptation phase demonstrated that normalized SPV decreased following adaptation in the light.

Thesis Supervisor: Dr. Laurence R. Young
Title: Apollo Program Professor of Astronautics
Department of Aeronautics and Astronautics

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The miracle isn't that I finished....

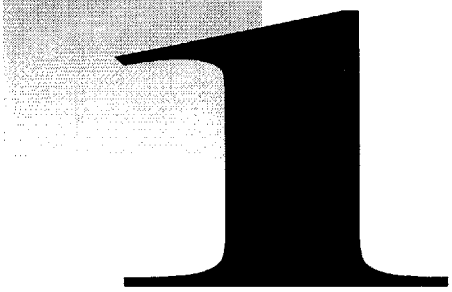
If you can imagine it, you can achieve it.
If you can dream it, you can become it.
-William Arthur Ward

The miracle is that I had the courage to start.

"We in the United States can lead the world in this noble venture or we can buy a ticket and just watch. I submit that America is proactive... If we lead the world, we will shape humankind's boldest adventure... We should be pursuing two parallel paths right now, and that's exactly what we are doing. These two parallel paths are robotic precursor missions and fundamental missions to understand the rigors of human space flight."

Daniel S. Goldin
Excerpt from oral remarks presented at the Steps to Mars Conference, July 15, 1995, Washington, D.C.

CHAPTER 1 INTRODUCTION



1.1 Physiological Effects of Long-Duration Space Flight

Long-duration exposure to weightlessness results in broad-spectrum physiological deconditioning. Despite significant flight experience in both the US and Russian space programs, the fundamental mechanisms triggering the degradation of wide-ranging physiological subsystems are unclear. Long-duration exposure to the stimulus of weightlessness, and to some extent, short-term exposure, results in alterations to bone physiology, skeletal muscle, sensorimotor integration, cardiovascular and pulmonary systems, endocrine and immune systems, and sociological behavior (National Research Council Space Studies Board, 1998).

The physiological response to the absence of gravity is both appropriate to the environmental requirement and demonstrative of human adaptability. The issue is, not whether the changes are appropriate for the microgravity environment, but rather if the changes detrimentally affect the safe return to and productivity in a gravito-inertial environment (Grymes, Wade, & Vernikos, 1996). Such responses, if left untreated, could lead to serious problems following return from weightlessness (Young, 1999). Therefore, counteractive measures must be taken to maintain the integrity of the body's physiological responses associated with specific gravito-inertial environments. In addition to protection from radiation exposure beyond the Earth's magnetic field, such countermeasures require urgent development before committing to human Mars exploration (Young, 1999).

1.2 Countermeasures

Recently, the case for artificial gravity as a countermeasure has been revived because existing treatments such as exercise, resistive training, lower body negative pressure, diet, fluid loading, and pharmaceuticals have proved ineffective in dealing with the complete gamut of physiological deconditioning associated with long-duration space flight. It is particularly difficult to assess the previous success of countermeasures due to variability between subjects, limited systematic observations using identical protocols, variability in mission duration and profile, and interaction between individual countermeasures (Grymes et al., 1996).

Countermeasures can be classified into three primary categories (Grymes et al., 1996):

- Those that are administered continuously or periodically throughout the flight to maintain the integrity of the body's physiological programs associated with a gravito-inertial environment. Examples include: artificial gravity, exercise, and lower body negative pressure.

- Those that restore or correct a deficit that is only of concern during a transition to a new gravito-inertial environment, g field, or a new activity (EVA), and is therefore administered immediately before such a transition. Examples include: fluid loading, mineral supplements, and gravity suits.

- Those that depend on the preflight selection to identify candidates who would be most adaptable to the space environment or most at risk. One example is an astronaut selection criterion for slow bone turnover.

The scientific community has failed to identify a sole countermeasure, or for that matter, a combination of existing countermeasures which is 100% effective in preventing physiological compromises upon return to Earth.

1.3 Artificial Gravity

The concept of artificial gravity has occupied the minds of scientists, engineers, and dreamers since the advent of the realization of human space flight. Speculations on the use of a rotating device to produce artificial gravity appear in Jules Verne's publication of *Around the Moon* in 1865. As early as 1911, Russian scientist E. K. Tsiolkovsky wrote in his work, *Space*

Exploration by Jet Devices, "Had it been even proved that people could not live without gravity, it would have been easily generated artificially in a gravity-free environment. To do this, spin has to be imparted to the human dwelling, even if it is a rocket; then as a result of action of a centrifugal force an apparent gravity of a desired magnitude, depending on a dwelling size and the rate of its rotation, is generated. This gravity is convenient because its magnitude can be arbitrarily low or high and because it can be always eliminated and initiated again" (Shipov, 1991). Large rotating structures are an unlikely solution because they are both complex and expensive. Short-radius centrifuges, on the other hand, offer a space-efficient, and cost-effective alternative.

1.4 Motivation

Artificial gravity is being actively pursued as a prospective countermeasure to prevent the physiological side effects associated with long-duration space flight. During rotation, inappropriate vestibulo-ocular reflexes, motion sickness symptoms, and illusory tilt sensations result from head movements made into and out of the plane of rotation. Additionally, frequent transitions between the rotating and non-rotating environment pose the challenge of maintaining appropriate adaptation schemas for various gravito-inertial environments in order to minimize recurring debilitating motion sickness symptoms and degradation in overall performance. However, based on numerous investigations concerning the plasticity of both human and animal vestibulo-ocular reflexes, it is reasonable to assume that with repeated exposure to short-radius centrifugation, inappropriate eye responses and motion sickness symptoms can be reduced. This research, referred to as the MIT artificial gravity adaptation study, considers several physiological and subjective measures of adaptation to the rotating environment. Specifically, this thesis examines the vestibulo-ocular reflex adaptation to head movements during short-radius centrifugation.

1.5 Hypothesis

The primary hypothesis was that repeated exposure to a series of yaw head movements made during short-radius centrifugation at 23 rpm in the light will result in a decrease in inappropriate

non-compensatory vertical eye movements, motion sickness symptoms, and illusory tilt sensations. Additionally, the acquired adaptation would be retained to some extent, if not completely, from one experimental session to the next. The secondary hypothesis was that this adaptation was context-specific to the rotating environment.

1.6 Thesis Organization

Chapter 2 introduces the physics associated with rotating structures, artificial gravity concepts and questions currently being addressed by the scientific community, and a brief overview of the former Soviet Union's artificial gravity research efforts. Next, the vestibular system is described with a special emphasis placed on reviewing the functionality of the vestibulo-ocular reflex. This chapter closes with an in-depth look at the experimental stimulus.

Chapter 3 describes the experimental methods employed in the MIT artificial gravity adaptation study. The design of the experiment, subject selection criteria, and equipment used are discussed. The experimental procedure is outlined in great detail.

Chapter 4 delves into the data processing and analysis techniques used to assess adaptation. The data reduction process is described and the tools used to process the data are highlighted. The measures selected to assess the degree of adaptation attained and maintained are presented in addition to the method used to replace missing data points.

Chapter 5 presents the results of the data analysis. This chapter focuses on the characteristics of the head movements conducted within the rotating environment, the normalized slow phase velocity values both before and following exposure to the light adaptation phase, and the measurement of cumulative slow phase position for the acceleration and deceleration phases of the experiment.

Chapter 6 discusses the major results from the MIT artificial gravity adaptation study and their potential implications. Comparisons are made between previous adaptation investigations and the present findings of this investigation. Subjective results are summarized and an 12-day pilot

study is explained. Recommendations concerning future research based upon the findings of this investigation are described.

Chapter 7 concludes this work by summarizing the main results and advocating additional research in the artificial gravity arena. Short-radius centrifugation is supported as a potential countermeasure to the adverse effects of long-duration space flight.

CHAPTER 2 BACKGROUND

2.1 Physics of Rotating Structures

The rotating environment can be characterized by centripetal accelerations, gravity gradients, Coriolis Forces, and cross-coupled angular accelerations. The acceleration due to Earth's gravitational force, denoted by the symbol g, has a magnitude approximately equal to 9.80 m/s^2 at the Earth's surface. Therefore, the magnitude of Earth's gravitational force on a body is equal to the mass of the body multiplied by 9.80 m/s^2. Similarly, we denote the acceleration associated with the centrifugal force in a rotating environment as artificial gravity. The magnitude of artificial gravity produced in a rotating environment is dependent on both angular velocity and radius according to the following relationship:

$$\alpha = \omega^2 r$$

where α is acceleration in meters/second^2, ω is angular velocity in radians/second, and r is radius in meters. Figure 1 shows the gravity level trade-offs when the rate of rotation (ω) and radius (r) are manipulated. The x-axis corresponds to the radius, which ranges between 1 and 50 meters.

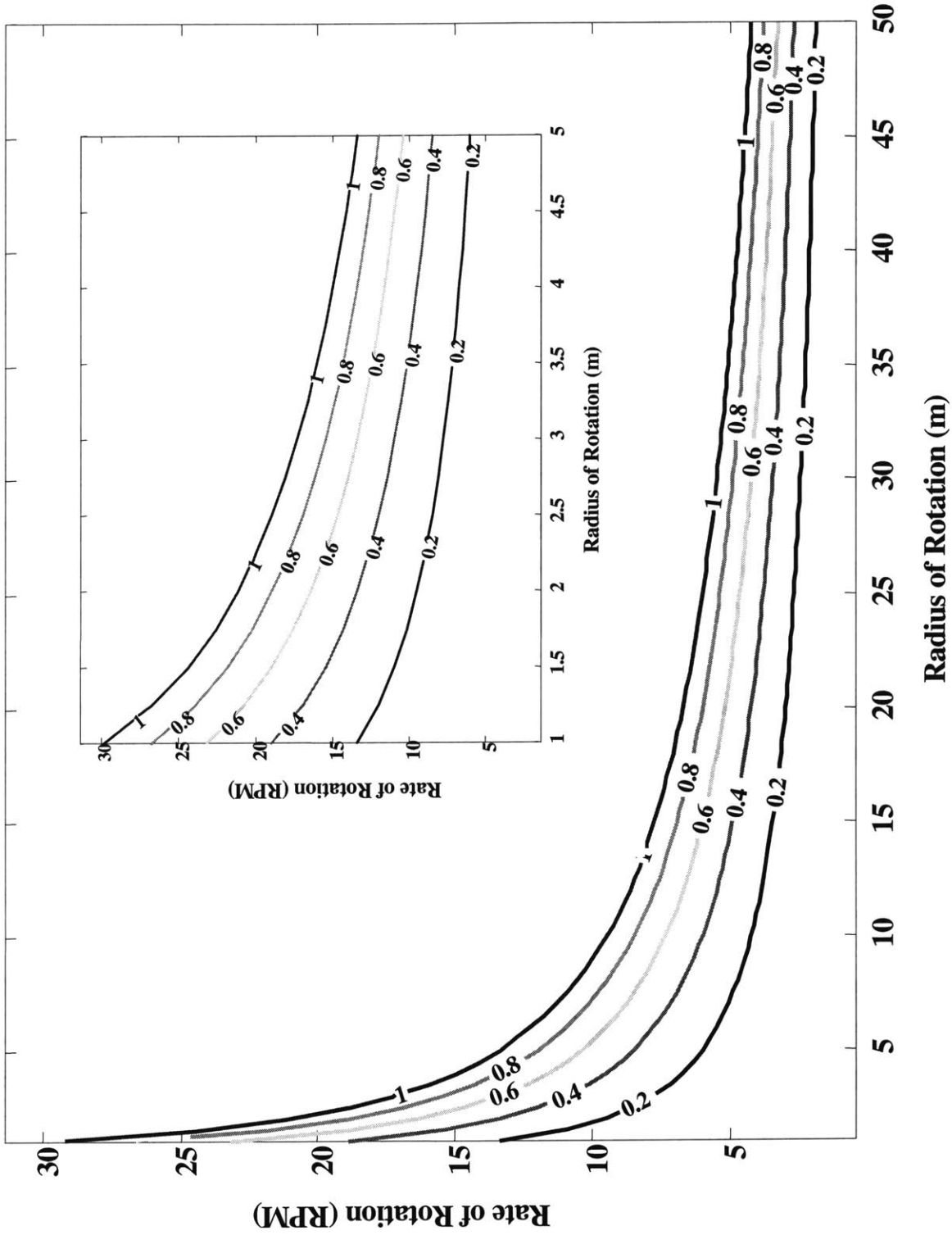


Figure 1. Artificial Gravity Level Tradeoff

Because the centripetal acceleration in a rotating environment is a linear function of radius, a linear 100 % gravity gradient exists from the center of rotation to the outer rim of the rotating environment (Diamandis, 1997). The gravity gradient can be mathematically expressed as the difference of radii divided by the radius at the outer rim of the rotating structure (Young, 2000). The long-term physiological consequences of exposure to gravity gradients are unknown.

In the early 1800's, French engineer and mathematician, G. G. de Coriolis, carried out a mathematical analysis of an apparent linear force generated when a body moved in a linear path within a rotating environment (Graybiel, 1975). This phenomenon, subsequently termed Coriolis Force, refers specifically to the forces and linear accelerations that occur when a body moves in a straight line within a rotating frame-of-reference with respect to a fixed inertial frame-of-reference (Young, 2000). The magnitude of the Coriolis Force is dependent on the velocity of the body moving linearly within the rotating environment and not on its position; bodies moving in a direction parallel to the axis of rotation will not experience Coriolis Forces. The right hand rule is a useful tool for determining the appropriate direction of the Coriolis Force when performing a cross-product calculation. The Coriolis Force as observed in the rotating frame-of-reference is given by the following equation:

$$F = -2\ m\ (\boldsymbol{\omega} \times \mathbf{v})$$

where m is the mass of the body, $\boldsymbol{\omega}$ is the angular velocity of rotating environment, and $\mathbf{v}$ is the linear velocity of the body.

For a complete mathematical analysis of Coriolis Forces, refer to Stone (1970) and Graybiel (1975).

Cross-coupled angular acceleration is the term assigned to the phenomenon that occurs when the head is tilted out of the plane of rotation when rotating about an axis that is not parallel to the axis of the tilt (Young, 2000). Originally this phenomenon was referred to as the Coriolis Phenomenon. Cross-coupled responses, due to the stimulation of the semicircular canals by the interaction of angular motion in two planes, can be analyzed in terms of the Coriolis Forces

induced within the endolymph fluid of the semicircular canal during head movements (Benson, 1999). According to both Benson (1999) and Young (2000), it is conceptually simpler to consider the semicircular canals as angular rate sensors and analyze how the displacement of the endolymph fluid with respect to the canal changes during cross-coupling head movements. The magnitude of the cross-coupled angular acceleration is the product of the two angular velocities times the sine of the angle between their axes of rotation. It is directed along an axis orthogonal to both the head velocity and the reference frame angular velocity, according to the right hand rule (Young, 2000).

$$\text{Cross-coupled orthogonal acceleration} = -(\omega_{Centrifuge} \times \omega_{Head})$$

where $\omega_{Centrifuge}$ is the angular velocity of the centrifuge and ω_{Head} is the angular velocity of the head. Cross-coupled angular accelerations are commonly experienced during flight when a pilot makes an angular movement of the head to read an instrument or check a switch while the plane is engaged in a constant rate of turn (Benson, 1999).

2.2 Human Factors

Radial or tangential translation in the rotating environment, such as angular head movements, can result in unexpected physiological, mechanical, and perceptual phenomena (Ramsey, 1971). These phenomena may result in a diminution in gross motor performance (self-locomotion, material handling, force and torque applications) and fine motor performance (dexterity, eye-hand coordination with head motions) (Stone, 1970). Additional side effects of movements within the rotating environment include spatial illusions, motion sickness, and a general degradation in overall performance (Ramsey, 1971). The degree to which these factors influence mission success will vary with the magnitude of the phenomena; they are primarily a function of angular velocity, the degree to which adaptation occurs, and the degree to which appropriate equipment design and mission constraints are employed (Ramsey, 1971). For example, controls and displays in the rotating environment could be designed such that crewmembers predominately make in-plane head movements thereby reducing disturbing effects associated with out-of-plane head movements and cross-coupled angular accelerations (Ramsey, 1971).

2.3 Artificial Gravity Concepts

Today's artificial gravity alternatives to the large rotating torus highlighted in historical science fiction movies consist of rotating tethered devices, fixed-truss assemblies, and on-board short-radius centrifuges (Young, 1999). Fundamental concerns pertaining to large rotating spacecraft remain the same:

- Radius and rate of rotation for effective performance and acceptable habitable conditions.
- Cost of attaining desired conditions as measured in dollars, weight, moments of inertia, angular momentum, rotational energy, fuel use, and stability (Stone, 1970, and Young, 1999).

As previously indicated, artificial gravity can take the form of large rotating structures or on-board short-radius centrifuges. Additionally, artificial gravity can be delivered continuously or intermittently. Large rotating structures, like Von Braun's 125-foot torus rotating at 3 rpm, would provide continuous gravity with minimal vestibular and motor control side effects (Young, 2000). Rotating spacecraft, regardless of the specific structure (torus, tethered device, or fixed-truss assembly), are complex in nature and costly. On-board short-radius centrifuges, on the other hand, can provide intermittent gravity at a lower technical and monetary price. However, short-radius centrifuges require higher angular velocities to obtain the centripetal accelerations of larger rotating spacecraft.

2.4 Artificial Gravity Questions

Despite significant ground-based research investigating human responses to centrifugation, minimal on-orbit research has been conducted to address the fundamental questions surrounding artificial gravity as a countermeasure to the negative physiological effects of long-duration space flight. At this time, the scientific community lacks the empirical knowledge to assess many critical issues regarding artificial gravity as outlined in the 1999 Artificial Gravity Workshop held in League City, Texas (Paloski, Young, 1999). Among the issues are:

- What relationships exist between operational performances and continuously applied artificial gravity (between 0 g and 1 g)? How does supplemental exercise affect these relationships?
- What relationships exist between operational performances and intermittently applied artificial gravity?
- What are the acceptable ranges of radius and angular velocity required to maintain operational performance in a rotating spacecraft? What are the optimal ranges for these same parameters?
- What is the human capacity for dual adaptation, and how can the transition process between different gravitational environments be investigated systematically?
- What are quantifiable standards for operational performance during a mission? What are the limits for degradation of the specific systems during various phases of a mission to Mars?

These questions must be answered before adopting artificial gravity as a countermeasure.

2.5 Review of Artificial Gravity Research

Extensive summaries of past research pertaining to slow-rotating room facilities and centrifuges have been annotated by Young (1999) and Shipov (1996), and chronologically tabulated by Hastreiter (1997). Because of the broad literature that exists describing the history of the United States' ground-based artificial gravity research, I will briefly summarize the former Soviet Union's major contributions.

In the 1960's, two ground-based rotating devices, MVK-1 and Orbita, developed in the Soviet Union, permitted scientists to examine the long-term effects of centrifugation on human subjects. The MVK-1 centrifuge allowed two subjects to rotate for up to seven successive days (Kotovskaya, 1981). The axis of rotation ran through the center of the floor and the centrifuge operated at speeds ranging from 0.9-6.6 rpm. The small cabin area (3 m^2) resulted in limited freedom of movement (Shipov, 1996). The 20-meter diameter Orbita on the other hand, had comfortable living conditions (7 m^2) that accommodated longer stays and a rotation rate that ranged from 1-12 rpm (Kotovskaya. 1981). Early studies concluded that head movements during the initial minutes of rotation resulted in illusions and dizziness, disrupted equilibrium during locomotion in the cabin, and hampered coordination of movements (Shipov, 1996). Following 30-60 minutes of rotation, subjects reported symptoms consisting of sweating, chills or hot

flashes, changes in pallor, excessive salivation, stomach discomfort, and vomiting (Shipov, 1996). Additionally, drowsiness, sluggishness, and headache symptoms were noted after 4-5 hours of rotation (Shipov, 1996).

Both the severity of reported motion sickness symptoms and the time required to adapt to prolonged rotation were directly related to angular velocity (Shipov, 1996). No subjects were reportedly ill when rotated at 1 rpm. When the rotation rate was increased to 1.8 rpm, head movements resulted in moderate motion sickness symptoms. These symptoms increased as the rotation rate was increased to 3.5 rpm. Shipov (1996) noted that head movements actually facilitated adaptation to rotation despite the fact that they generally elicited increased motion sickness symptoms. Freedom of movement was also noted to affect the adaptation process. On the small MVK-1 rotating room, motion sickness symptoms were severe at relatively slow rotation rates (i.e., 1.8 rpm). On the larger Orbita however, no symptoms were reported at 1.8 rpm (Shipov, 1996). It is important to note that adaptation to a rotating environment occurred for human subjects at angular velocity rates less than 6 rpm after six to eight days of rotation (Shipov, 1981). Therefore, the degree of one's motor activity in the rotating system not only determined the severity of symptoms of motion sickness, but substantially influenced adaptation to rotation (Kotovskaya. 1981). At rotation rates exceeding 6 rpm, adaptation was only achieved with the use of special countermeasures (incremental increases in rotation rate, selection of subjects showing tolerance to vestibular exposures, preliminary training, and the use of pharmacological countermeasures against motion sickness) (Shipov, 1996).

In 1975, experiments with plants and lower vertebrates, specifically fish and turtles, were flown aboard the Cosmos-782 biosatellite. These experiments demonstrated that the biological effect of 1 g generated via an on-board centrifuge during long-duration space flight, has basically the same character as the terrestrial force of gravity (Shipov, 1981). The Biosatellite rotating platform had a radius of 37.5 cm that was rotated at 52 rpm to generate approximately 1 g at the outer rim. Following the flight, the centrifuged plants and animals were compared to the ground-based control groups. No significant biological differences were reported. The 18.5-day Cosmos-936 flight (August 3-22, 1977) provided a further platform for the continuation of 1 g studies in space. The rats used in this investigation were separated into five groups: a weightless group, a

weightless group with artificial gravity, a control group, a ground-based centrifuged group, and a control group subjected to simulation of launch, reentry, and landing forces. The biosatellite housed 30 rats, 20 in the weightless group and 10 in two on-board centrifuges. During the flight the centrifuges were rotated at 53.5 rpm (radius equaled 32 cm) to generate approximately 1 g at the radius. Thirty days prior to the flight, clinical examinations were conducted in parallel with surgical implantations of biosensors and/or operations on some rats (i.e., labyrinthectomy), training, and selection (Gurovsky et al, 1980). On the recovery day, ten rats from the weightless group and five rats from the artificial gravity group were sacrificed for morphological and biochemical analysis (Gurovsky et al, 1980). The remaining weightless group animals (both non-artificial gravity and artificial gravity) were used in physiological examinations at various intervals during re-adaptation. They were subsequently sacrificed 25 days post-flight for morphological and biochemical analysis (Gurovsky et al, 1980). The results showed normalizing effects of artificial gravity on the functional state of the myocardium, musculoskeletal and excretory systems in laboratory rats (Gurovsky, et al, 1980, Shipov, 1981). Adverse effects were reported due to artificial gravity involving functions that required visual, vestibular, and motor coordination (Shipov, 1981).

Although several parabolic flights and sub-orbital rockets have been used to examine the physiological effects of g levels measuring less than 1 g, no research has been conducted to date to address such effects during long-duration space flight (Shipov, 1996). Biosatellite Cosmos studies, however, showed that 0.3 g was enough to prevent atrophic muscular alteration for turtles and rats (Shipov, 1981). This result coincides with the experimentally determined minimum effective magnitude of artificial gravity necessary for normal locomotor and postural activity in man, rats, and mice, as well as bioelectrical muscular activity in dogs (Shipov, 1981). On this basis, the general consensus amongst the former Soviet Union scientists was that the minimum effective AG level is 0.3 g (Kotovskaya, 1981, Shipov, 1996). Interestingly, in the early 20th century, Russian scientist Tsiolkovsky estimated that 0.28 g was the minimum force of gravity necessary to maintain physiological integrity (Shipov, 1981). As a result of Soviet ground-based rotating room studies, 6 rpm was reported to be the maximum acceptable angular velocity rate supporting timely adaptation (Shipov, 1981). Therefore, given these two values that characterize artificial gravity systems (maximum angular velocity equaling 6 rpm and a

minimum gravitational force equaling 0.3 g), the required radius for a rotating platform would have to be at least ten meters in length (Shipov,1981).

2.6 The Vestibular System

The vestibular system is the primary organ responsible for maintaining equilibrium during motion and spatial orientation. Vestibular inputs to the postural control system elicit muscle responses and adjustments in body position to prevent falling. Vestibular influences on eye movements stabilize the eyes in space during head movements (Young, 1974).

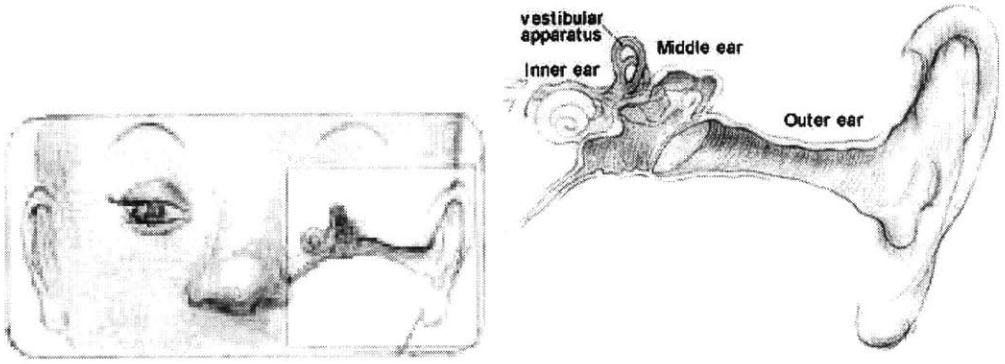


Figure 2. Schematic of Vestibular System
(Lujan & White, 1999)

The auditory and vestibular systems are intimately connected. The inner ear (Figure 2), positioned in the compact petrous part of the temporal bone, is comprised of the osseous labyrinth (bony labyrinth) and the membranous labyrinth. The osseous labyrinth consists of three parts: vestibule, semicircular canals, and cochlea (Figure 3) (Gray, 1970). Within the osseous vestibule, the membranous labyrinth diverges from the shape of the bony cavity and forms two membranous sacs, the utricle and saccule. The membranous labyrinth, a continuous membrane, is suspended inside the bony labyrinth and filled with endolymph fluid. Endolymph fluid resembles intracellular fluid and is high in potassium and low in sodium. The ionic composition is necessary for vestibular and auditory hair cells to function optimally (Gray, 1970). The space between the membranous and bony labyrinths is filled with perilymph, which resembles normal cerebral spinal fluid.

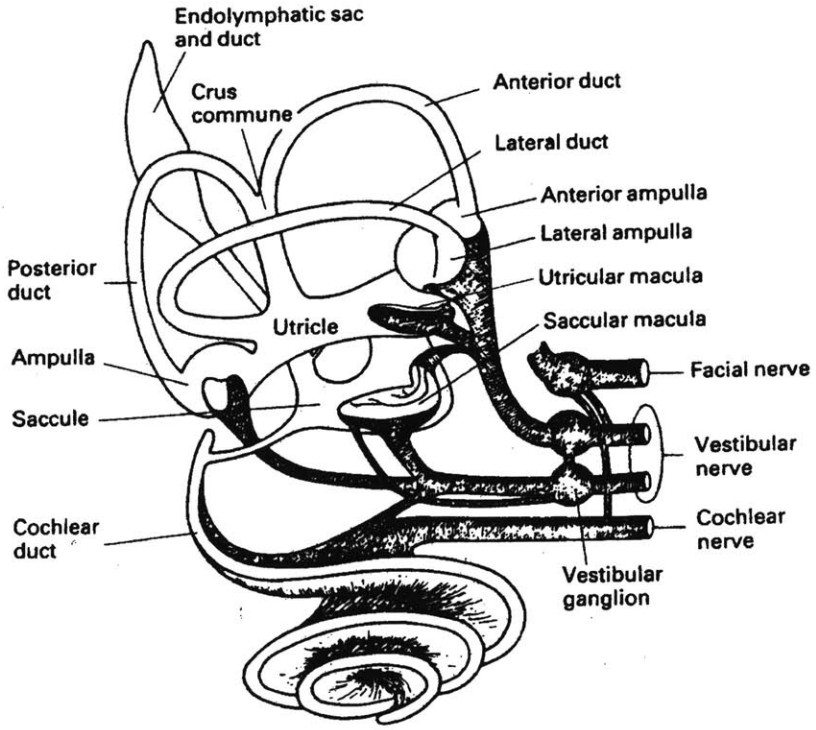


Figure 3. Anatomy of the Vestibular System
(Benson, 1999)

2.6.1 Otolith Organs

Within both the utricle and saccule is a sheet of hair cells called the macula whose cilia and calcium carbonate granules termed otoliths are embedded in a gelatinous mass. The specific gravity of the otoliths is several times greater than that of the surrounding endolymph (Goldstein, 1974). The otoliths provide the inertia, so that when the head is tilted, the otolith-gel mass slides downhill, and lags behind when the head is accelerated with respect to inertial space (Figure 4) (Young, 1984a). Linear acceleration or tilting of the head stimulates the utricle and results in the transmission of a shearing or bending force to the hair cells (Goldstein, 1974). The utricle and saccule detect linear acceleration and changes in orientation with respect to the gravity vector (Figure 5) (Young, 1984a). The hair cells in the utricle and saccule are polarized and arrayed such that collectively, they detect acceleration in all three directions (Young, 1984a). The utricle lies generally horizontally in the ear and can detect any motion in the horizontal plane. The saccule is oriented vertically, so it can detect primarily motion in the sagittal plane (Molavi, 1999).

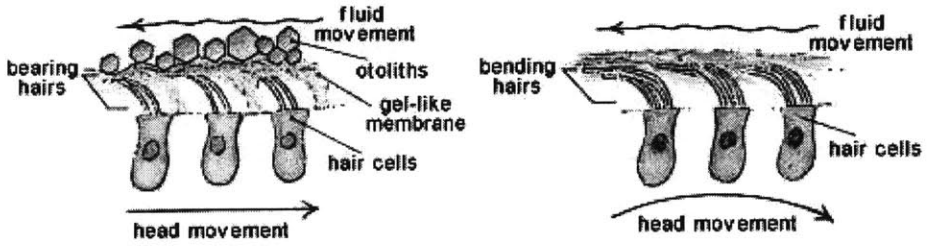


Figure 4. Vestibular Hair Cell Dynamics
(Lujan & White, 1999)

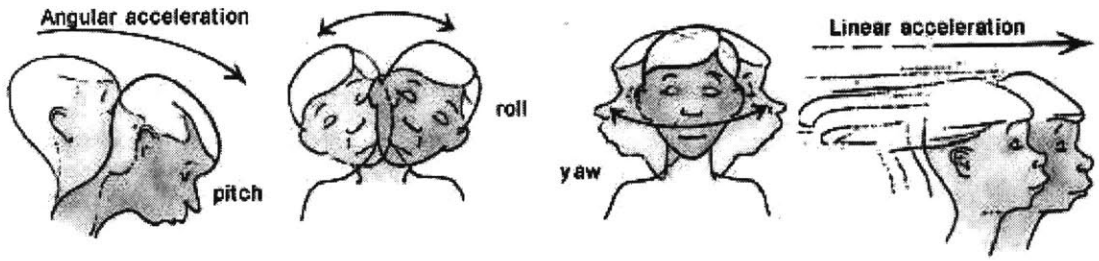


Figure 5. Angular and Linear Head Accelerations
(Lujan & White, 1999)

2.6.2 Semicircular Canals

The superior, posterior, and lateral semicircular canals are located in each labyrinth. The fluid-filled canals lie in nearly orthogonal planes, with the exception of the lateral or horizontal canal, which is pitched upward by an angle of 25-30 degrees from the horizontal plane of the head (Young, 1974). The superior and posterior canals lie approximately at right angles to one another and to the lateral canal and at 45-55 degrees from the sagittal and frontal planes (Young, 1974). The canals are aligned such that the two lateral canals of the two ears are parallel, and the posterior canal of one ear is in nearly the same plane as the superior canal of the other ear. This nearly orthogonal arrangement of synergistically paired canals facilitates the generation of afferent signals indicating rotation in any direction, which evokes compensatory eye movements (Young, 1974).

The semicircular canals detect angular acceleration (Figure 5). Each semicircular canal measures roughly 0.8 mm in diameter but the three canals are unequal in length (Gray, 1970). At the end

of each canal, the diameter dilates to more than twice the diameter of the canal tube to form the ampulla which houses the sensory hair cells (Figure 6). The ampulla is the site of the transduction of mechanical torque or displacement to neural afferent signals via sensory cells (Young, 1974). The hair cells are located on the crista that sits in the ampulla. The crista is covered by a gelatinous cupula approximately the same density as endolymph fluid (Young, 1974). The canals of the membranous labyrinth are filled with endolymph. Endolymph is slightly more dense and viscous than water (Young, 1974). The fluid serves to protect the delicate mechanism from mechanical shock and accounts for its behavior as a motion transducer (Young, 1974). The cupula forms a seal across the ampulla preventing endolymph fluid from circulating. The hair cells are arranged in bundles that project up into the cupula. Each bundle of hair cells is polarized. The longest hair cell within a bundle is referred to as the kinocilium. The remaining hair cells decrease in length as the relative distance from the kinocilium increases. The resting discharge of the hair cells increases when the cilia are deflected toward the kinocilium and decreases when the cilia are deflected away from the kinocilium. Angular accelerations displace the endolymphatic fluid, causing a subsequent motion of the cupula (elastic torque to return the cupula to its rest position) that stimulates the sensory cells (Figure 4).

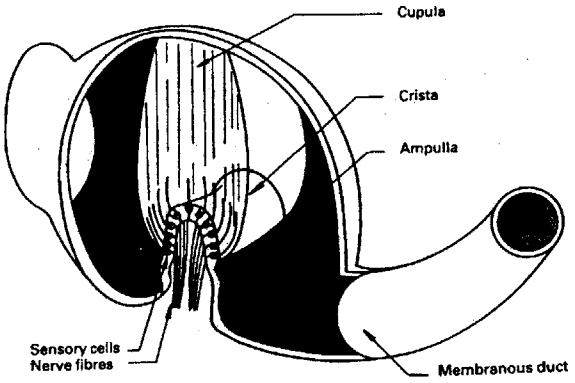


Figure 6. Ampulla
(Benson, 1999)

The cupula dynamics activate the hair cells responsible for coding the afferent discharge (Figure 7). In the absence of stimulation, there is a resting discharge (Gray, 1970; Young, 1974). The canals on either side of the head operate in a push-pull rhythm; when one is excited, the other is inhibited (Molavi, 1997).

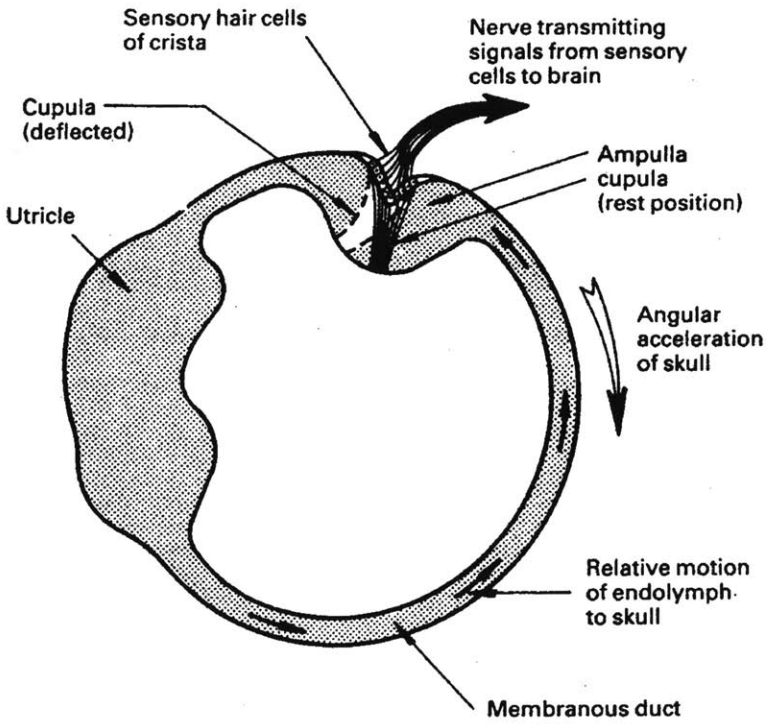


Figure 7. Semicircular Canal Dynamics
(Benson, 1999)

One of the primary roles of the semicircular canal system is to aid in maintaining stable vision during head movements. The semicircular canals exert direct control over the eyes thereby compensating for head movements. The eye is controlled by three pairs of muscles: the medial and lateral rectus, the superior and inferior rectus, and the inferior and superior oblique (Molavi, 1997). The eye muscle planes are not parallel to the planes of the semicircular canals (Schultheis & Robinson, 1981). Therefore, a head rotation in the plane of one canal yields a response in all pairs of eye muscles.

2.7 Vestibulo-Ocular Reflex

The vestibulo-ocular reflex (VOR) has the primary function of stabilizing the eyes during head movements (Quinn, 1998). Stable visual images can be attained during conditions of steady gaze and/or slow head movements by central nervous system processes that minimize retinal slip. Fast head movements, on the other hand, require VOR generation of requisite compensatory eye movements because the visual processing of retinal slip is too slow to stabilize the image (about

70 msec) (Liefeld, 1993). The VOR operates in an open-loop feed-forward manner, generating eye movements of equal magnitude or lower, but in the opposite direction based on head velocity estimates derived from the output of the semicircular canals (Quinn, 1998). The first order vestibular afferents from the semicircular canals encode a signal proportional to head velocity within the 0.03-to 3 Hz frequency range (Quinn, 1998). The VOR uses this information to rapidly generate compensatory eye movements (approximately 10 msec latency). This provides a reflex movement fast enough to compensate for head movements ranging from 0.01 to 7 Hz (Quinn, 1998). However, for all but very low frequencies of stimulation, the semicircular canal output reflects angular velocity rather than angular acceleration of the head with respect to inertial space. The semicircular canals fail as angular-velocity transducers for stimulation frequencies less than 0.1 Hz (outside the normal physiological range) (Young, 1974).

VOR gain refers to the ratio of eye velocity to head velocity. When the ratio of eye velocity to head velocity is equal, the VOR gain equals 1. The phase of VOR is defined by the relationship between the peak eye velocity and peak head velocity. A VOR phase equal to 0 degrees refers to the condition when the peak eye velocity is exactly 180 degrees out-of-phase with the peak head velocity (Quinn, 1998).

When head movements are particularly large or continuous in nature, the magnitude of the required compensatory eye movements can exceed the ± 90-degree mechanical limitation of eye rotation (Liefeld, 1993). In this situation, the eye will quickly jump in the direction of motion (termed fast phase), and then continue tracking from the new position. Nystagmus is defined as an involuntary movement of the eye and is characterized by a fast phase in one direction followed by a tracking phase (slow phase) in the opposite direction. When a visual scene is presented to the subject, the eye velocity of the slow phase (SPV) is equivalent to the velocity of the visual scene relative to the head at speeds less than 100 degrees/second (Liefeld, 1993). The dynamics of the nystagmus can be understood by developing an analogy to the dynamics of a typewriter. The fast phase, or saccade, is analogous to the resetting function of the typewriter when the operator reaches the end of a line. Resetting the typewriter is an extremely quick and efficient means for advancing to the next line to resume typing. Generally, the nystagmus resets in ± 10-degree increments. The slow phase, or tracking phase, can be compared to the operator

typing a line of text at a smooth and regular pace. Physiologically, nystagmus results in a saw-tooth pattern, consisting of alternating slow compensatory eye movements in the direction opposite the head acceleration and rapid resetting eye movements in the direction of head acceleration (Liefeld, 1993). Nystagmus can be observed with EOG, coils, or video imaging systems in the horizontal, vertical, and torsional directions.

VOR is capable of being modified by several outside variables. For example, in a study conducted by Barr, Schultheis, and Robinson (1976), VOR was consciously modified by subjects rotating sinusoidally from 0.1 to 1.0 Hz in the dark when assigned the task of either imagining and staring at a fixed point within their rotating environment or fixating on a visual target. When rotated in the dark at 0.3 Hz, subjects tasked with performing mental arithmetic had a gain equal to 0.65. On the other hand, when subjects were asked to fixate on imaginary targets in the dark that were stationary in space, the gain rose to 0.95. When subjects imagined targets rotating with them on the chair the gain fell to 0.35. Barr et al. concluded that the ability to modulate the gain of the vestibulo-ocular reflex does not depend entirely on the smooth pursuit system; rather, higher centers modulate eye velocity such that it is appropriate to the subject's choice of a frame-of-reference, whether or not vision is available (Barr, et al., 1976).

Collins demonstrated in a series of experiments that both mental alertness and sleep deprivation affect the magnitude of nystagmus. During rotational stimulation subjects were instructed in various test sessions to perform mental arithmetic, make estimates of subjective sensations, reproduce durations of sound stimuli, and assume a state of reverie. The reverie state resulted in significantly less recorded nystagmus than the other tasks, while mental arithmetic was the most efficacious means of obtaining a vigorous response. They concluded that a factor of alertness appeared to be an important condition for the maintenance of nystagmus (Collins, 1960). Furthermore, Collins (1962) reported a decrease in nystagmic response during states of mental relaxation for six subjects tested in a series of ten rotary trials. In a consequent study of control and sleep-deprived groups (each comprised of ten male subjects), sleep deprivation was shown to result in a decline in nystagmus produced by angular acceleration/deceleration of the rotating device (Collins, 1986).

2.8 VOR Plasticity

Miles and Lisberger (1981) stated that it would be advantageous if the vestibular system had the capability of developing an appropriate VOR gain in response to abnormal stimulation and retaining that gain without the need for continual recalibration. They termed this modifiable system with the ability to retain the modified state without reinforcement system *plastic*. The term *VOR adaptation*, first introduced in a series of papers written by Gonshor and Melvill Jones (1976), is now regularly used in discussing vestibular system plasticity regarding modification in the gain and/or phase of the VOR (Quinn, 1998). The terms *adaptation of the VOR* or *adaptive changes in the VOR* were introduced at that time to describe changes in the gain and/or phase of the VOR; adaptation referred not to the mechanism, but to the functional implication of the reflex modification (Quinn, 1998). VOR adaptation, however, has been established in the literature for over 20 years to mean the altering of gain and/or phase of the VOR (Quinn, 1998). This term has caused confusion because, at the simplest level of interpretation, three mechanisms can describe the modification of a response evoked by a reflex mechanism: sensory adaptation, habituation, or associative learning (Quinn, 1998).

The term sensory adaptation refers to an alteration of the reflex due to some process local to the sensory receptor that affects the output of the afferent fibers (Quinn, 1998). Gonshor and Melvill Jones (1976) performed an experiment that showed that short durations of attempted visual fixation on mirror-reversed images of the surroundings during sinusoidal head and body rotation resulted in a decrease of the vestibulo-ocular response when measured in the dark. In a further investigation, they examined the effects upon the VOR of prolonged vision-reversal during naturally occurring head movements. Free head movements with vision-reversal produced a similar effect to the strictly sinusoidal movements used in the first experiment. Interestingly, the daily level of VOR attenuation was retained overnight and return to normal vision following completion of the study spanned several days. A practical example of sensory adaptation is the adaptive response that accompanies the usage of prescription glasses or contacts. For instance, when an individual changes to a stronger prescription, the higher magnification requires a larger VOR to maintain image stability and subsequently, the individual adopts the appropriate VOR gain (Young, 2000). An extreme example of such adaptation occurs with the use of left-right

reversing prisms as used by Melvill Jones and Gonshor, which reverse the visual field and require a change in the direction of the VOR for retinal stabilization (Young, 2000). Context-specific dual adaptation is a term assigned to the phenomenon that addresses people's ability to simultaneously develop and maintain appropriate internal programs for different environments (i.e., visual). One example of context-specific adaptation is people's ability to develop and maintain visual acuity when looking up or down through the two different sections of bifocals (Young, 2000). Context-specific adaptation of gravity-dependent vestibular reflex responses is currently being explored by the National Space Biomedical Research Institute's (NSBRI) Neurovestibular Team. In general, this research consists of adapting reflexive eye movements (saccades, angular vestibulo-ocular reflex, linear vestibulo-ocular reflex, or the vestibulo-collic reflex) to a particular change in gain or phase in one gravito-inertial environment followed by subsequent adaptation to a different gain or phase in a second gravito-inertial force condition. In this situation, the gravito-inertial force serves as the context cue. Once the subject is adapted to both gravito-inertial conditions, the subject is presented with the context cues to assess the retention of the previously learned adapted responses. Preliminary results indicate that the varying g-level produced during parabolic flights can serve as an effective context cue for adapted saccadic responses (NSBRI Retreat, 2000).

In contrast to adaptation, habituation results in a reduced response to repeated exposure to the stimulus (Young, 2000). Habituation refers to a decrease in the magnitude of reflex activation not directly attributable to some receptor mechanism but also independent of the combined input from a separate sensory system for this modification (Quinn, 1998). For example, subjective vestibular responses and nystagmus strength/duration decrease in response to frequently repeated angular-acceleration stimulation (Young, 2000).

Associative learning refers to modification in reflex output as a result of some contingency being established between separate, identifiable, and controllable events (Quinn, 1998).

Three primary mechanisms are used to alter/modify the VOR function: lenses and prisms, optokinetic drums, and cross-axis training. Gonshor and Melvill Jones (1976) used vision-reversing (Dove) prisms to alter the gain and phase of the VOR. Vision reversing prisms operate

under the principle that in normal conditions, head movements in a given direction (i.e., to the right) result in compensatory eye movements in the opposite direction (image moves to the left). When a subject makes a head movement to the right while donning the vision reversing prisms, the actual image appears further to the right. Appropriate compensation is achieved when the VOR generates a reversed eye movement that is actually in phase with the head movement. One can also attain a similar effect using mirror-reversals of visual images or by having the subject wear telescopic lenses that increase or decrease apparent image movement without altering its phase; 2x magnifying lenses require a doubling of the gain and .5x minifying lenses require a halving of the gain (Quinn, 1998). In order for VOR compensation to occur, the subject must receive continual feedback of image movement (retinal slip) during active or passive head rotation (Quinn, 1998). Miles and Fuller (1974) showed through a series of experiments with monkeys wearing telescopic spectacles (magnifying and diminishing visual scene) that the vestibulo-ocular system of the rhesus monkey is both plastic and adaptive. Note that in both the cases of Dove prisms used by Melvill Jones and Gonshor and the telescopic lenses employed by Miles and Fuller, the gain always rose or fell in such a way as to lessen or eliminate retinal image slip during head movements (Schultheis & Robinson, 1981).

It is also possible to alter the VOR gain by forced body rotation coupled with same-plane optokinetic stimulus. Optokinetic drum rotations in the same direction as head movements result in decreases in VOR gain. Conversely, drum rotations in the opposite direction of the head movement yield increases VOR gain (Quinn, 1998).

Schultheis and Robinson (1981) coined the term cross-axis adaptation to describe their VOR modification when vertical plane sinusoidal rotation was paired with horizontal plane rotation of an optokinetic drum pattern. In an experiment with cats, an optokinetic drum with feedback control was driven horizontally in proportion to the vertical head position while the cats' heads were passively pitched. Cross-axis nystagmus was the term assigned to represent the horizontal eye movements produced by pure vertical head movements. This so-called cross-axis VOR plasticity appeared to have the purpose of eliminating retinal slip during head motion. The cross-axis nystagmus seemed to depend on the magnitude and direction of image slip on the retina during training (Schultheis & Robinson, 1981). If the cat remained in the fixed position

overnight following training without moving its head, the horizontal nystagmus generated by vertical head movements continued. The cross-axis nystagmus was unlearned more quickly than it was learned; if the adapted animal was rotated vertically without the drum present, the cross-axis nystagmus disappeared within a half hour. Peng, Baker, and Peterson (1994) coupled 19 degrees/sec vertical pitch vestibular rotations (0.25 Hz) with 28 degrees/sec horizontal optokinetic oscillations and recorded EOG in the dark at various rotational frequencies. They found that in all subjects, directional training produced slow phase horizontal VOR eye movements that were not present during vertical rotations before adaptation, furthering the evidence that the frequency response characteristics of adaptive cross-axis VOR gain are similar in humans and cats.

Considerable controversy surrounds the discussion of the locus of plasticity (Quinn, 1998). Both the brainstem (vestibular nucleus) and cerebellar (flocculus) have been proposed as the neural locus for VOR plasticity (Quinn, 1998).

2.9 Motion Sickness

Motion sickness occurs in both humans and animals with normal vestibular systems. Motion sickness typically results from exposure to a wide variety of motion and visual stimuli. Physical signs of motion sickness include vomiting and retching, pallor, cold sweating, yawning, belching, and flatulence (Oman, 1996). Subjective sensations include stomach discomfort, nausea, headache, and drowsiness (Oman, 1996). The *sensory conflict theory* was originally based on the notion that motion sickness results not specifically from motion, but from conflicting signals provided by different sensory modalities (Oman, 1996; Young, 1984a); conflicting signals for example, within a sensory organ (i.e., semicircular canal versus otolith) or between sensory systems (i.e., visual versus vestibular) (Young, 1984a). The contemporary view, known as the *sensory-motor conflict theory* recognizes that conflict signals are most likely essential for maintenance of balance and control of body movement. This view supports a conflict processing strategy that 1) sparks corrective postural movements given postural disturbances and 2) initiates sensory-motor learning in order to maintain a correct "internal model" for the behavioral characteristics of the body (Oman, 1996). For detailed information

concerning the conflict theory or motion sickness assessment as pertaining to this experiment, refer to Lyne (2000).

2.10 Experimental Stimulus

Head movements made within rotating environments produce inappropriate non-compensatory eye responses, disorientation, and illusory tilt sensations as a function of two distinct, but often confused phenomenon: cross-coupled angular accelerations and the movement of the semicircular canals into and out of the plane of rotation. In the MIT artificial gravity adaptation study, both stimuli produce concurring directional illusory tilt sensations and inappropriate eye movements in response to yaw head movements conducted on-board the clockwise rotating short-radius centrifuge. However, the two stimuli have differing time constants. For example, the stimulus due to the cross-coupled angular acceleration is present only when the head is in motion. On the other hand, moving the canals into and out of the plane of rotation results in substantial aftereffects. Because of the predominant effect of moving the canals into and out of the plane of rotation, the effect of the cross-coupled angular acceleration is considered to be negligible in this adaptation investigation. For a complete comparison of the two stimuli, refer to Lyne (2000).

Although the vertical canals (superior and posterior) do not lie exactly in the pitch and roll axes of the skull, the brain is able to resolve the rotation transduced by these receptors into these orthogonal axes (Benson, 1999). For illustrative purposes, it is both reasonable and desirable to represent the semicircular canals as two sets of three equivalent orthogonal rate sensors in the pitch, roll, and yaw axes of the head. These equivalent canals facilitate comprehension of the vestibulo-ocular reflexes resulting from angular velocity stimuli within a rotating frame-of-reference. The equivalent canals will further be referred to as the pitch, roll, and yaw canals registering angular velocity in the pitch, roll, and yaw directions, respectively.

Consider the experimental setup with the subject lying supine on a clockwise rotating short-radius centrifuge, head positioned at the center of rotation, and "right-ear-down" (RED) flush against the platform. Yaw head movements are made after a sustained period of constant velocity

rotation. A yaw head movement is defined as a 90-degree turn from the RED position to "nose-up" (NU) or vice-versa. Examining the relative position of the semicircular canals, one discovers that the equivalent yaw canal never enters the plane of rotation during a yaw head movement from the RED to NU position. Therefore, from this point forth, it will be excluded from the analysis, although, of course, it still registers the brief yaw head motion. In the RED position, the pitch canals are positioned in the plane of rotation while the roll canals are out of the plane of rotation. When the subject turns to the NU position, the pitch canals are removed from the plane of rotation while the roll canals are placed in the plane of rotation (Figure 8).

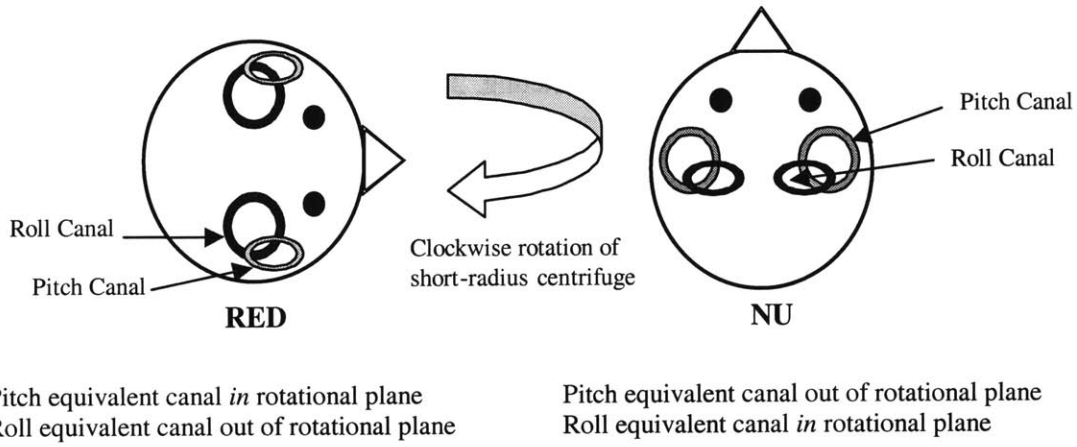


Figure 8. Equivalent Pitch and Roll Canals

For simplicity, consider one set of equivalent orthogonal semicircular canals. If the subject is originally in the RED position at the onset of rotation, the cupula of the pitch equivalent canal, deflected by the initial angular acceleration, will have returned to its neutral resting position after a minute or more of rotation. Specifically, after constant angular velocity has been achieved and maintained for more than ten seconds, the pitch equivalent canal does not signal the constant angular velocity to the brain because no relative displacement exists between the fluid and the paired semicircular canal. However, the canal retains all the angular momentum of its ring of endolymph rotating about a horizontal axis as viewed from the stationary frame-of-reference. When the head is yawed from the RED to NU position, the pitch equivalent canal is suddenly removed from the plane of rotation. The inertia of the endolymph fluid continues to drive the fluid in its original clockwise direction of rotation causing the cupula to deflect in the direction of the rotating fluid. The cupula deflection creates the sensation of pitch forward. Following the

step of angular velocity, the fluid begins to decelerate forwards. Figure 9 illustrates the dynamics of the endolymph fluid and cupula as the equivalent pitch canal, initially in the plane of rotation, is removed from the plane of rotation (from left to right).

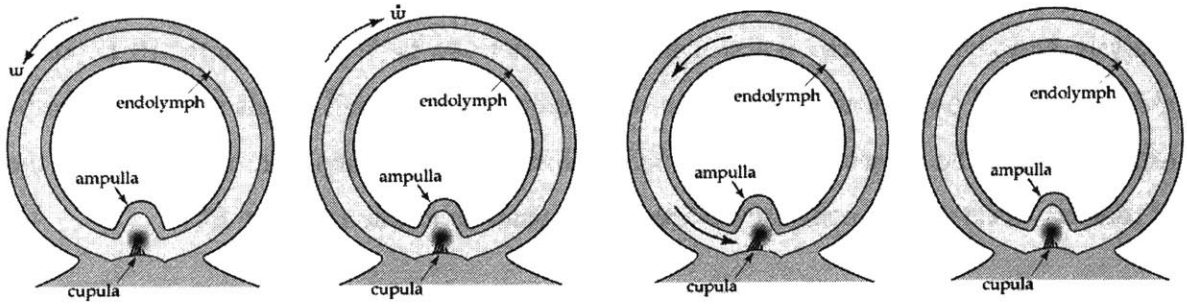


Figure 9. Equivalent Pitch Canal Removed from the Plane of Rotation
(Molavi, 1997; Cheung, 2000)

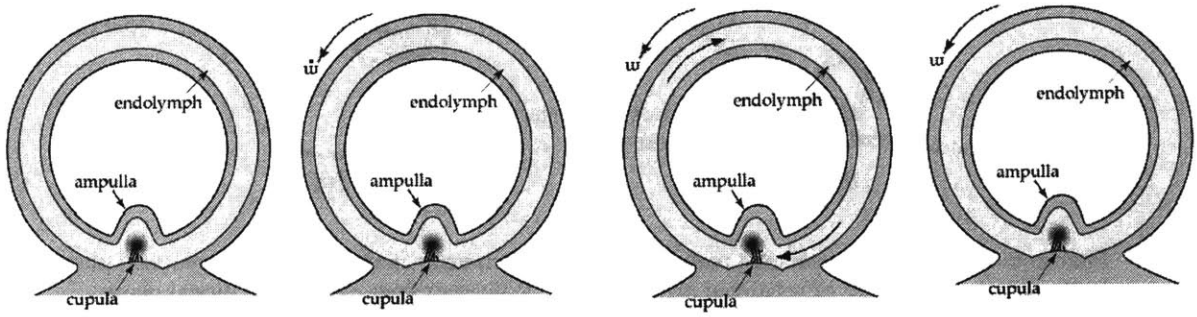


Figure 10. Equivalent Roll Canal Placed into the Plane of Rotation
(Molavi, 1997; Cheung, 2000)

Simultaneously, as the pitch equivalent canal is removed from the plane of rotation, the roll equivalent canal is brought into the plane of rotation. The inertia of the fluid initially causes it to flow in the opposite direction to the short-radius centrifuge direction of rotation and results in a deflection of the cupula. The subject in turn feels a roll in the direction of rotation of the short-radius centrifuge (clockwise). Figure 10 illustrates the dynamics of the endolymph fluid and cupula as the equivalent roll canal, initially out of the plane of rotation, is placed into the plane of rotation (from left to right). On the return movement from the NU position to RED, the pitch equivalent canal is reintroduced into the plane of rotation and the equivalent roll canal is removed from the plane of rotation. This results in a pitch backward and counterclockwise roll sensation.

Head movements conducted in the dark do not result in as severe motion sickness symptoms as those made in the light because in the dark, the vestibular system provides the only input with respect to position in space. Eye compensation for head movement conducted in complete darkness cannot utilize the CNS mechanism to minimize retinal slip. Therefore, regardless of the magnitude of the head movement, compensatory eye movements are generated in their entirety by the VOR (Liefeld, 1993). In the MIT artificial gravity study, a non-compensatory vertical eye movement is produced in addition to the expected horizontal compensatory eye movement in response to yaw head turns from the RED to NU position and vice-versa. Because of the lack of visual cues, the perceived pitch forward (head tilting/tumbling over feet) sensation is accompanied with a vertical nystagmus with the fast phase in the direction of the acceleration (downward), and the slow phase in the opposite direction (upward). When the head is turned from the NU to RED position, the subject senses a pitch backward (feet tilting/tumbling over head) sensation that coincides with a vertical nystagmus with the fast phase in pitch upward direction and the slow phase in the pitch downward direction.

CHAPTER 3 EXPERIMENTAL METHODS

3.1 Design

The MIT artificial gravity adaptation study was designed to inquire as to whether or not repeated exposure to short-radius centrifugation results in a decrease of the non-compensatory vertical nystagmus produced by out-of-plane yaw head movements and a decrease in the magnitude of subjective sensations, motion sickness symptoms, and autonomic responses. It was also designed to determine whether this supposed context-specific adaptation could be maintained for a day or a week.

Dependent measures included the magnitude of the inappropriate non-compensatory vertical nystagmus, Pensacola Motion Sickness Score, degree of motion sickness (0-20 scale), perceived magnitude and direction of pitch sensation experienced, and heart rate. Additional dependent measures included verbal responses and post motion sickness. These measures were recorded pre-, per-, and post-rotation during three sessions (Day=1, 2, 8). This thesis focuses on the non-compensatory vertical nystagmus as a means of assessing the extent to which adaptation is attained and maintained.

3.2 Subjects

Experimental subjects were selected from the MIT Department of Aeronautics & Astronautics student population with the aid of a questionnaire and follow-up personal interviews. Volunteers with histories of vestibular abnormalities, heart conditions, respiratory problems, anti-

depressants or barbiturates medications, extreme susceptibility to motion sickness, or previous artificial gravity experience were excluded from the experiment.

Eight healthy human subjects (four males, four females), ranging in age from 19 to 25 yrs (22.9 ± 2.2 yrs) participated in the experiment. The mean height and weight were 173.2 ± 11.8 cm and 68.9 ± 11.7 kg, respectively. All eight subjects were right handed. The criterion for subject selection is listed below. Complete information regarding disqualifying medical conditions is outlined in Appendix B. Subjects selected had no known vestibular or oculomotor abnormalities. All subjects signed and submitted a consent form (Appendix A).

Subjects met the following criteria:

- Age 18-30 years old
- Sex: 4 females, 4 males
- Height 5'0"- 6'2" (1 feet = 0.3048 meter, height 1.53m-1.88m)
- Weight less than 200lbs (1lbs = 0.4536 kilogram, weight less than 90 kg)
- Athletic condition some form of exercise ≥ 3 days/week
- Ability to perform necessary motor tasks (entry/exit from platform, turn on/off battery operated lights, operate pitch wheel, etc.)
- Good communication skills and the ability to relate experiences verbally
- Tolerant to severe motion sickness

Caffeine and alcohol were restricted from the diet 24 hours preceding the experiment.

3.3 Equipment

The experimental apparatus was composed of the Massachusetts Institute of Technology Man Vehicle Laboratory short-radius centrifuge, ISCAN infrared video imaging system, Watson angular rate sensors, Acumen heart rate monitor system, pitch wheel for the assessment of tilt sensations, and several motion sickness surveys.

3.3.1 Short-Radius Centrifuge

The MIT short-radius centrifuge, a two-meter radius rotating platform (Figures 11 & 12) was conceptualized and constructed by Peter Diamandis in 1988. The short-radius centrifuge was dismantled following the completion of Diamandis' thesis and reconstructed in 1996 with minor modifications including the addition of a 660H200 Browning Gear belt and Focus 2 DC Drive motor controller with magnetic reversing kit, dynamic braking kit, and voltage signal follower from Olmstead-Flint, Inc. The original steel base plate, gears, gear reducer, central support shaft with bearings, aluminum honeycomb platform, side rails, wind canopy, and Browning 1 hp DC motor were reused (Tomassini, 1997).

The centrifuge was driven by a 1 hp Olstead Flint electric motor through a 50:1 gear reduction. Smooth controlled rotational velocity profiles were achieved with Lab View/PID Control Toolset software and hardware in conjunction with the Focus 2 DC Drive motor controller (Cheung, 2000). Accurate tachometer readings with low levels of noise were accomplished with a Hewlett Packard optic encoder (256 CPR) mounted at the worm gear. The centrifuge was instrumented with a safety belt and on-board emergency stop button that cut power to the centrifuge when activated by the subject. A 32-channel slip ring through the shaft of the bed permitted the transmission of data to the data collection PC. An on-board video camera was mounted to one end of the platform and provided real-time video images of the subject during the light adaptation phase. The ISCAN eye imaging goggles, Watson angular rate sensors, pitch wheel, and on-board video camera were wired through the slip ring. The footplate was adjustable to accommodate participants ranging in height from 5 ft (1.52 m) to 6'2" (1.88 m). A light-proofed canopy, constructed out of aluminum crossbars, plastic (3M transparent heat shrink), and black cloth covered the subject obscuring external visual cues. Figure 12 depicts the centrifuge without the black cloth covering.

Two 300 MHz personal computers (AMD-K6 processors/WIN 95 OS/e-machine®) were used for ISCAN data collection and short-radius centrifuge velocity control, respectively. Three monitors were available to display video images from both eyes and from the on-board video camera. Two VCR's were used to record video data from the left eye and the on-board video

camera. Two 12-V/7.0 Ah sealed rechargeable lead-acid batteries powered the ISCAN goggles and on-board video camera. Three Motorola TalkAbout two-way radios® were used for communication between the subject on the centrifuge and the two primary operators. A portable eye calibration stand was constructed to allow eye calibrations while the subject was on the platform. Three battery operated 6-V lights were fastened to the platform to provide light during the light adaptation phase. A fleece eye goggle cover was sewn to aid in the elimination of light cues. Counterweights were available to accommodate subjects of varying weights.

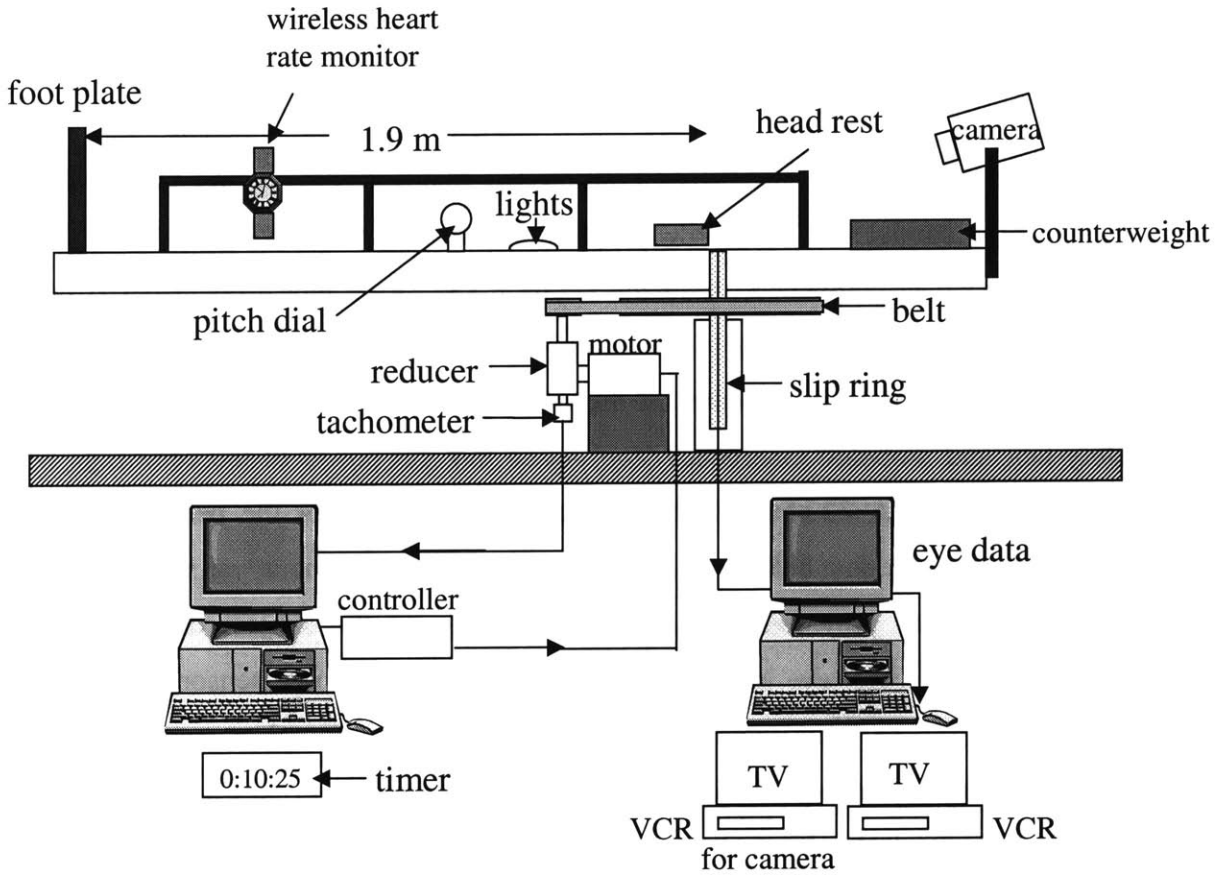


Figure 11. Schematic of Short-Radius Centrifuge

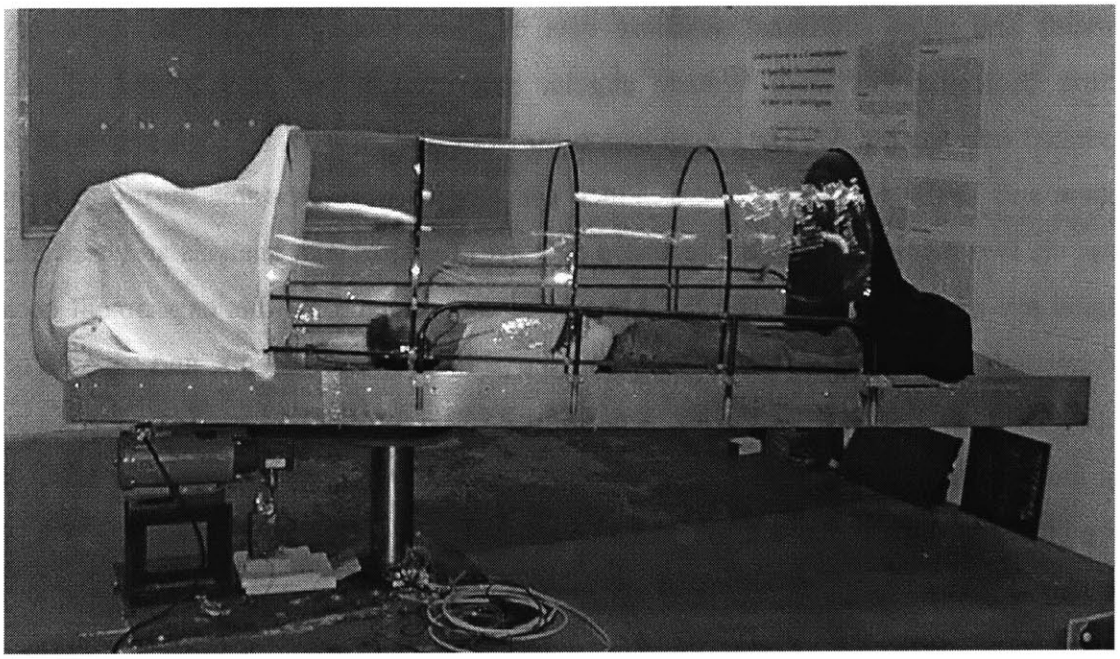


Figure 12. MIT Short-Radius Centrifuge (with transparent canopy)

3.3.2 ISCAN Video Eye Imaging Hardware and Software

The ISCAN miniature eye imaging system (Model: RK-716PCI) was a lightweight, non-invasive, eye imaging assembly (Figure 13) with a digital image processor that automatically tracked the center of a subject's pupil and a reflection from the corneal surface. The assembly consisted of a solid-state single-chip video camera, infrared optics (IR), LED illuminator, and 45-degree hot mirror. The binocular imaging assembly weighed approximately 2.5 ounces. The ISCAN system illuminated the eye with IR LEDs in order to create a contrast between the pupil and iris. Since the illumination was not on the optic axis, the pupil served as the IR "sink." The iris and surrounding areas reflected the IR. The "dark pupil" image was captured by the miniature video cameras and processed with software routines resulting in accurate horizontal and vertical positional eye traces. The digital processor operated at a sample rate of 60 Hz and the subject's eye position was determined within accuracy typically better than 0.3 degrees over a ± 20-degree horizontal and vertical range. The system accommodated subjects wearing contact lenses. The ISCAN Raw Eye Movement Data Acquisition Software program, compatible with

Windows 95 operating systems, allowed the operator to view horizontal and vertical eye movements and eight additional auxiliary data channels graphically on the laboratory data collection dedicated PC. Both Watson angular rate sensors and pitch wheel signals were incorporated into the ISCAN Data Acquisition Software program through a Keithley Metrabyte backplane and DAS-1600 series board. Video eye images were viewable during experimental sessions via two monitors and were recorded (left eye) for later data analysis and verification of the digital eye movement data. The ISCAN system was selected for this experiment because it was lightweight, comfortable to wear, non-restrictive to head movements, and capable of good resolution with low drift characteristics. A customized fleece cover was used to wrap the goggles during the eye recordings in the dark to eliminate extraneous light produced by LEDs on the rotating platform. This cover was manually removed and replaced by the subjects prior to and following the light adaptation phase as appropriate.

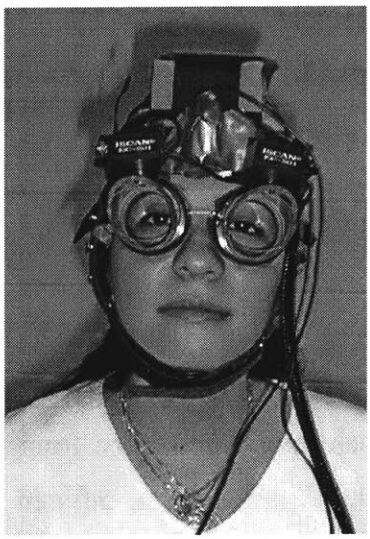


Figure 13. Subject Donning ISCAN Equipment

3.3.3 Watson Angular Rate Sensors

The Watson Industries solid-state single-axis angular rate sensors provided an analog output voltage proportional to the angular rate about their sensing axes with respect to inertial space. Two single-axis rate sensors were used for the yaw and pitch planes of rotation. The sensors were sewn and taped onto an adjustable cap. The pitch sensor was fixed at the top of the cap and the yaw sensor was mounted to the forehead area. Each sensor was cylindrical with a length of

2.00" (5.08 cm) and 1.13" (2.86 cm) diameter. Each sensor weighed 85 grams (3 oz.) and was powered by ± 15-V power supply. The sensors had the capability to sample data at 350 Hz. However, because the signals were incorporated into the ISCAN Data Acquisition Software program (sampling rate = 60 Hz), the angular rate sensor sampling rate was reduced to 60 Hz.

3.3.4 Acumen Heart Rate TZ-Max 100 Monitor and Omron Digital Blood Pressure Monitor

An Acumen TZ-Max 100 heart rate monitor measured the heart rate during the experiment. This equipment included a data storage watch, a chest transmitter, and an adjustable elastic strap. Heart rate signals were transmitted wirelessly from the belt to a digital watch worn on the subject's wrist. The data was stored in the watch and was downloaded to the PC following centrifugation via serial docking port hardware and interface software. Heart rate was sampled every five seconds. The Acumen watch had the capability to store a maximum of 760 data points. The chest transmitter was attached to the chest at the solar plexus. Aquasonic electrode gel was spread on the electrodes of the transmitter to serve as a couple medium and promote improved transmission of the heart signals to the chest transmitter. The heart rate monitor system featured two-way computer communication, a programmable delay recording start, advanced memory heart rate sampling, progress tracking, and Windows 95/98 compatibility.

The Omron Digital Blood Pressure Monitor HEM-711 was used to collect blood pressure measurements before and after centrifugation. Blood pressure was measured in both the erect and supine position.

3.3.5 Subjective Measurement Tools

Several subjective measurement tools were used to assess the level of discomfort and tilt sensations experienced by the subjects both prior to and following the experimental session. The tools included:

- Pensacola Motion Sickness Survey
- Motion Sickness Score
- Post Motion Sickness Score

- Verbal Accounts
- Pitch Wheel
- World Up Computer Animation

A complete discussion of the subjective experimental equipment and protocol can be found in Lyne (2000).

3.3.5.1 Pensacola Motion Sickness Survey

The Pensacola Motion Sickness Survey (Graybiel, Wood, Miller, & Cramer, 1968) was performed on subjects immediately following centrifugation. Nausea, temperature, pallor, salivation, drowsiness, headache, and dizziness categories were used to assess the subject's overall motion sickness symptoms. The operator discussed with the subject their symptoms to determine both appropriate category and overall scores.

3.3.5.2 Motion Sickness Survey

Subjects rated their overall level of discomfort periodically throughout the experiment on a scale from 0 to 20, where 0 equated to "I am fine" and 20 represented vomiting. Subjects were polled repeatedly throughout the experiment in an attempt to monitor their overall well being and ability to complete the experiment. During the light adaptation phase, subjects were polled at minute intervals. If a subject gave a motion sickness rating at or above 15, they were asked to reduce the number of head movements until their score settled to a rating equal to 12.

3.3.5.3 Post Motion Sickness Survey

Subjects rated their overall level of discomfort hourly until sleep following the completion of the experiment on a scale from 0 to 20, where 0 equated to "I am fine" and 20 represented vomiting. Subjects recorded a score for the following morning as well.

3.3.5.4 Verbal Accounts

Subjects were asked to make a set of head movements both before and after the light adaptation phase and report on their perceived subjective sensations. No distinction was made in the instructions provided regarding whether to report perceived self-motion with respect to the torso or the head. The head movement consisted of a 90-degree yaw rotation from "right-ear-down" (RED) to "nose-up" (NU) followed by a 90-degree yaw rotation from RED to NU. Immediately following the first head movement, subjects were instructed to remain in the NU position and describe their sensations. Subjects communicated with the operators via Motorola two-way radios. Subjects were trained prior to the start of the experiment and instructed to use vocabulary such as "roll", "pitch" and "yaw". Subjects verified the magnitude of the perceived motion experienced in degrees. Following centrifugation, subjects were given time to explain in detail their experiences and reenact tilt illusions using an inflatable astronaut.

3.3.5.5 Pitch Wheel

The pitch wheel detector consisted of a four-inch wooden disc mounted to a potentiometer. Subjects manipulated the pitch wheel during the experiment to indicate the amount and direction of pitch experienced during yaw head movements. The dial provided tactile information concerning the resting orientation (body horizontal) and 90-degree extreme values. Subjects who reported feeling a pitch sensation during the verbal account were asked to input a value into the pitch detector, if appropriate. The pitch wheel signals were collected through the ISCAN Data Acquisition Software program.

3.3.5.6 World Up Computer Animation

World Up®, a software development and delivery environment for building 3D/VR applications by Sense8 Corporation, was used to recreate perceived head motions following centrifugation. After completing the protocol, subjects were asked to recreate their sensations using a computer model simulation developed by D. Parker at the University of Washington. Subjects used a two-degree-of-freedom space ball to manipulate an animated head graphic. The software interfaced

with external motion trackers and recorded rotation and translation motion. Simulations were created to capture the illusory motion experienced by subjects during the first set of yaw head movements conducted during centrifugation in the dark prior to and following the light adaptation phase. Recorded animations were played back and modified to confirm that the animations were a true representation of the subjects' sensations.

3.4 Experimental Procedure

All subjects participated in an identical series of three pre-, per-, and post-rotation data collection sessions. Each session consisted of eye reflex recordings during head movements, a subjective battery of tests, and heart rate measurements. Subjects were tested on Days 1, 2, and 8. Day 1 sessions typically spanned two hours due to subject training activities and instrumentation fittings. Day 2 and 8 sessions lasted approximately one hour and 15 minutes.

Subjects were instructed to avoid both alcohol and caffeine consumption 24 hours preceding a session. Female subjects were asked to avoid the application of facial creams/powders and eye cosmetics on the day of a session in order to eliminate ISCAN eye tracking errors.

On Day 1, the operator described the experimental protocol to the subjects. The subjects were informed of their right to terminate the experiment at any time for any reason. Potential motion sickness symptoms were also detailed. Consent forms were provided and signed by both the subject and operator. Subjects' height, weight, and standing blood pressure were measured prior to session training. Subject height was used to determine footplate positioning and weight was used to aid in the appropriate placement of subsequent counterweights to balance the platform. Systolic and diastolic measurements were acquired twice throughout the session while standing erect and lying down in the supine position on the platform both prior to and following rotation. The Acumen heart rate chest transmitter was attached to the chest and the digital watch to the subjects' right wrist.

Next, subjects were trained to use the terms yaw, pitch, and roll to describe self-motion as pertaining to this particular experiment. An inflatable astronaut toy served as a hands-on training

tool to verify that the desired descriptive vocabulary was thoroughly understood and retained. Subjects were familiarized with the 0-20 motion sickness scale and introduced to the pitch wheel. World Up software was demonstrated, followed by baseline data collection.

The ISCAN eye imaging goggles were placed on the subjects' head and adjusted to provide a comfortable fit and centered eye video image. Subjects then donned the adjustable fabric cap embedded with the angular rate sensors. Subjects were positioned supine with their head at the center of rotation and feet flush against the footplate. The safety belt was fastened and the subjects were instructed on how to operate the emergency stop button, battery operated lights, pitch wheel, Motorola hand radio, and fleece eye cover. The subjects rehearsed three-five sets of 90-degree yaw head movements from the RED to NU position.

The support structure was then removed from beneath the platform and the platform was balanced. A calibration eye test stand was adjusted to a distance of 71 cm above the subjects' eyes. The calibration stand consisted a five point cross with spacing equal to 12.5 cm. The angular spread of the points was equal to ten degrees. Calibration was performed through the ISCAN Raw Eye Movement Data Acquisition Software program. A trial data collection session was conducted to ensure that the ISCAN system was operating properly and that the calibrated values were recorded. The heart rate monitor and session clock were started simultaneously. The lightproof canopy was placed over the platform and the centrifuge and immediate area were inspected for impinging obstacles.

Three operators were responsible for data collection during a session. Operator 1 was responsible for debriefing the subject, collecting consent forms, training the subject with respect to verbal responses, collecting motion sickness scores throughout the session, conducting the Pensacola Motion Sickness Survey, and conducting the World Up computer recreations of subjective tilt.

Operator 2 was responsible for collecting height, weight, and history information, taking the blood pressure readings, instrumenting the subject with the heart rate monitor, counting head movements during the light adaptation phase, recording video data from the eyes and the on-board video camera, and documenting the session timeline.

Operator 3 was responsible for powering all equipment, instrumenting the subject with the ISCAN eye imaging goggles and angular rate sensors, calibrating the eyes, collecting the eye data, and communicating instructions to the subject throughout the experiment.

All operators were responsible for the safety of the subject and the safety checks associated with the operation of the short radius centrifuge. The detailed protocol checklist can be found in Appendix C.

Vestibulo-ocular reflex data collection occurred throughout all 11 phases of the session. Figure 14 depicts the 11 phases and the corresponding rotation status of the centrifuge, lighting conditions, and timing of subjective tests. The comprehensive eye reflex data collection session spanned approximately 20-30 minutes depending on the motion sickness status of the subjects and their ability to articulate perceived motion sensations. Table 1 displays the test conditions per each phase in a typical session.

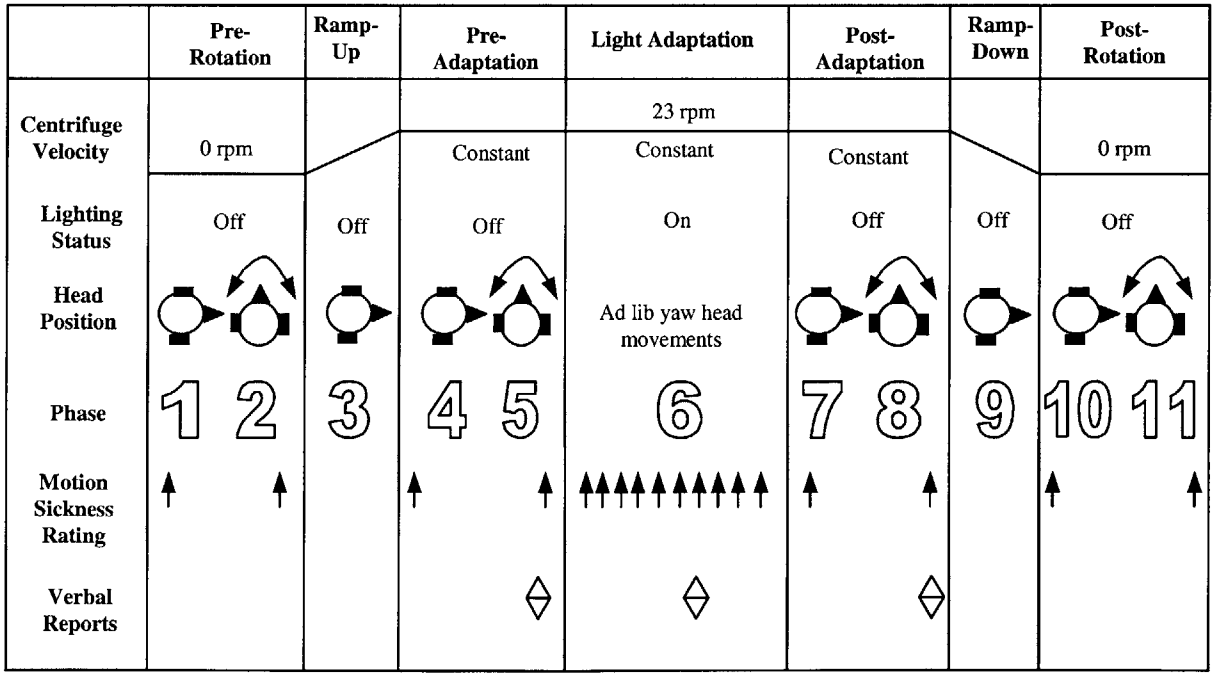


Figure 14. Protocol

Phases 1-2, termed pre-rotation baseline data collection, occurred in the dark with the centrifuge stationary. Phase 1 involved the subject lying still for 30 seconds. During Phase 2 the subject

made three sets of yaw head movements as per operator instructions. A set of head movements was defined as a 90-degree yaw head turn from "right-ear-down" (RED) to "nose-up" (NU) in followed by a 20 second "hold" period in the NU position and a subsequent NU to RED 90-degree yaw head turn back to the starting position (Figure 15). For Phases 2, 5, 8, and 11, subjects were instructed to make the 90-degree yaw head turns in one second.

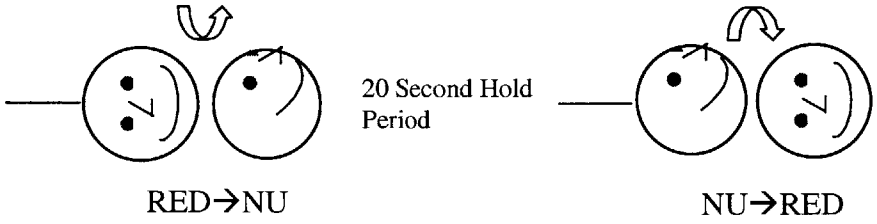


Figure 15. Yaw Head Movement

The subjects began each phase in the RED position and remained RED throughout the phase unless instructed otherwise. During Phase 3 the centrifuge followed a constant linear ramp for 23 seconds from 0 rpm to a constant angular velocity of 23 rpm; this provided acceleration of six degrees/second^2. The centrifuge was then operated at 23 rpm throughout Phases 3-9, to provide the equivalent of an artificial gravity gradient of 100% that was greatest at the feet (approximately 1g) and zero at the head. The centrifuge rotated in the clockwise direction. All subjects reported feeling stationary after approximately 20 seconds of rotation at constant velocity. Phases 4-5, termed the pre-adaptation/per-rotation baseline data collection, occurred in the dark with the centrifuge rotating at a constant velocity. During Phase 5 the subjects made three sets of yaw head movements in response to the operator's instructions as in Phase 2, followed by a fourth set of head movements for subjective analysis. Following the fourth RED to NU head turn, the subjects reported their perceived sensations and dialed in the magnitude and direction of the experienced pitch component, if applicable, to the pitch wheel. The same procedure was repeated for the fourth NU to RED head movement. Phase 6, the light adaptation phase, was conducted for ten-minutes with the interior lights on. Subjects were instructed to remove the fleece eye hood, turn on the lights, and engage in self-regulated yaw head movements. Subjects were encouraged to make as many yaw head movements as tolerable. If a subject gave a motion sickness rating at or above 15, they were asked to reduce the number of head movements until their score reached 12. Motion sickness scores were collected at one-minute intervals.

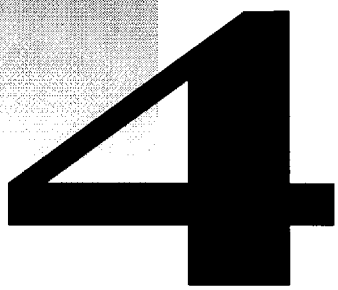
Phase	Rotation Status	Head Position	Lighting	Time
1	Stationary	Stationary	Dark	30 seconds
2	Stationary	6 yaw head movements	Dark	3 minutes
3	Accelerating	Stationary	Dark	30 seconds
4	Constant Velocity	Stationary	Dark	30 seconds
5	Constant Velocity	8 yaw head movements	Dark	3 minutes
6	Constant Velocity	Self-regulated yaw head movements	Light	ten-minutes
7	Constant Velocity	Stationary	Dark	30 seconds
8	Constant Velocity	8 yaw head movements	Dark	3 minutes
9	Decelerating	Stationary	Dark	30 seconds
10	Stationary	Stationary	Dark	30 seconds
11	Stationary	6 yaw head movements	Dark	3 minutes

Table 1. Testing Conditions Per Phase

Following the light adaptation period, the fleece eye hood was replaced over the ISCAN goggles by the subjects, and the lights were turned off for the remainder of the experiment. Phase 7-8, termed the post-adaptation/per-rotation baseline data collection, occurred in the dark with the centrifuge still rotating at constant velocity. During Phase 8 the subjects made three sets of yaw head movements as per operator instructions, like Phase 5, followed by a fourth set of head movements for subjective analysis. During Phase 9 the centrifuge followed a constant linear ramp from 23 rpm to 0 rpm. Phases 10-11, titled the post-adaptation baseline data collection, occurred in the dark with the centrifuge stationary. During Phase 11 the subjects made three sets of yaw head movements according to operator instructions like Phase 2.

Following Phase 11, the subjects remained in the supine position on the platform while the canopy and instrumentation were removed. Operator and subjects worked together to assess the Pensacola Motion Sickness Score. Then subjects gave their verbal report of illusory tilt and reenacted, if necessary, their subjective sensations with the inflatable toy. Subjects were escorted to the neighboring laboratory to create the computer simulation using World Up. At the completion of the session, subjects were given a post motion sickness rating sheet to complete over the next 24 hours. Subjects were asked to rate their motion sickness symptoms from 0-20 hourly following the completion of the session.

CHAPTER 4 DATA ANALYSIS



4.1 Data Reduction

The ISCAN Raw Eye Movement Data Acquisition Software program produced calibrated eye position data based on calibration procedures previously described in the Experimental Methods section. Following the completion of a session, ISCAN data was saved in ASCII format and converted to text format. Former Man Vehicle Laboratory graduate student David Balkwill modified his Matlab data analysis software to accommodate this particular investigation. His routines utilized order statistic filters to automatically remove noise, differentiate the position eye signals, and remove fast phases in the velocity signal. Current graduate student Carol Cheung composed two additional routines that allowed the operator to manually select specific head movements and their corresponding eye responses. The author developed modified code to calculate the cumulative slow phase position during the acceleration and deceleration phases and assisted both David Balkwill and Carol Cheung in the development and fine-tuning of the routines. The Matlab code used to filter and analyze the data can be found in Appendix F. The primary routines and subroutines are summarized in Table 2.

Eye signals were screened in Matlab graphically to ensure that the responses in both eyes were synchronized and void of spontaneous nystagmus or other irregularities. Specifically, Phase 1 data was screened for spontaneous nystagmus and Phase 2 data was screened for inappropriate non-compensatory responses during yaw head movements while the short-radius centrifuge was stationary. All eight subjects held normal gaze for the 30 seconds of eye data collection during Phase 1 and none exhibited VOR abnormalities. Although the ISCAN video eye imaging system was binocular, only the left eye was used for this particular analysis. Furthermore, this thesis

only presents the left vertical eye movement data. It should be noted that the expected horizontal eye movement in response to yaw head movements was consistently observed throughout Phases 2, 5, 6, 8, and 11, in addition to the inappropriate non-compensatory vertical eye movement. However, the purpose of this research was to demonstrate that the inappropriate vertical response could be reduced, if not eliminated in its entirety, with multiple exposures to the aforementioned stimulus. Therefore, horizontal eye movements were left out of the analysis.

Matlab Routines	Functionality
batch_bed.m	read raw ISCAN data into a Matlab array preserving data collection headings, utilized order statistic filters to remove noise, differentiate the position eye signals, and remove fast phases in the velocity signal
review_bed.m	allowed the operator to manually edit the slow phase velocity envelope to remove missed fast phases
head.m	allowed the operator to select a given head movement and calculated the area under the curve, peak head velocity, duration of head movement in seconds, and time to peak head velocity
eye.m	allowed the operator to select a given head movement and curve fitted an exponential curve to the slow phase velocity curve of the eye response
cum_spv.m	allowed the operator to select the onset of accel/decel of the centrifuge and then integrated the area under the SPV left vertical eye curve beginning 7 seconds after the indicated onset of accel/decel for 20 seconds to determine cumulative slow phase position

Table 2. Matlab Routines

Phases 3, 5, 8, and 9, acceleration, pre-adaptation, post-adaptation, and deceleration phases, respectively, were analyzed with the use of custom designed Matlab routines. Phases 3 and 9, consisted of the subject lying supine in the RED position during short-radius centrifuge acceleration (0 rpm → 23 rpm rotation rate) and deceleration data (23 rpm→ 0 rpm rotation rate), respectively. Phase 5, the pre-adaptation phase consisted of three sets of yaw head turns from the RED to NU position and the return trip to RED in the dark during centrifugation. Phase 8, the post-adaptation phase, followed the ten-minute light adaptation period. Phase 8 also consisted of three sets of yaw head turns from the RED to NU position and the return movement to RED in the dark during centrifugation.

4.2 Order Statistic Filtering

Prior to data analysis, ISCAN data was filtered using two non-linear order statistic (OS) filters and one linear filter. This particular technique was used to remove noise in the eye position signal, to differentiate the position signal (linear filter), and to remove saccades in the eye velocity signal. An Adaptive Asymmetrically Trimmed-Mean (AATM) filter, analyzed the amplitude distribution of the data samples to determine which of the samples were slow-phase (Engelken, 1991). The adaptive filter estimated SPV based on the local statistical properties of the eye-velocity signal and extracted the slow phase velocity envelope from the eye velocity signal yielding an evenly sampled SPV estimate without resorting to the various interpolation or extrapolation schemes generally used (Engelken, 1990). The AATM filter performed under the assumption that the eyes spent more time in slow phase than in the fast phase (Engelken, 1991). The *batch_bed.m* routine and corresponding subroutines were used to perform the order statistic filtering and digital fast phase removal procedures. Filter output corresponded to relatively smoothed SPV profiles. Detailed information pertaining to the filtering routines can be found in Balkwill (1992).

4.3 Head Movements

The Watson Angular Rate Sensors were calibrated manually to determine the coefficient necessary to convert the output voltage signal to degrees per second of angular velocity. For subject numbers 2, 4, 6, 7, and 9, the coefficient was 6.2189. After the completion of the fifth subject's data collection session, the sensors were returned to Watson Industries for repair because they were dropped and subsequently damaged. Upon receipt of the returned sensors, the new coefficient was calculated by manual calibration procedures. For subject numbers 10, 11, and 12, the coefficient was 1.1646. Each head movement, which appeared as a spike in the data, was then manually selected using the computer mouse. The *head.m* algorithm integrated under the curve and output the magnitude (in degrees) of the selected head movement. Additionally, peak velocity, time to peak velocity, and duration of head movement were calculated. Figure 16 presents an example of processed data from one subject on Day 1 during Phase 5 (pre-adaptation phase). In this instance, the subject had just completed a head movement from the RED to NU

position. Filtered and de-saccaded left vertical eye position, slow phase velocity, and the angular rate of the head movement are plotted from top to bottom, respectively.

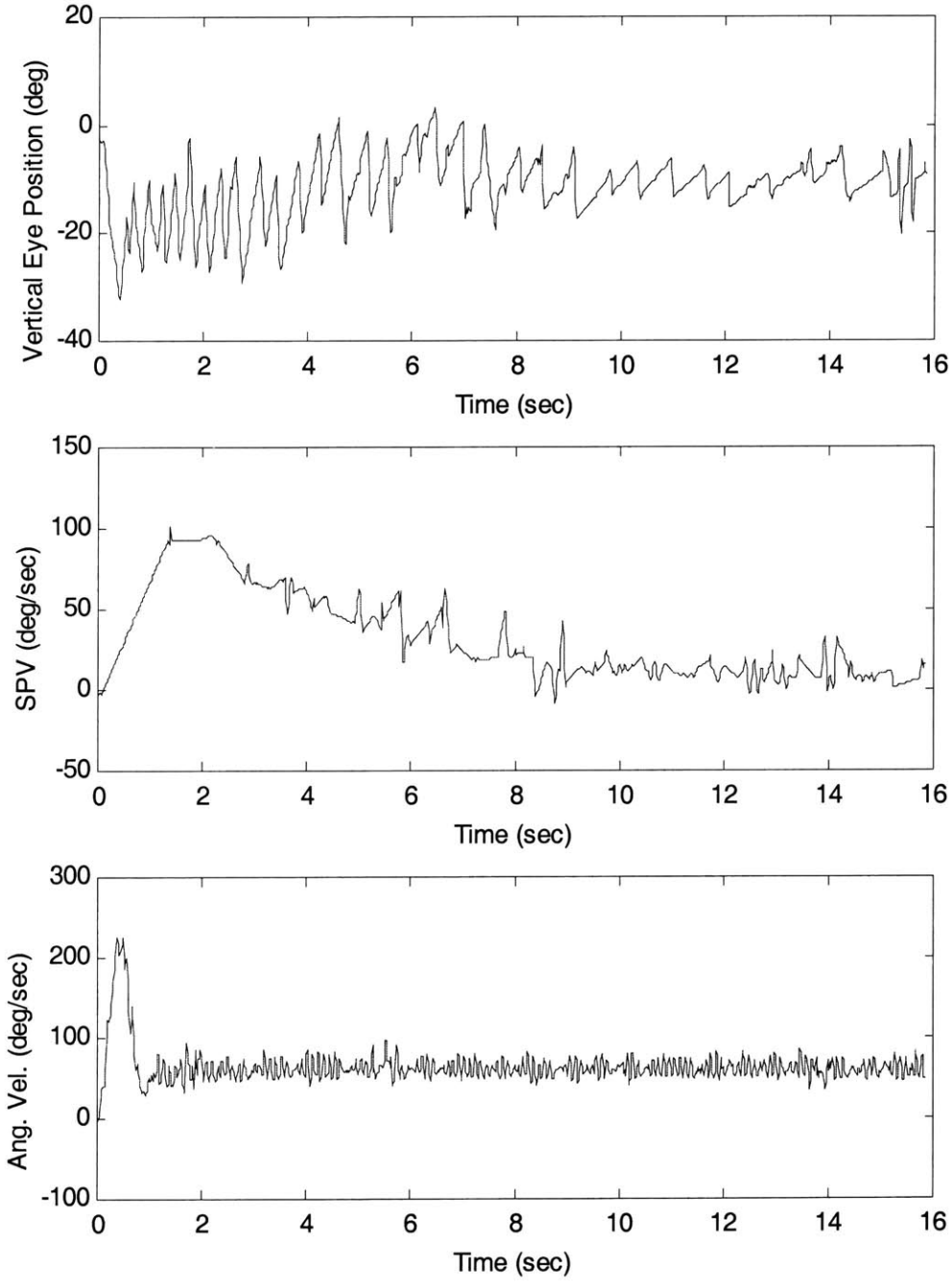


Figure 16. Exemplar Filtered and De-saccaded Vertical Eye Data

4.4 SPV Curve Fitting and Goodness of Fit

The *eye.m* routine was used to manually select a particular head movement and generate a first-order exponential curve fit to the decaying SPV eye response (SPV curve fit=Ae-(t/τ)). Computer-generated curve fits were either accepted or re-calculated depending on visual inspection of goodness of fit. Figures 17-19 illustrate several SPV envelopes fitted with the computer generated first-order decaying exponential curve. All four figures are from the same subject and represent the VOR response to the second head movement from the RED to NU position. Figure 17 is comprised of two plots; the plot on the left shows the SPV curve fitted data (R^2 value not significant) on Day 1 Phase 2 and the plot on the right shows the SPV curve fitted data on Day 8 Phase 11 (R^2 value not significant). As expected, virtually no vertical eye movements are present during yaw head movements conducted in the non-rotating environment. The magnitude of A is substantially greater on Day 1 than on Day 8 as shown in Figures 18 and 19.

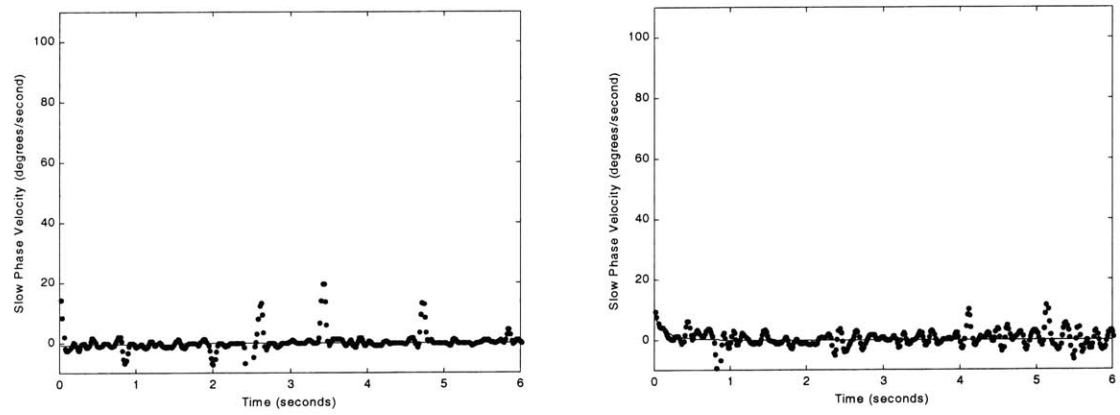


Figure 17. SPV Curve Fitted Data for One Subject During Stationary Phases Day 1 Phase 2 RED→NU Repetition 2, and Day 8 Phase 11 RED→NU Repetition 2, respectively

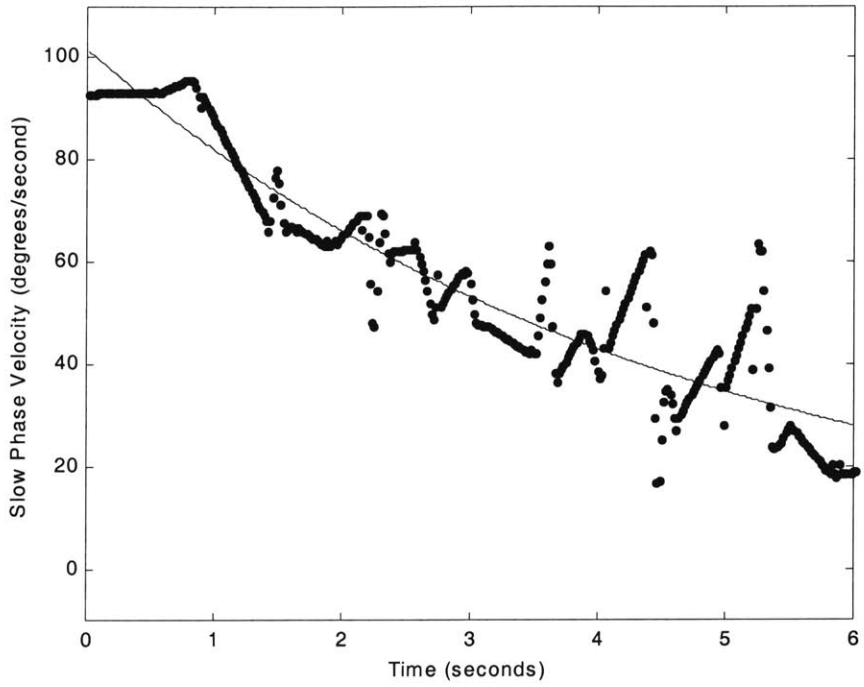


Figure 18. SPV Curve Fitted Data for One Subject Pre-Adaptation Day 1 Phase 5 RED→NU Repetition 2

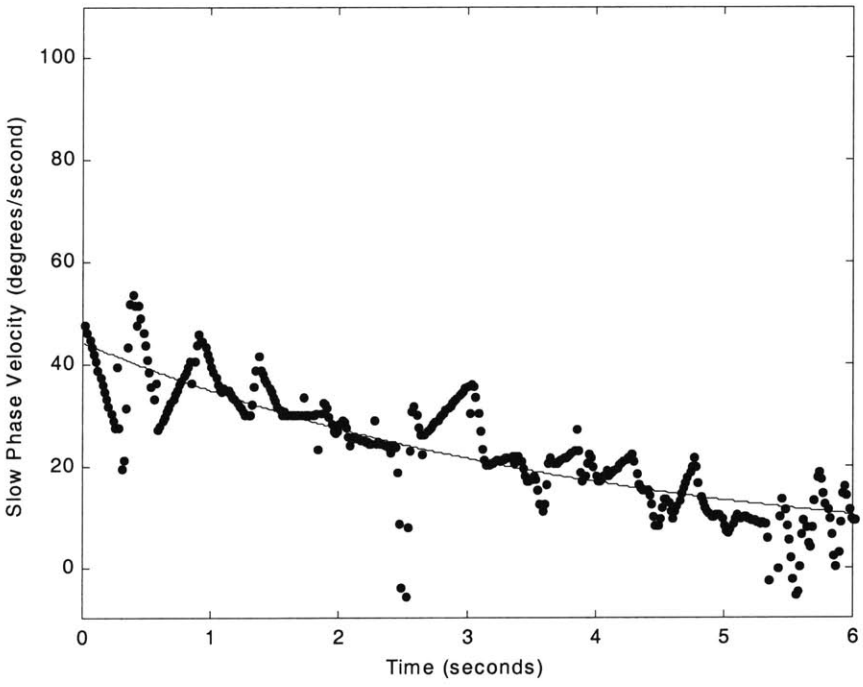


Figure 19. SPV Curve Fitted Data for One Subject Post-Adaptation Day 8 Phase 8 RED→NU Repetition 2

Values for A, the magnitude of the SPV response, and τ, the time for the exponential decaying curve to reach 1/e, were tabulated in a spreadsheet (Appendix E). For each head movement the corresponding SPV data and computer generated curve fit were re-plotted on a semi-log scale. An F-test for simple linear regression was performed. A significant F value indicated that the underlying slope of the regression line was not zero. The actual test statistic was computed by dividing the regression mean square by the residual mean square.

$$F = \text{regression mean square/residual mean square}$$

This test statistic was compared to $F_{1,\ n-2}$ in a standard F-distribution table. All curve fits associated with head movement repetitions conducted in the pre-/post-adaptation phases were significant according to the F-test.

R^2 values were computed by dividing the regression sum of squares by the total sum of squares. R^2 values ranged in value from 0.2-0.8 for random curve fits selected from a sample of 4 subjects. Additionally, basic statistics were performed on all τ values measuring less than 20 seconds (280/286 cases). The mean of the τ values equaled 4.57 $\pm$ 2.1 seconds. Based on the τ mean and standard deviation, a histogram was constructed of τ values less than 10 seconds. As seen in Figure 20, the τ values appeared fairly normally distributed. The fact that the distribution of τ values was fairly normally distributed indicated that the curve-fitting algorithm was consistently fitting curves between subjects and phases.

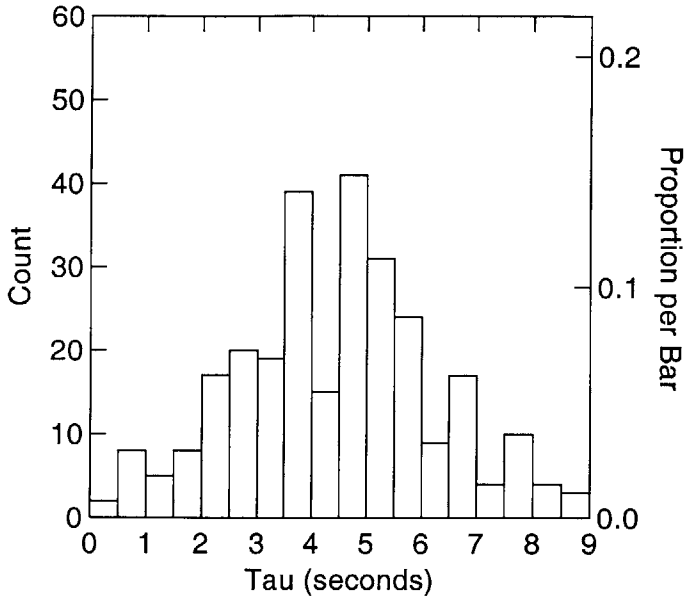


Figure 20. Histogram of τ Values

4.5 Normalized SPV Calculation

A normalized SPV parameter was selected to evaluate the degree of VOR adaptation. Normalized SPV was calculated by dividing the magnitude of the SPV response (A) by the stimulus; in this case, the stimulus was represented as the product of the sine of the magnitude of the head movement in radians times the angular velocity of the rotating environment (23 rpm equals 138 degrees/second).

$$\text{Normalized SPV} = A/[\sin(\text{head movement} * \Pi/180) * 138]$$

where A is the magnitude of the exponentially decaying curve fitted to the SPV envelope in degrees/second.

4.6 Replacing Missing Values

For the purpose of performing statistical analyses, data was organized in a spreadsheet format per subject, per day, per phase, per head position (RED to NU vs. NU to RED), and per repetition. Only one subject was missing data due to equipment failure (Day 3, Phase 8, Head Position: both RED to NU and NU to RED, and Repetition 3). Four subjects, including the subject with missing data due to equipment failure, comprised the 6/286 cases of curve fits with τ values greater than 20 seconds; recall, that the 20 second τ value was selected as the cutoff between an acceptable and unacceptable curve fit because during Phases 5 and 8, subjects were instructed to make head movements in strict 20 second intervals. Therefore, a total of four subjects had missing normalized SPV data cells within the database due to either equipment failure or curve fits with τ values greater than 20 seconds. On the remaining four subjects with complete data sets, the normalized SPV parameter showed a significant decrease in normalized SPV between Repetition 1 and Repetition 3 ($F(1,3)=15.123$, $p<.030$) according to the SYSTAT (V9) General Linear Model univariate repeated measures ANOVA. Repetition 1 was significantly greater than the average of Repetition 2 and 3 ($F(1,3)=10.682$, $p<.047$). Fortunately, among the four subjects with either missing data or τ values exceeding the cutoff, only Repetitions 2 and 3 were bad. Therefore, as appropriate, all missing Repetition 2 values were replaced with Repetition 3 values and vice-versa. Furthermore, curve fits with τ values greater than 20 seconds, were replaced with corresponding Repetition 2 and 3 normalized SPV values.

4.7 Cumulative Slow Phase Position

Cumulative slow phase position was calculated by taking the integral of the SPV curves during centrifuge acceleration and deceleration phases; Phase 3 and Phase 9, respectively. The Matlab code called *cum_spv.m* calculated the cumulative area under the SPV envelope by considering a 20 second portion of the curve beginning seven seconds after the onset of acceleration or deceleration (phase dependent) as manually indicated by the operator.

CHAPTER 5 RESULTS

5.1 Head Movements

The head movements were analyzed by SYSTAT (V9) General Linear Model univariate repeated measures ANOVA. Occasionally, the corresponding multivariate analysis gave a significant result (which is quoted) when the univariate analysis did not. There was no significant effect of Day (1, 2, or 8) on the magnitude of or on peak velocity of head movement (as measured in degrees). There was a significant ($F(1,6) = 13.286$, $p < .011$) decrease in peak head velocity, and a significant ($F(1,6) = 6.25$, $p < .05$) increase in time required to make a head movement, as between pre- and post-adaptation (Phases 5 and 8). Note the normalized SPV parameter takes the variations of head velocity into account.

5.2 Normalized Slow Phase Velocity

Four subjects provided complete data sets (none missing due to equipment failure or normalized SPV values with τ values greater than 20 seconds). The normalized SPV parameter showed significant main effects of Day ($F(2,6) = 9.245$, $p < .0150$), Phase (pre-/post-adaptation) ($F(1,3) = 12.346$, $p < .039$), and Phase *x* Repetition ($F(2,6) = 5.407$, $p < .045$). Contrasts between Repetitions showed a significant decrease in normalized SPV between Repetition 1 and Repetition 3 ($F(1,3) = 15.123$, $p < .030$). Repetition 1 was significantly greater than the average of Repetition 2 and 3 ($F(1,3) = 10.682$, $p < .047$). Overall, Phase was significant for normalized SPV values for Repetitions 2 and 3, but not for Repetition 1. This information was used to replace the

missing normalized SPV values and those derived from tau values exceeding the 20 second τ cutoff as described earlier in section 4.6.

Next, a general linear model ANOVA analysis was run on normalized SPV for eight subjects against Day, Phase, Head Position, and Repetition, (3, 2, 2, and 3) levels, respectively. There was a significant effect of Day ($F(2,14)=11.399$, $p<.001$), Phase ($F(1,7)=6.651$, $p<.037$), and Head Position x Repetition ($F(2,14)=8.717$, $p<.003$) demonstrating that normalized SPV decreased following adaptation in the light. A multivariate analysis of Day x Phase ($F=5.867$, $p<.039$) also gave a significant result though the corresponding univariate result was not significant. Figure 21 illustrates the general decrease of the normalized SPV parameter both between and within Days.

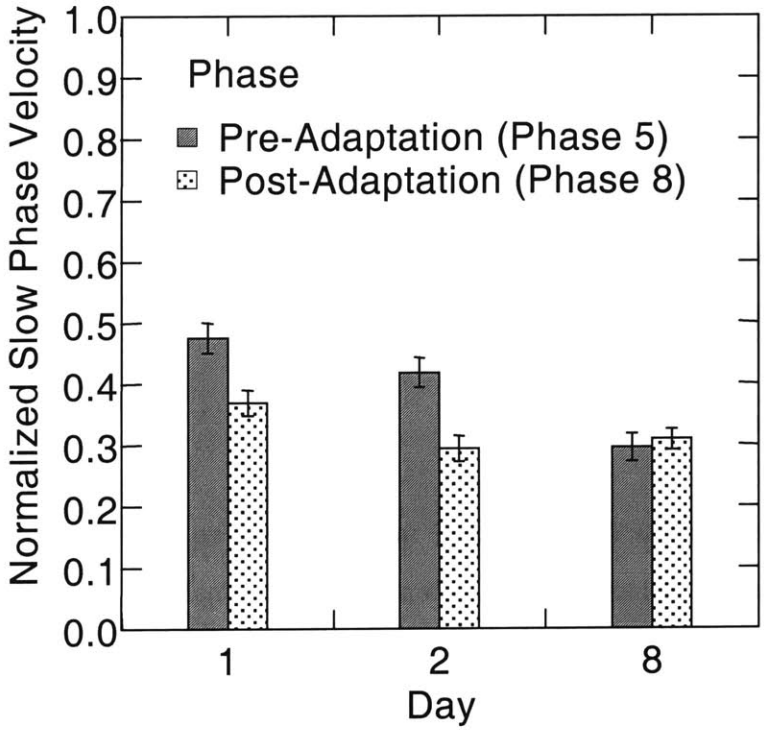


Figure 21. Mean Normalized Slow Phase Velocity for Pre- and Post-Adaptation (over three days of testing - all eight subjects)

No significant main effects of Day, Phase, or Head Position on the normalized SPV parameter were found for Repetition 1 trials taken alone. The graph, however, suggests a general decrease from pre- to post-adaptation phases on Days 1 and 2 (Figure 22). This effect was captured by the Page (non-parametric) Test (StatXACT, version 4.0) which showed a significant ($p<.001$) decreasing trend across Days for the RED to NU position in the pre-adaptation phase. The Page Test was highly significant ($p<0.0082$) over Days and across Phases 5 and 8 (pre-/post-) for head movements made in both directions.

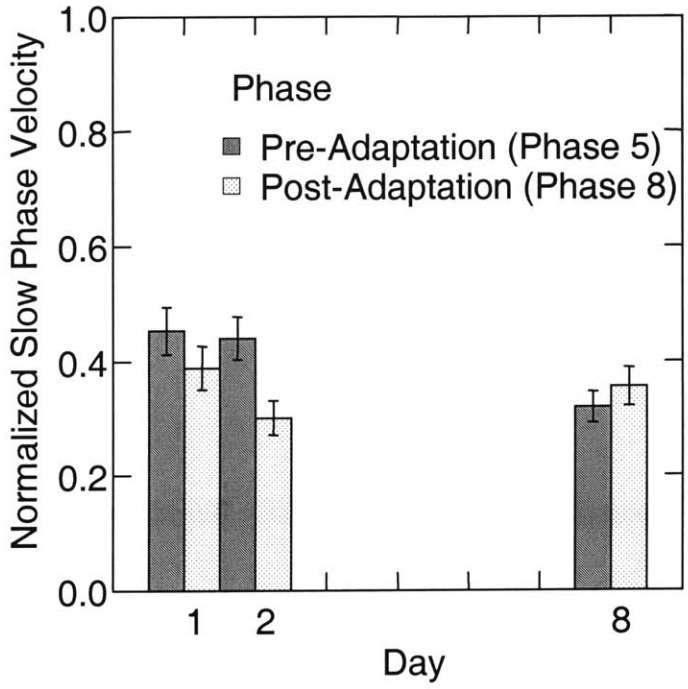


Figure 22. Normalized SPV Values Corresponding to the First Repetition (averaged over all eight subjects)

Although Head Position showed no main effect, the values of the normalized SPV for the NU to RED position are consistently higher than those for the RED to NU position (Figure 23).

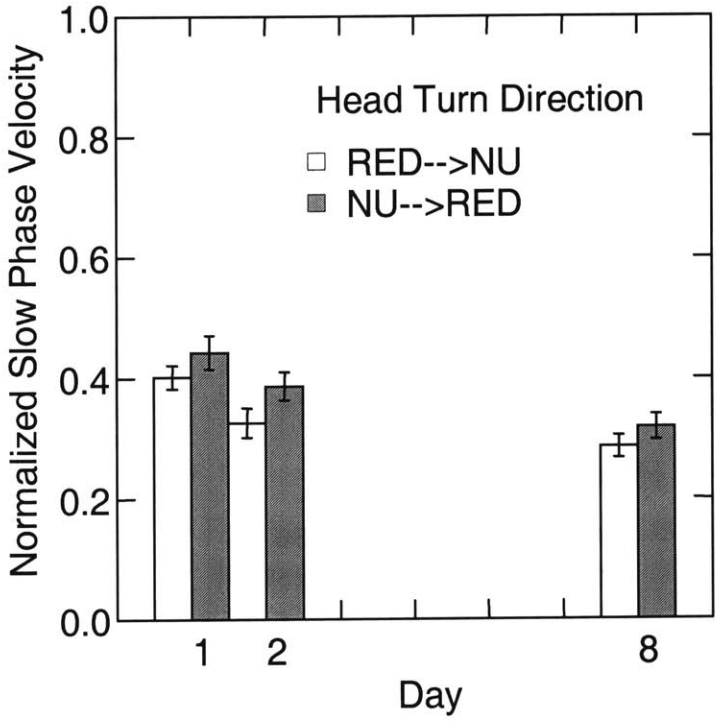


Figure 23. Normalized Slow Phase Velocity Based on Head Position

5.3 Cumulative Slow Phase Position

The cumulative slow phase position was analyzed by ANOVA on seven subjects against Day and Phase (one subject was excluded from the analysis due to equipment failure during the deceleration phase (9)). The main effect of Day was significant by multivariate ANOVA analysis ($F= 23.322$, $p<.003$); that of Phase was insignificant. Figure 24 shows the decay of the cumulative slow phase position for each of the eight subjects by Day in paired phases (acceleration/deceleration).

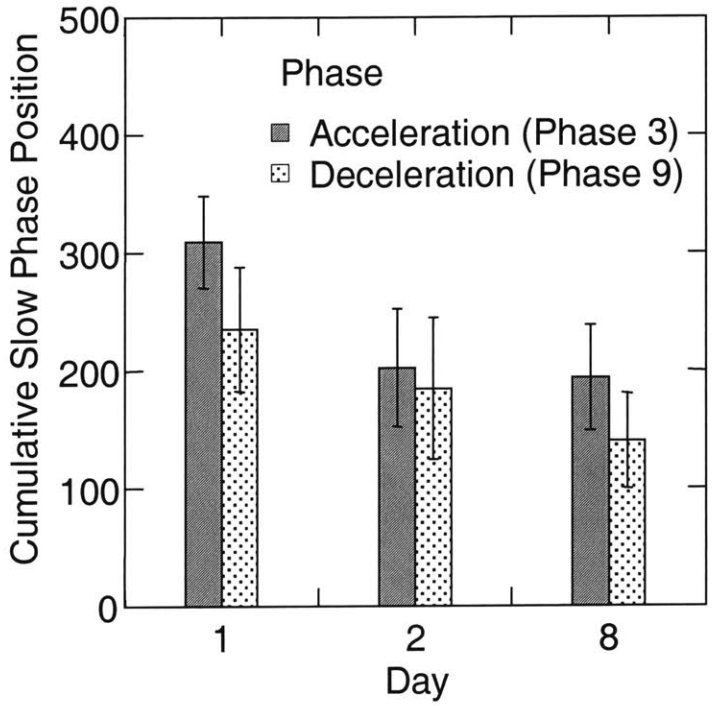


Figure 24. Cumulative Slow Phase Position Paired in Phases Over Days

CHAPTER 6 DISCUSSION

6.1 Major Results and Implications

Vertical eye movements are non-compensatory inappropriate vestibulo-ocular reflexes produced in response to yaw head turns made into and out of the plane of rotation during centrifugation. In the context of this work, adaptation was defined as the reduction in the magnitude of the normalized SPV parameter.

6.1.1 Normalized Slow Phase Velocity

The normalized SPV parameter showed significant main effects of Day, Phase (pre-/post-adaptation), and Phase *x* Repetition. Figure 21 shows that the greatest amount of VOR adaptation was achieved between Day 1 Phase 5 (pre-adaptation) and Day 2 Phase 8 (post-adaptation). At the end of Day 2, normalized SPV averaged over eight subjects had decreased by roughly one-third of its initial magnitude. Virtually complete retention of the adaptation was attained by the end of Day 2 and retained for five-days without exposure to centrifugation. The results indicate that no further adaptation occurred on Day 8 following exposure to the light adaptation phase. Normalized SPV values both before and after the light adaptation phase on Day 8 appear approximately equal. However, upon examining the subjects on an individual basis, one notices that several subjects do in fact show continued decreases in normalized SPV values following exposure to the light adaptation phase on Day 8. Individual subject plots can be found in Appendix D.

The subjects' systems do not appear to conform to the strict definition of *plastic* as defined earlier by Miles and Lisberger. No significant main effects of Day, Phase, or Head Position on the normalized SPV parameter were found for Repetition 1 trials taken alone. This non-significant finding indicates that the system potentially required the feedback provided by first head movement (Repetition 1) in the rotating environment to either 1) switch internal programs in order to suppress the non-compensatory vertical eye movements or 2) reroute to an appropriate program. In other words, these results lead one to believe that first head movement conducted in the rotating environment served as the cue for context-specific adaptation.

6.1.2 Cumulative Slow Phase Position

Throughout Phases 3 and 9, the acceleration and deceleration phases, respectively, the subjects were lying in the supine and RED position. Vertical nystagmus was observed even though no head movements were conducted. The vertical eye movements were appropriate in this case because the equivalent pitch canals were positioned in the plane of rotation during acceleration and deceleration. Therefore, when the centrifuge began to rotate in the clockwise direction, the endolymph fluid within the equivalent pitch canal displaced the cupula, which discharged the hair cells and produced a compensatory vertical nystagmus with the fast phase in the pitch upward direction and the slow phase in the pitch downward direction. Upon deceleration of the centrifuge, the cupula in the equivalent pitch canal was displaced in the opposite direction. The resulting vertical nystagmus had a fast phase in the pitch downward direction and a slow phase in the pitch upward direction.

The decrease in vertical cumulative slow phase position (integral of the slow phase velocity envelope) was significant for the main effect of Day. Phase, however, was insignificant. Figure 24 shows that the greatest decrease in cumulative slow phase position was achieved between Day 1 Phase 3 (acceleration) and Day 8 Phase 9 (deceleration); the cumulative slow phase position (averaged over seven subjects) decreased to nearly one-half its initial value. Despite the fact that Phase was insignificant, Figure 24 shows that the magnitude of the cumulative slow phase position decreased within Days thereby suggesting the presence of both habituation and adaptation. The decrease in cumulative slow phase position illustrated VOR suppression of an

appropriate compensatory response to the rotational stimulus. This finding leads one to believe that the context-specific cue was actually comprised of both the act of making a head movement within the rotating environment (Repetition 1) and the rotating centrifuge itself.

6.1.3 Asymmetries in Vertical Eye Movements and Illusory Sensations

Numerous investigators have reported asymmetrical vertical eye movements in response to pitch head movements or vertically moving visual fields. The development of asymmetrical vertical optokinetic nystagmus and vestibular nystagmus has been well documented in several species of animals, but remains questionable or absent in humans (Young, 1984b). Benson and Guedry, Hixson and Niven, and Collins have reported stronger upward vertical nystagmus than downward vertical nystagmus in humans (Young, 1984b).

During the acceleration phase of the MIT artificial gravity adaptation study, the vertical fast phase was in the upward direction. The deceleration phase, on the other hand, elicited a vertical fast phase in the downward direction. It is possible that a vertical eye movement asymmetry was present in this investigation. However, if this were the case, the effect may have been partially hidden within the results. This could be attributed to the fact that the cumulative slow phase position during the acceleration phase was consistently higher over days despite insignificant main effect of Phase (3 versus 9). Therefore, the lower average cumulative slow phase position value during deceleration phases could be due in part to the presence of a vertical eye movement asymmetry in addition to habituation and adaptation.

Guedry et al. (1992) exposed 43 subjects to a series of experiments combining linear and angular accelerations in order to confirm or deny anecdotal information indicating that deceleration of a centrifuge run generates substantially greater magnitude spatial illusions than is experienced during the acceleration. They also sought to compare perceptual dynamics with VOR. 41 of the 43 subjects reported that perceptual effects were much greater during deceleration (of the two subjects that did not report, one was confused and unable to compare magnitudes, the other had small effects in both acceleration and deceleration and uncertainty about the comparison).

However, the VOR did not reflect the acceleration/deceleration difference that was so evident in the dynamics of the spatial orientation perception (Guedry, Rupert, McGrath, & Oman, 1992).

Both the main effect of Head Position on normalized SPV and the subjective verbal reports regarding the magnitude of the perceived sensation as a function of the direction of the head movement (RED to NU versus NU to RED) were insignificant. However, in a recent subjective investigation performed on a larger number of subjects in the same laboratory, Hecht et al. (2000) reported an asymmetry between the persistence of illusory body tilt and the direction of head movement. Yaw head turns from the RED to NU position were associated with longer durations of perceived tilt.

Graybiel et al. (1961) also reported an asymmetry between perceived illusions and direction of head turn within the rotating environment. Four subjects, rotated for 64 hours, were asked to estimate with a 0-10 rating scale the magnitude of their subjective reactions produced by both passive and active angular head displacements. Magnitude estimates of the oculogyral illusion declined for all subjects from one test period to another, with the major decline occurring between the first and second test periods. The oculogyral illusion can be defined as an apparent movement of objects in the visual field having its origin in stimulation of the sensory receptors in the semicircular canals (Graybiel, 1961). Although the oculogyral illusion does not perfectly coincide with the recorded vestibular nystagmus, it corresponds closely with recorded vestibular nystagmus in magnitude-growth during constant angular acceleration and duration characteristics (Graybiel, 1961). Three of the four subjects tested reported the highest magnitude estimates in response to the return to upright from left tilt. All four subjects consistently reported that the magnitude of the perceived illusion was lowest when moving from the upright position to the left tilt. Additionally, they gave higher magnitude estimates when reporting active movements (head alone) versus passive movements (head and body). Note that the active movements were twice as fast as the passive movements.

Benson and Guedry also reported a bias in response to cross-coupled stimuli based on the direction of head movements. They observed a greater level of nystagmus frequency, visual

blurring, tracking performance deterioration, and SPV during the pitch-forward than during the pitch-back phase of oscillations of human subjects (Woodman & Griffin, 1997)

6.1.4 Dual Adaptation

The issue of dual adaptation is of particular interest to the MIT artificial gravity study because the use of short-radius intermittent centrifugation as a countermeasure requires that astronauts be able to 1) smoothly transition between the rotating and non-rotating environment, and 2) conduct head movements without negative side-effects during rotation. Therefore, astronauts must develop the capability to store internal programs that suppress inappropriate VOR within rotating environments and maintain the mechanisms that allow them to switch between such programs depending on the specific gravito-inertial environment.

According to Welch et al. (1993), if subjects adapt repeatedly to a sensory rearrangement, with intervening re-adaptation to normal vision, they begin to develop a separate adaptation to each simulation, a phenomenon referred to as dual adaptation. Welch et al. (1993) found that alternating adaptation and re-adaptation to ± 15-diopter displacement produced dual adaptation in the exposure, post exposure, and re-adaptation phases of the experiment. Dual adaptation was observed by the end of 12 alternation cycles. Their data indicates that dual adaptation will occur when subjects alternate both between a prismatically displaced and a normal visual field, and between opposite displacements.

In two additional experiments, Welch et al (1998) re-examined the possibility that the human VOR was subject to dual adaptation. In their first experiment, the subjects actively made head movements during alternating exposure to a visual-vestibular rearrangement (target/head gain =0.5) and a normal environment (target/head gain=0.0). These conditions produced both adaptation and dual adaptation of the VOR. In their second test, the exposure to the 0.5 gain involved externally controlled passive whole body rotation. Their results reported VOR adaptation but no evidence of dual adaptation.

6.1.5 Context-Specific Dual Adaptation

Failure to adapt to intermittent centrifugation could result in repeated episodes of motion sickness. Brief bouts of motion sickness may be tolerable early in a mission; however, it would be unacceptable if these symptoms were to re-occur each time the astronaut transitioned between different gravito-inertial environments. Thus, adaptation not only has to be achieved, it also has to be appropriate for the environment (i.e., non-rotating, rotating, 1 g, or 0 g). Additionally, astronauts must be able to make the appropriate transitions quickly.

Shelhamer et al. (1992) demonstrated that humans could adjust their VOR gains depending on situational context. Shelhamer and his colleagues set out to determine if one of the corresponding non-visual cues could be used to create two "stored" VOR gains simultaneously in a subject, and if this context cue could determine which gain should subsequently be used. Their experimental setup consisted of an optokinetic drum rotating with or against sinusoidal chair oscillation that served to drive gain up when the subject looked up and down when the subject looked down. Following two hours of such stimulation, distinctive gains within the subject were established depending on which direction they looked. They demonstrated that subjects could learn to store two VOR gains simultaneously and, depending on context, could switch form one to the other. Context-specific dual adaptation has also been observed in experienced deep-sea divers. When comparing experienced and novice deep-sea divers, experienced divers reported relatively few face-mask induced visual distortions when first entering the water and very rapid re-adaptation upon emerging (Lurid, Kinney, 1970).

The subjects that participated in the MIT artificial gravity adaptation study did not exhibit inappropriate non-compensatory vertical nystagmus during Phase 11 testing. This indicates that the adaptation attained was not inappropriately recalled for the non-rotating frame-of-reference.

6.1.6 Adaptive Generalization and Transfer of Adaptation

The principles of adaptive generalization, or "learning to learn," and transfer of adaptation are also of particular interest. For example, questions posed following the MIT artificial gravity study include:

- Are subjects capable of adaptive generalization? Specifically, has the system "learned to learn" in which case one would expect to see some degree of suppressed VOR when the centrifuge is rotated in the counterclockwise direction?
- Would head movements from the "left ear down" (LED) to "nose-up" (NU) or NU to the LED position in a clockwise rotating environment yield significantly different results from the RED to NU head movement? Or would the system transfer the adaptation?

In an experiment conducted by Guedry (1964), 32 men were positioned four feet off-axis and rotated at 7.5 rpm for several hours. During rotation, subjects were immobile except for a series of frontal plane head movements in a particular quadrant of that plane varying from subject to subject. Nystagmus, illusory phenomenon, and nausea were reduced after repeated head movements. However, transfer of the observed "habituation" was not observed when subjects experienced other vestibular stimulation including that induced by head movements made in "unpracticed quadrants" of the same plane. Welch and et al. (1993, 1998) have also attempted to answer similar questions regarding the transfer of adaptation. In addition to observing dual adaptation to the 15-diopter prismatic displacement in 1993, substantial adaptive generalization to a 30-diopter displacement was reported. Additionally, in a series of two experiments conducted in 1998, the first experiment showed no evidence of adaptive generalization when tested with at target/head gain of 1.0. Similarly, no evidence of adaptative generalization was noted in the second experiment either.

Guedry (1965) rotated nine men at ten rpm for 12 days. Tests conducted before and after the 12-day run demonstrated that nystagmus and subjective effects produced by head movements during the accustomed direction of rotation (counterclockwise) had diminished noticeably. Nonetheless, during clockwise rotation one hour following the end of the 12-day run, nystagmus and subjective reactions approximately equaled reactions prior to the 12-day run. Two days later, responses to both rotation directions were suppressed as compared with initial levels of response. A partial decline in response was still present after three weeks without exposure to rotation.

6.2 Possible Concerns

6.2.1 Data Collection

Issues concerning the quality of the data collected and presented should be addressed. It is important to recall that no manual editing was conducted following the digital fast phase stripping process. Therefore, on occasion, a few fast phases appeared in the SPV data. As previously mentioned, two data points were lost due to equipment failure for one subject. Seven additional data points were replaced as described in the data analysis section due to extremely noisy data that could not be properly curve-fit.

6.2.2 Self-Regulated Light Adaptation Phase Head Movements

In a study to investigate the design of an adaptation schedule to the rotating environment, Reason and Graybiel (1969) found no measurable differences in the degree of adaptation acquired given six conditions of exposure ranging from 30 to 180 sequences of eight head motions during rotation. Consequently, a second experiment was performed that sampled a stimulus range of less than 30 sequences. Only the shortest exposure produced a measure of adaptation that was significantly less than that in the other conditions. These results indicate that the degree of adaptation achieved by subjects in this experiment might not be significantly affected by the number of head movements made during the light adaptation phase.

In the MIT artificial gravity adaptation study, subjects were instructed to make ad lib yaw head movements during the light adaptation phase. The number of head movements conducted on the first day of testing for example, ranged from 32-218. Inspection of the cumulative number of head movements show that five subjects increased head movements during the light adaptation phase from Day 1 to Day 2 (Lyne, 2000). Note that subjects who showed an increase in head movements also showed a corresponding decrease in peak motion-sickness (excluding the subjects who showed negligible motion-sickness scores) (Lyne, 2000). Subjects who showed a decrease in the number of head turns experienced an increase in peak motion-sickness symptoms (excluding the subjects who showed negligible motion-sickness scores) (Lyne, 2000).

Below is a cursory listing of observations comparing the number of head movements, subsequent normalized SPV values, and subjective results that uncover intriguing correlations requiring further investigation.

- Subjects who *increased* the number of head movements conducted during the light adaptation phase from Day 1 to Day 2 and showed a *decrease* in normalized SPV values and peak motion-sickness scores.
- Subjects who *decreased* the number of head movements conducted during the light adaptation phase from Day 1 to Day 2 and showed a *decrease* in normalized SPV values and an *decrease* in motion sickness scores.
- Subjects who *decreased* the number of head movements conducted during the light adaptation phase from Day 1 to Day 2 and showed a *decrease* in normalized SPV values and an *increase* in motion sickness scores.
- Subjects who conducted a large number of head movements during the light adaptation phase (>100) and reported very low motion-sickness scores and showed a *decrease* in normalized SPV values.
- Subjects who conducted a large number of head movements during the light adaptation phase (>100) and reported very low motion-sickness scores but had non-distinct patterns in normalized SPV over both Phases and Days.

Comparisons between motion sickness symptoms and normalized SPV values will be further explored in a forthcoming publication.

6.2.3 Visual Tasks

Subjects in this experiment were not given instructions regarding where to fixate during head movements in either the dark or the light setting. Some subjects commented that they fixated on visual cues inside the canopy during the light adaptation phase. Others did not allude to any specific technique. Guedry (1964) performed an experiment in the slow rotating room (45 deg/sec) with subjects immobilized with the exception of head movements restricted to one plane and to a particular quadrant. Visual targets were presented with each head movement to one group of subjects; another group of subjects made all head movements in the dark. Tests conducted in darkness before and after the habituation series revealed pronounced reductions in nystagmus and subjective symptoms in the practiced quadrant only in the "visual task" group. The other group showed no reduction of nystagmus in either the practiced or unpracticed quadrant. This experiment not only indicated that vision can be an important factor in habituation

of human subjects to vestibular stimulation, but that fixed visual targets could contribute to decreases in vestibular response. As previously discussed in the background section, Barr et al. (1976) showed that VOR could be consciously modified by subjects rotating in the dark when assigned the task of either imagining and staring at a fixed point within in their rotating environment or fixating on a visual target. Results from the MIT artificial gravity study could confound interpretation if some subjects unconsciously adopted a "visual task" strategy while others did.

6.2.4 Mental Alertness

It is also worthwhile to draw attention to a study performed by Collins (1962) that reported that low levels of mental alertness also cause partial suppression of the VOR. Due to the busy schedules of MIT students, subjects were given flexibility regarding testing times. Subjects were tested between the hours of 6:00 am and 10:00 pm. Because caffeine was banned 24 hours before the experiment, some subjects suffering from lack of sleep occasionally appeared drowsy during centrifugation. This confounding factor could make it difficult to solely attribute decreases in normalized SPV to adaptation. In fact, some fraction of the decreasing normalized SPV values could be attributable to low levels of mental alertness.

6.2.5 High Angular Velocities

In the 1960's, Graybiel et al. conducted a number of studies on adaptation to moving about in a slow rotation room. The general conclusion of these studies, some of which involved rotation durations as long as 21 days, was that it would be difficult to adapt individuals to velocities of rotation greater than 3 or 4 rpm because of the disorientation and vestibular side effects elicited by head movements during rotation. They concluded that humans can adapt to a rotation rate of 3 rpm, and that a 14-day period of rotation at this rate causes no significant changes in general condition or performance. In contrast, no adaptation took place when subjects were rotated at 10 rpm for 12 days, implying that this rotation rate is close to the upper threshold of endurance (Shipov, 1996).

Guedry and Graybiel (1962) rotated seven men at 5.4 and 10 rpm in a slow rotating room for 64 hours. Based on the intensity ratings of recorded nystagmus, there were declines of 66 and 39 %, respectively, for the 5.4 and 10 rpm tests from day 1 to day 4. Thus, there was a greater decline in the response to the lower rate of rotation.

Based on the results of the MIT artificial gravity study, it is questionable whether or not complete suppression of the inappropriate non-compensatory vertical nystagmus can be attained. It is entirely possible that normalized SPV values could decrease with additional exposure to the stimulus (in days), increased duration of the light adaptation phase (in minutes), or a lower rate of rotation (in rpm).

6.3 Subjective Results

Verbal accounts of perceived pitch obtained during rotation and post-experiment motion-sickness scores provide clear evidence of adaptation to the stimulus between Day 1 and 2, and partial retention of adaptation on Day 8 (Lyne, 2000). Figure 30 shows the decrease in the Pensacola Motion Sickness Scores with Day. The median values decreased from 10 on Day 1, to 4 on Day 2, and to 3 on Day 8. A Friedman Test (a non-parametric test based on measurement ranking) showed a significant decrease over all three days. The greatest decrease was found to occur between Day 1 and Day 2. This trend is extremely similar to the trend observed in the normalized SPV data. World Up® computer animations of subjective sensations and motion-sickness scores obtained during the experiment, conversely, did not provide conclusive evidence of adaptation or retention of adaptation (Lyne, 2000). Complete subjective results can be found in Lyne (2000).

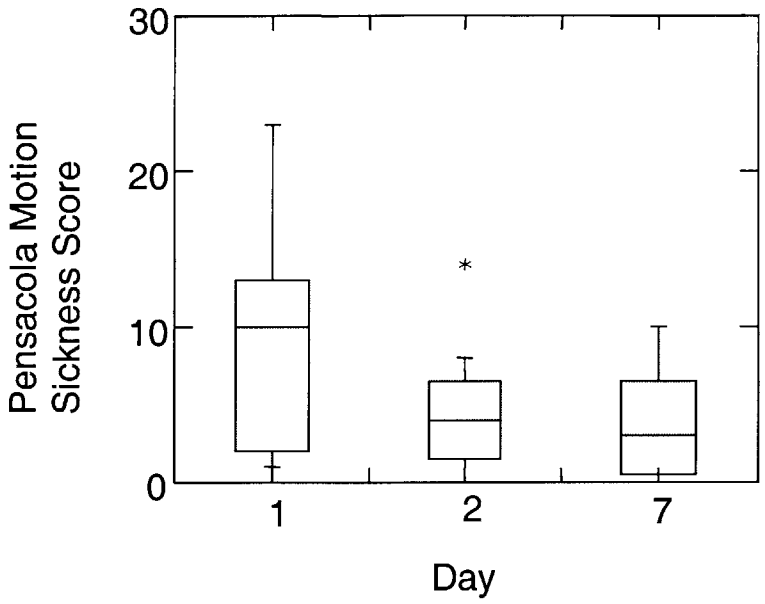


Figure 25. Pensacola Motion Sickness Scores
(Lyne, 2000)

6.4 Pilot Study Results

The overall "leveling-off" effect of the mean normalized SPV values (all eight subjects) observed on Day 8 prompted a pilot study designed to examine the effects of increased exposure to short-radius centrifugation. In this pilot study, the author served as the subject and was rotated on the MIT short-radius centrifuge for 12 consecutive days. ISCAN data was only recorded on Days 1, 5, and 12 (on the eye recording days the full protocol was used). On the remaining days, the subject was placed on the centrifuge in the RED position and immediately accelerated to 23 rpm; neither the ISCAN imaging goggles nor the Watson angular rate sensors were worn on these days. Once a constant velocity had been achieved, the subject was instructed to turn on the lights and make ad lib yaw head movements throughout the ten-minute light adaptation period. The subject reported motion sickness scores on a 0-20 scale, overall magnitude of perceived sensation estimates for head movements on a 0-10 scale, and filled out post motion sickness surveys accounting for the period time following the termination of the session until sleep.

A difference between the pilot subject and the overall normalized SPV value for the eight subjects was observed in the final degree of adaptation achieved at the end of each respective investigation. Figure 26 shows the normalized SPV values for both Phase 5 (pre-adaptation) and Phase 8 (post-adaptation) for Days 1, 5, and 12. The normalized SPV value on Day 12 during Phase 8 was approximately 2.3. For the eight subject study, the overall normalized SPV value on Day 8 during Phase 8 was 3.2.

The subject reported a noticeable decrease in both motion sickness scores and assessment of magnitude estimates from Day 4 and onward. Prior to Day 4, the subject reported maximum motion sickness ratings during rotation of 18, 16, and 12, on Days 1 through 3, respectively. Magnitude estimates of perceived sensation following head movements in the dark decreased to a value of 2 (on the 1-10 scale) by Day 4. Prior to Day 4, the subject reported magnitude estimates of 10, 8, and 6, on Day 1, 2, and 3 respectively. Similar trends were observed in the post-motion sickness scores.

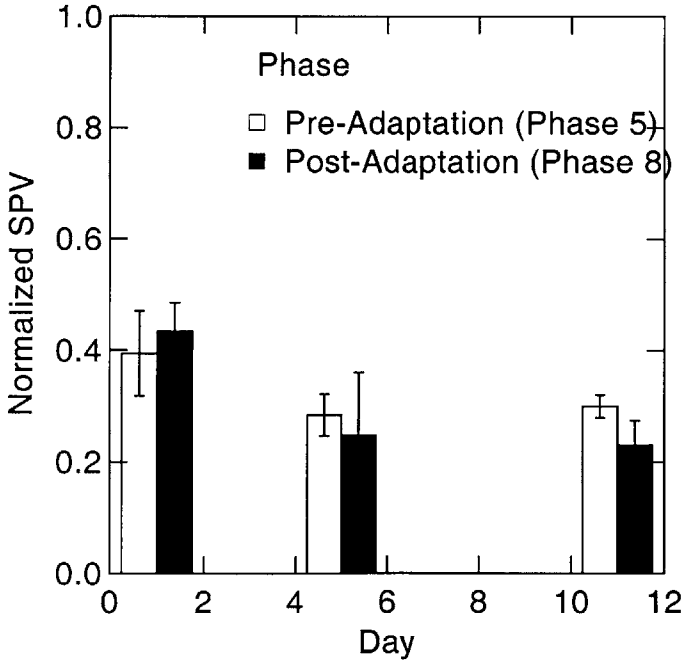


Figure 26. Pilot Study Normalized SPV for Day 1, 5, and 12

On Day 12 following the normal protocol, the subject was exposed to a series of novel stimuli in an attempt to assess transfer of adaptation and/or signs of generalized adaptation. The centrifuge was rotated in the opposite direction (counterclockwise) while the subject conducted head movements from RED to NU and NU to RED. This stimulus proved extremely provocative. Similarly, rotation in the clockwise direction and head movements from NU to LED and LED to NU, were also exceptionally stimulating. The subject did note, however, that the estimated magnitude of the subjective responses decayed quickly with additional repetitions.

There appeared to be a slight disconnect between the amount of adaptation achieved as represented by the magnitude of the normalized SPV measured in the dark and the oculogyral illusions experienced during the light adaptation phases. The subject noted that by Day 4, following the first set of head movements in the light (Repetition 1), the oculogyral illusion was negligible. The subject reported being able to read text while conducting head movements in the light without visual illusions. Throughout the 12-day pilot study, the subject consistently used a visual tracking technique; during each head movement, the subject would seek out two small bolts on the interior frame of the canopy (one visible in the RED position and the other visible in the NU position) and hold gaze. Although the inappropriate non-compensatory vertical eye movements did not disappear entirely by the twelfth consecutive day of rotation, motion sickness did. Based on results from the pilot study, perhaps motion sickness assessment tools should be considered the primary criterion for adaptation in future studies. Increasing the number of exposures to short-radius centrifugation beyond that of the pilot study should be explored.

6.5 Recommendations

Recommendations for future research fall into several categories. These categories include: transfer of adaptation/generalized adaptation, duty cycle augmentation, and tasks to enhance adaptation, and hardware adjustments that could make centrifugation sessions more comfortable for the subject.

Future research should exam the effects of transfer of adaptation and generalized adaptation as attempted in the pilot study via head movements in different quadrants (LED to NU and NU to

LED) and rotation of the centrifuge in the opposite direction. Also, the adaptation duty cycle should be augmented in an attempt to filter out the effects of longer or more frequent exposures to short-radius centrifugation. Future pilot studies should consider examining:

- Daily rotation for a month's duration with the ten-minute light adaptation period
- A protocol with fewer exposures, but longer light adaptation exposures
- Trials with a reduced rate of rotation

Visual tracking tasks should be implemented to study the degree to which subjects' adaptation improves. Figure skaters have been traditionally considered to have suppressed normal vestibular reactions. In a series of experiments performed by Collins (1966), figure skaters were tested with caloric irrigations, laboratory rotation, and on-ice studies. Results showed that in the absence of opportunities for visual fixation, moderate vestibular stimulation produced brisk nystagmus and sensations of motion. Following on-ice spins, the skaters demonstrated nystagmus, loss of equilibrium, and disorientation when they attempted to maneuver with eyes closed. Collins concluded that the skaters had learned to exercise some visual control over their vestibular reactions.

Simple hardware adjustments such as automating the on-board centrifuge lights, increasing the airflow throughout the canopy during sessions, and reducing motor noise with the use of ear plugs could make the experience more enjoyable.

CHAPTER 7 CONCLUSIONS

The results of this investigation showed that subjects partially adapted to head movements conducted during short-radius centrifugation at 23 rpm. The adaptation was maintained, to a large extent, over a five-day period without centrifugation. The maximum number of days to which the partial adaptation can be retained is unknown. At the end of Day 2, normalized SPV averaged over eight subjects had decreased by roughly one-third of the initial magnitude.

Future studies need to address the acquisition, retention, and generalization of this adaptation to different head movements and to different rotating environments. Conditions for complete adaptation as well as optimal adaptation schedules also require investigation. It is entirely possible that complete adaptation cannot be attained at high rates of rotation (on the order of 20-30 rpm). The results from 12-day pilot study suggest that the criteria for adaptation should be carefully evaluated; motion sickness symptoms were negligible despite the fact that, normalized SPV was not entirely eliminated.

Assuming that the same mechanism that causes adaptation to centrifugation on Earth is also functional in microgravity, these results indicate that humans should be able to partially adapt to short-radius countermeasures in weightlessness. Additionally, astronauts may be capable of pre-adapting to short-radius centrifugation before space flight. Pre-adaptation training would enable them to transition between the rotating and non-rotating environments with minimal negative side-effects such as inappropriate eye movements, illusory sensations, or motion sickness. In summary, the results provide evidence of partial acquisition and retention of adaptation, which

supports the continued evaluation of short-arm centrifugation as a potential countermeasure against the debilitating effects of the long-duration space flight.

REFERENCES

Balkwill, M.D. (1992). *Changes in human horizontal angular VOR after the Spacelab SLS-1 mission.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Benson, AJ. (1999). Spatial Orientation. In J. Ernsting, A.N. Nicholson, & D.J. Rainford (Eds.), *Aviation Medicine* (3rd edition) (pp. 444-446). Oxford: Butterworth Heinemann.

Cheung, C.C. (2000). *Regulator control of a short-radius centrifuge and subjective responses to head movements in a rotating environment.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Collins, W.E. (1960). *Further Studies of the Effects of Mental Set Upon Vestibular Nystagmus* [Report No. 443]. Fort Knox, KY: US Army Medical Research Laboratory.

Collins, W.E. (1966). Problems in Spatial Orientation: Vestibular Studies of Figure Skaters. *Transactions American Academy of Ophthalmology and Otolaryngology*, July-August, 575-578.

Collins W.E, & Guedry F.E. (1962). Arousal Effects and Nystagmus During Prolonged Constant Angular Acceleration. *Acta Oto-laryng., 54*, 349-361.

Collins W.E. (1986). *Effects of Sleep Loss on Vestibular Response During Simple and Complex Vestibular Stimulation* [DOT/FAA/AM-86/9]. Washington, DC: U.S. Department of Transportation, Federal Aviation Administration.

Diamandis, P.H. (1988). *The artificial gravity sleeper: A deconditioning countermeasure for long duration space habitation.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Diamandis, P.H. (1997). Countermeasures and artificial gravity. In S. E. Churchill (Ed.), *Fundamentals of space life sciences.* Malabar, FL: Krieger.

Engelken, E.J., Stevens, K.W., & Enderle, J.D. (1991). *Optimization of an adaptive nonlinear filter for the analysis of nystagmus.* [Rocky Mountain Bioengineering Symposium, April 12-13, Mayo Clinic].

Engelken, E.J., & Stevens, K.W. (1990). A new approach to the analysis of nystagmus: An application for order-statistic filters. *Aviation, Space, and Environmental Medicine, 61*, 56-78.

Eyeson-Annan, M., Peterken, C., Brown, B., & Atchison, D. (1996). Visual and vestibular components of motion sickness. *Aviation, Space, and Environmental Medicine, 67*, 955- 962.

Goldtstein, M.H. Jr. (1974). The auditory periphery. In V.B. Mountcastle (Ed.), *Medical Physiology, 1*, (13th ed.) (pp. 382-411).

Gonshor, A., & Jones, M. (1976). Extreme vestibulo-ocular adaptation induced by prolonged optical reversal of vision. *Journal of Physiology, 256*, 381-414.

Gray, H. (1970). The organs of the senses. In C.M. Goss (Ed.), *Gray's anatomy* (28th ed.) (pp. 1091-1098). Philadelphia: Lea & Febiger.

Graybiel, A. (1975). Angular velocities, angular accelerations, and coriolis accelerations. In Editors: M. Calvin, & O.G. Gazenko (Eds.), *Foundations of space biology and medicine, 2* (pp. 247-257). Washington, DC: National Aeronautics and Space Administration.

Graybiel, A., Guedry, F.E., Johnson, W., & Kennedy, E.R. (1961). *Adaptation to bizarre stimulation of the semicircular canals as indicated by the oculogyral illusion.* Fort Knox, KY: U.S. Army Medical Research Laboratory.

Graybiel, A., Wood, C.D., Miller, E.F., & Cramer, D.B. (1968, May). Diagnostic criteria for grading the severity of acute motion sickness. *Aerospace Medicine*, 453-455.

Grymes, R.A., Wade, C.E., & Vernikos, J. (1996). Biomedical issues in the exploration of mars. In C.R. Stoker, & C. Emmart (Eds.), *Strategies for mars: A guide to human exploration, 86* (pp. 225-239). San Diego, CA: Univelt.

Guedry, F.E. (1964). Visual control of habituation to complex vestibular stimulation in man. *Acta Oto-Laryngologica, 58,* 377-389.

Guedry, F.E. (1965). Habituation to complex vestibular stimulation in man: transfer and retention of effects from twelve days of rotation at 10 r. p. m. *Perceptual and Motor Skills, 21*, 459-481. (Monograph Supplement 1-V21).

Guedry, F.E., Collins, W. E., & Graybiel, A. (1964). Vestibular habituation during repetitive complex stimulation: A study of transfer effects. *Journal of Applied Physiology, 19*(5), 1005-1015.

Guedry, F.E., Rupert, A.H., McGrath, B.J., & Oman, C.M. (1992). The dynamics of spatial orientation during complex and changing linear and angular acceleration. *The Journal of Vestibular Research, 2*, 259-283.

Gurovsky, N.N., Gazenko, O.G., Adamovich, B.A., Ilyin, E.A., Genin, A.M., Korolkov, V.I., Shipov, A.A., Kotovskaya, A.R., Kondratyeva, V.A., Serova, L.V., & Kondratyev, Yu.I. (1980). Study of physiological effects of weightlessness and artificial gravity in the flight of the biosatellite Cosmos-936. *Acta Astronautica, 7*, 113-121.

Hastreiter, D. (1997). *Artificial gravity as a countermeasure to space flight deconditioning: The cardiovascular response to a force gradient.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Hecht, H., Kavelaars, J., Cheung, C, & Young, L.R. (2000, forthcoming). *Artificial gravity: Orientation illusions and heart rate changes during short-radius centrifugation.* (manuscript submitted for publication).

Kotovskaya, A.R., Galle, R.R., &. Shipov, A.A. (1981). Soviet research on artificial gravity. *Kosmicheskaya Biologiya I Aviakosmicheskaya, 2,* 71-79.

Liefeld, J.T. (1993). *Changes in human horizontal angular VOR after the Spacelab SL-1 mission.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Lujan, B.F., & White, R.J. (1999). *Human physiology in space: A curriculum supplement for secondary schools.* Retrieved April 20, 2000 from the World Wide Web: http://www.nsbri.org/HumanPhysSpace/index.html.

Lurid, S.M., & Kinney, J.S. (1970). Underwater vision. *Science, 13,* 1454-61.

Lyne, L. (2000). *Artificial gravity: Evaluation of subjective adaptation of head movements during short-radius centrifugation.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Miles, F.A. (1974). Single unit firing patterns in the vestibular nuclei relative to voluntary eye movements and passive body rotation in conscious monkeys. *Brain Research, 71,* 215-224.

Miles, F.A., & Braitman, D.J. (1980). Long-term adaptive changes in primate vestibuloocular reflex II. Electrophysiological observations on semicircular canal primary afferents. *Journal of Neurophysiology, 43*(5), 1426-36.

Miles F.A., & Fuller, J.H. (1974). Adaptive plasticity in the vestibulo-ocular responses of the rhesus monkey. *Brain Research, 80,* 512-516.

Miles, F.A., & Lisberger, S.G. (1981). Plasticity in the vestibulo-ocular reflex: A new hypothesis. *Ann. Rev. Neuroscience, 4,* 273-99.

Molavi, D.W. (1997). Washington University School of Medicine neuroscience tutorial: auditory and vestibular pathways. Retrieved March 19, 2000, from the World Wide Web: Molavi, 1997.

National Research Council Space Studies Board (1998). *A Strategy for Research in Space Biology and Medicine in the New Century.* Washington, DC: National Academy Press.

National Space Biomedical Research Institute (2000). *Retreat 2000 Program and Project Information.* Core Research Program 1997-1999.

Oman, C.M. (1996). Sensory conflict theory and space motion sickness: Our changing perspective. *Journal of Vestibular Research, 8,* 51-56.

Paloski, W.H., & Young, L.R. (1999). *Artificial gravity workshop: Proceedings and recommendations* [NASA/NSBRI Workshop Proceedings League City, Texas, January 14-15, 1999].

Peng, GC, Baker, JF, & Peterson, BW. (1994). Dynamics of directional plasticity in the human vertical vestibulo-ocular reflex. *Journal of Vestibular Research, 4*(6), 453-60.

Pouliot, C. F. (1993). *Changes in the horizontal angular vestibulo-ocular reflex of SLS-2 space shuttle astronauts due to weightlessness.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Quinn, K.J. (1998). Classical conditioning using vestibular reflexes. *Journal of Vestibular Research, 8*(2), 17-133.

Ramsey, R.H. (1971). Human factors and artificial gravity: A review. *Human Factors, 13*(6), 533-542.

Reason, J.T, & Graybiel, A. (1969). *An attempt to measure the degree of adaptation produced by differing amounts of coriolis vestibular stimulation in the slow rotation room* [NASA Order R-93]. Pensacola, FL: Naval Aerospace Medical Institute.

Schultheis L.W., & Robinson D.A. (1981). Directional plasticity of the vestibulo-ocular reflex in the cat. In B. Cohen (Ed.), *Annals of the New York Academy of Sciences, 374*, 504-512.

Shelhamer, M., Robinson, D.A., & Tan, H.S. (1992). Context-specific adaptation of the gain of the vestibulo-ocular reflex in humans. *Journal of Vestibular Research, 2*, 89-96.

Shipov, A. A, Kotovskaya, A. R., & Galle, R. R. (1981). Biomedical Aspects of Artificial Gravity, R. R., Institute of Biomedical Problems, USSR Ministry of Health, Moscow, USSR, *Acta Astronautica, 8*(9-10), 1117-1121.

Sienko, K., & Wu, R. (1999). Artificial gravity as a countermeasure and training tool [Massachusetts Institute of Technology, course 16.423: Aerospace physiology and life support engineering, final course project].

Stone, R.W. (1970). *An overview of artificial gravity* [NASA SP-314] (pp. 23-33). Pensacola, FL: Naval Aerospace Medical Research Laboratory. Rpt. in Fifth Symposium on the Role of the Vestibular Organs in Space Exploration, Washington, DC.

Tomassini, A. M. (1997). *The effect of coriolis forces on performance of two-handed tasks.* Unpublished S.M. Thesis, Massachusetts Institute of Technology.

Welch, R.B., Bridgeman, B., Anand, S., & Browman, K.E. (1993). Alternating prism exposure causes dual adaptation and generalization to a novel displacement. *Perception and Psychophysics, 54*, 195-204.

Welch, R.B., Bridgeman, B., Williams, J.A., & Semmler, R. (1998). Dual adaptation and adaptive generalization of the human vestibulo-ocular reflex. *Perception and Psychophysics, 60*(8), 1415-1425.

Woodman, P.D, & Griffin M.J. (1997). Effect of direction of head movement on motion sickness caused by coriolis stimulation. *Aviation, Space, and Environmental Medicine, 68*(2), 93-98.

Young, L.R. (1974). Role of the vestibular system in posture and movement. In V.B. Mountcastle (Ed.), *Medical Physiology, 1*, (13th ed.) (pp. 704-721). St. Louis: C.V. Mosby.

Young, L.R. (1984a). Perception of the body in space: mechanisms. In I.D. Smith (Ed.), *Handbook of physiology-the nervous system III* (pp. 1023-1066). American Physiological Society.

Young, L.R. (1984b). *Visual/Vestibular/Proprioceptive Adaptation to Weightlessness.* Proposal Submitted to National Aeronautics and Space Administration in Response to A.O. No. OSSA-2-84.

Young, L.R. (1999). Artificial gravity considerations for a mars exploration mission. *Annals of the New York Academy of Sciences, 871*, 367-378.

Young, L. R. (2000, forthcoming). Spatial orientation. In P.S. Tang & M.A. Vidulich (Eds.), *Principles and Practice of Aviation Psychology*. Mahwah, NJ: Erlbaum.

APPENDIX A: CONSENT FORM

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAN-VEHICLE LABORATORY
CONTEXT-SPECIFIC ADAPTATION OF OCULOMOTOR RESPONSES TO CENTRIFUGATION
CONSENT FORM

I have been asked to participate in a study on adaptation to movement in a rotating environment. I understand that participation is voluntary and that I may end my participation at any time for any reason. I understand that I should not participate in this study if I have any medical heart conditions, respiratory conditions, if I have any medical conditions which would be triggered if I develop motion sickness, if I am under the influence of alcohol, caffeine, anti-depressants, or sedatives, if I have suffered in the past from a serious head injury (concussion), or if there is any possibility that I may be pregnant. My participation as a subject on the MIT Artificial Gravity Simulator (AGS) involves either the testing of equipment or actual experimental trials.

Prior to rotation on the AGS, I will be oriented to the rotator and data acquisition instrumentation. I understand that my height, weight, heart rate, blood pressure, and general medical history may be measured and recorded. During the experiment I will wear eye imaging goggles, angular rate sensors, and a heart rate monitor. How these devices will feel has been described to me. I agree to participate in possible stationary monitoring periods before and/or after rotation.

My rotation on the AGS will not exceed the following parameters:

- acceleration no greater than 1 rpm/s
- G level at my feet no greater than 1.5 G
- time of rotation not exceeding 1 hour

I understand that these parameters are well within the safe limits for short-radius rotation. I can terminate rotation at any time by pressing the emergency stop button, the use of which has been demonstrated to me.

I understand that during rotation I may develop a headache or feel pressure in my legs caused by a fluid shift due to centrifugation. I may also experience nausea or motion sickness, especially as a result of the required head movements. The experimenter may terminate the experiment if I report a pre-determined degree of motion sickness symptoms. In addition, I understand that my heart rate may increase due to the rotation speed; this is no greater than that sustained during aerobic exercise, and will be constantly monitored. During and after the experiment I will be asked to report my subjective experience (how I feel, how I think I perceive my head movements, etc.), both verbally and by using computer animations. In addition, I will be asked to report a motion sickness rating both during and at half-hour intervals after the experiment, until I go to bed. This data will be recorded anonymously.

I understand that serious injury could result from falling off the AGS while it is rotating. I will be loosely restrained at the waist/chest. The restraint must be fastened in order for the AGS to

rotate. If the restraint is unlatched, the AGS will stop. In addition, the AGS is equipped with side railings similar to those on a hospital bed.

I will be continuously monitored by at least one experimenter in the same room, and I will be equipped with a 2-way headset communication system connected to the observing experimenter. The investigator can also see me through a video camera mounted on the AGS, and in this way determine the nature of any problems that arise.

I am aware that there may be aftereffects, including malaise and slight vertigo when I turn my head. If I happen to experience such aftereffects, I have been instructed not to operate a vehicle.

If I am a participant in experimental trials, I tentatively agree to return for additional trials (at most 10) requested by the experimenter. I understand that a possible protocol for an actual trial will consist of a short period of supine rest in the dark, followed by a period of head movements (ranging from 90 degrees to the left, to vertical, to 90 degrees to the right) in the dark, followed by a period of similar head movements in the light, and that this trial could be repeated many times. During these head movements, my head will move at approximately a speed of 0.25 meters per second.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights (further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822).

Monetary compensation for those who are not members of the Man-Vehicle Laboratory will be $10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D. (MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature of and the purpose of this experiment and the risks involved, and agree to participate in the experiment.

Subject _____ Date _____

Experimenter _____ Date _____

APPENDIX B: SUBJECT POOL CRITERIA/SCREENING QUESTIONS

We desire subjects with the following characteristics:

- Age: between 20-29 years old
- Sex: 5 males, 5 females
- Height: 5'0"-6'2" measured to the nearest inch
- Weight: less than 200 lbs.
- Athletic Condition: some form of exercise ≥ 3 days/week
- Good communication skills and ability to relate experiences verbally
- Tolerant to severe motion sickness

Collect responses to the following questions:

- Right vs. left handedness
- Sleep quality within recent weeks prior to the study
- Current medications
- Medication/physiological history
- Allergies
- Describe what it feels like to be riding in a car that goes over a large bump in the road
- Vision (glasses, contacts)
- Previous virtual reality experience
- Previous centrifuge experience

Requirements 48 hours prior to experiment:

- No alcohol
- No sedatives *
- No anti-depressants

Requirement 24 hours prior to experiment:

- No caffeine

*Reference Mass Eye and Ear's requirements for complete list of unacceptable drugs prior to participation in the experiment

The subject confirms not to have one of the following problems or diseases:

- Frequent or severe headaches
- Dizziness or fainting spells
- Paralysis
- Epilepsy
- Disturbances in consciousness
- Loss of control of nervous system functions
- Neuritis

- Loss of memory or amnesia
- Lazy eye
- Cross looking of the eyes
- Cylindrical eye lenses
- Reduced eye movements
- Astigmatisms
- Ear, nose and throat trouble
- Hearing loss
- Chronic or frequent colds
- Head injury
- Asthma
- Shortness of breath
- Pain or pressure in the chest
- Medication (check for sedatives, anti-dizziness, anti-depressants, birth prevention medication is allowed
- Substance dependence or abuse (includes alcohol, and drugs like sedatives, anxiolytics cocaine, marijuana, opiodes, amphetamines, hallucinogens or other psychoactive drugs or chemicals)
- Diagnosis of psychosis, bipolar disorder or severe personality disorders
- Heart problems (check for Angina pectoris, coronary heart disease, myocardial infarction in the past, cardiac valve replacement, pacemaker.
- High or low blood pressure
- Recent loss or gain of weight
- Moderate car, train, sea or air sickness
- Thyroid trouble
- Inability to perform certain motions
- Inability to assume certain positions

Medical disqualifying conditions:

Experiences with the rotating bed or other rotating devices in a research environment
Neurological problems now and in the past (check for epilepsy, disturbances in consciousness, loss of nervous system functions)

- Lazy eye
- Cross looking of eyes
- Reduced eye movements
- Astigmatisms
- Cylindrical eye lenses
- Medication (check for sedatives, anti-depressants, birth prevention medication is allowed)
- Substance dependence or abuse(includes alcohol, and drugs like sedatives, anxiolytics cocaine, marijuana, amphetamines, hallucinogens or other psychoactive drug or chemicals)
- Diagnosis of psychosis, bipolar disorder or severe personality disorders

- Heart problem (check for Angina pectoris, coronary heart disease, congenital heart disease, myocardial infarction in the past, cardiac valve replacement, pacemaker)
- Ear nose and throat problems

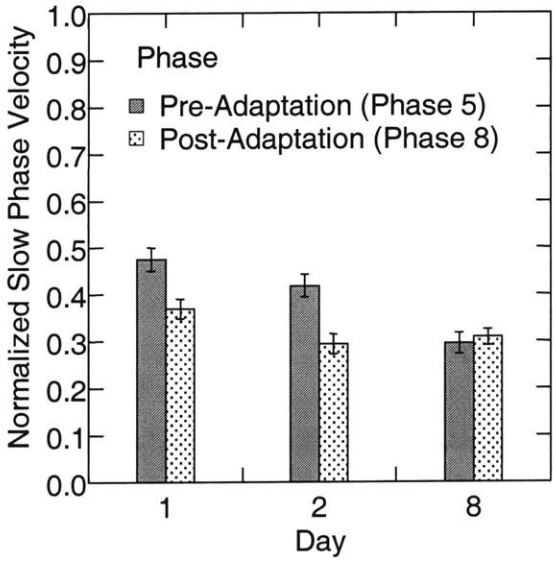
APPENDIX C: BASIC OPERATOR PROTOCOL

1. Describe experimental protocol
2. Sign consent form
3. Collect subject information
    - Height
    - Weight
4. Collect blood pressure (standing)
5. Instrument subject with heart rate sensor and watch
6. Debrief subject on subjective analysis techniques (refer to Lyne, 2000)
7. Power ISCAN
8. Power Watson sensors
9. Power video camera
10. Power data collection computer
11. Power Lab View computer
12. Power monitors (3)
13. Power VCR's (2)
14. Align/adjust eye goggles on subject
15. Place cap with angular rate sensors on subject's head
16. Position subject on bed
17. Fasten safety belt
18. Familiarize subject with instruments on bed
    - safety kill switch
    - onboard lights
    - pitch wheel
    - vomit bag
19. Calibrate eyes
20. Calibrate pitch wheel
21. Collect sample data for pitch wheel
22. Balance bed
23. Power walkie-talkies and perform sound check
24. Practice head movements
25. Practice pitch wheel operation
26. Place fleece hood over eye goggles
27. Collect blood pressure (lying supine)
28. Start heart rate watch and experimental clock simultaneously
29. Fix canopy to centrifuge
30. Perform walk around to verify cabinets are closed and all obstacles are removed
31. Secure safety rope
32. Power short-radius centrifuge
33. Power laboratory red lamps
34. Turn off laboratory lights
35. Adjust eye images as needed
36. Phase 1
37. Phase 2
38. Phase 3

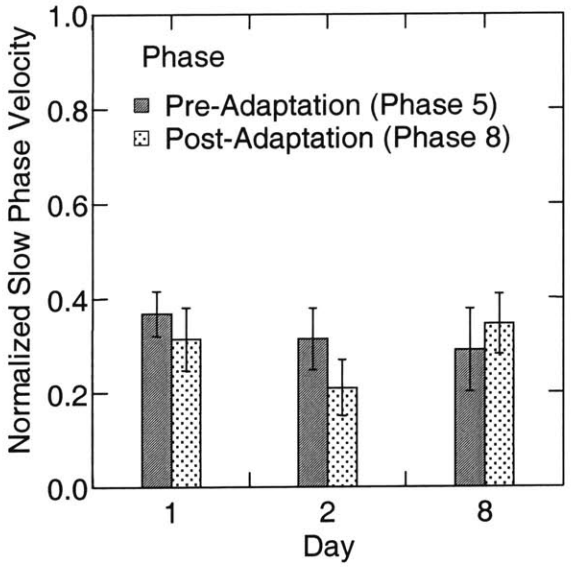
39. Phase 4
40. Phase 5
41. Phase 6
42. Phase 7
43. Phase 8
44. Phase 9
45. Phase 10
46. Phase 11
47. Save data
48. Turn on lab lights
49. Secure short-radius centrifuge
50. Remove canopy
51. Remove cap and eye goggles
52. Collect blood pressure (lying supine)
53. Debrief subject (motion sickness surveys)
54. Collect blood pressure (standing)
55. World Up computer simulation
56. Disseminate post motion sickness survey

APPENDIX D: INDIVIDUAL SUBJECT DATA

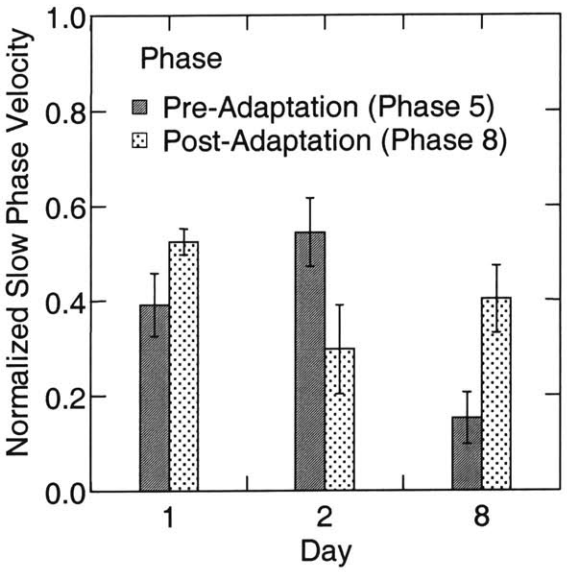
Normalized SPV (eight subjects)



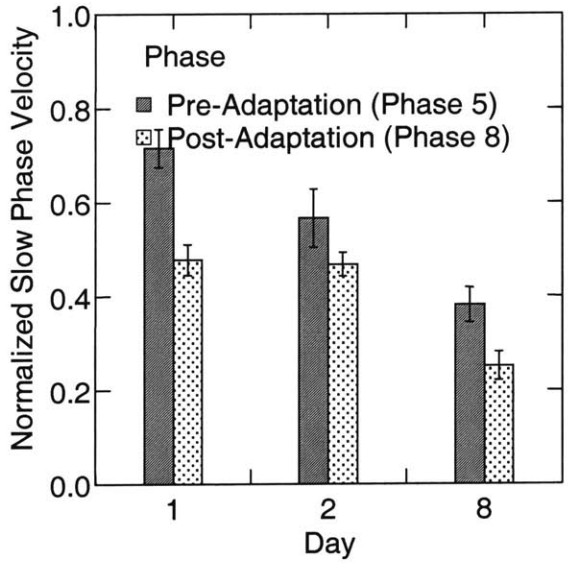
Normalized SPV Subject 2



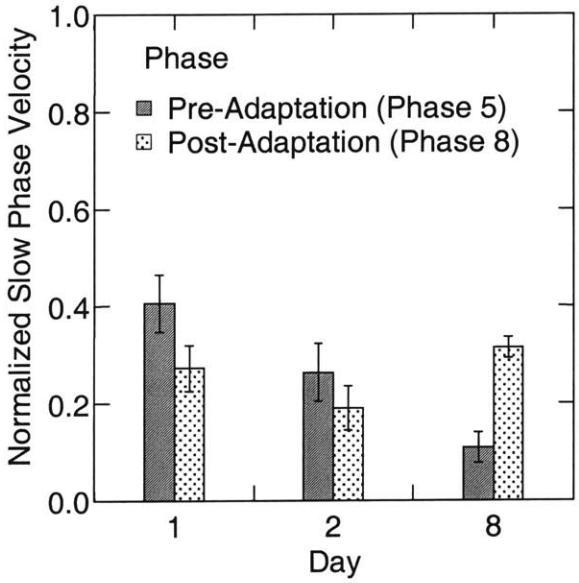
Normalized SPV Subject 4



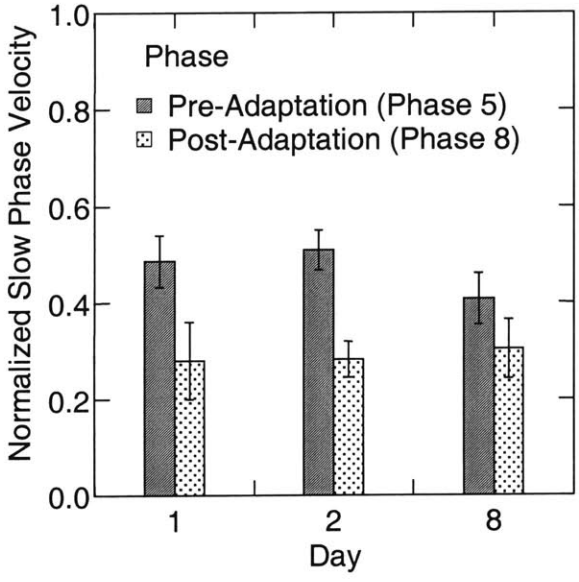
Normalized SPV Subject 6



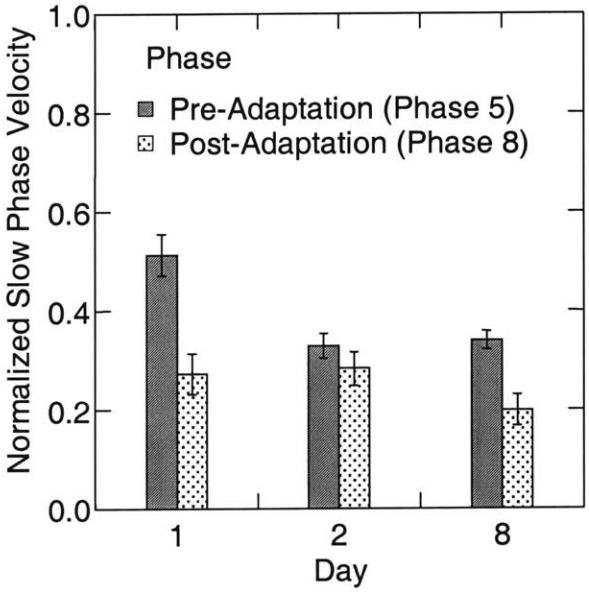
Normalized SPV Subject 7



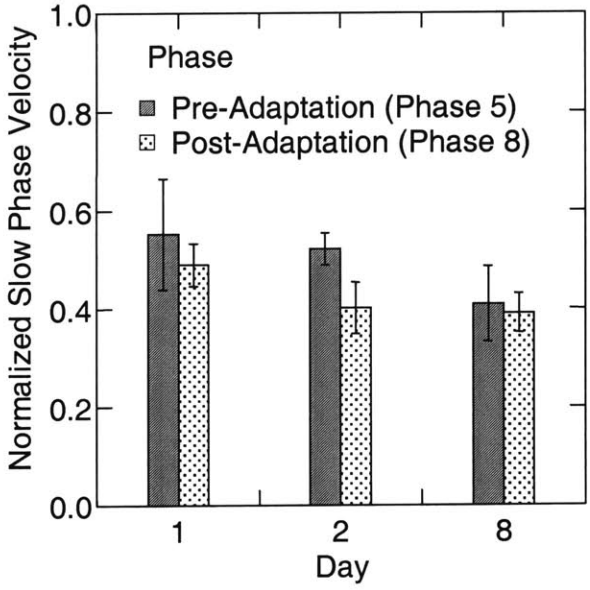
Normalized SPV Subject 9



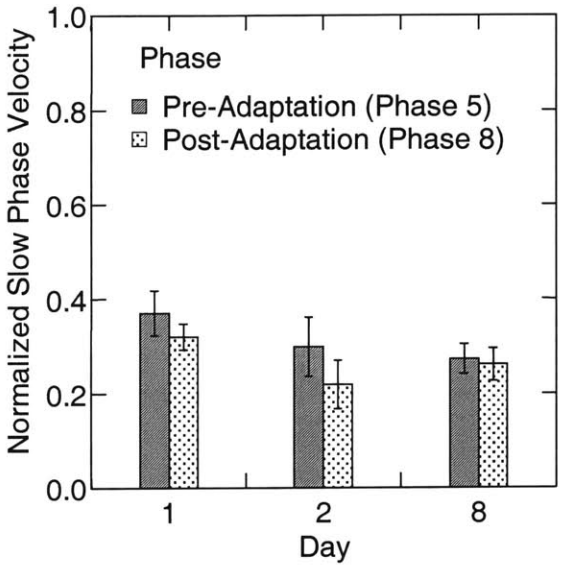
Normalized SPV Subject 10



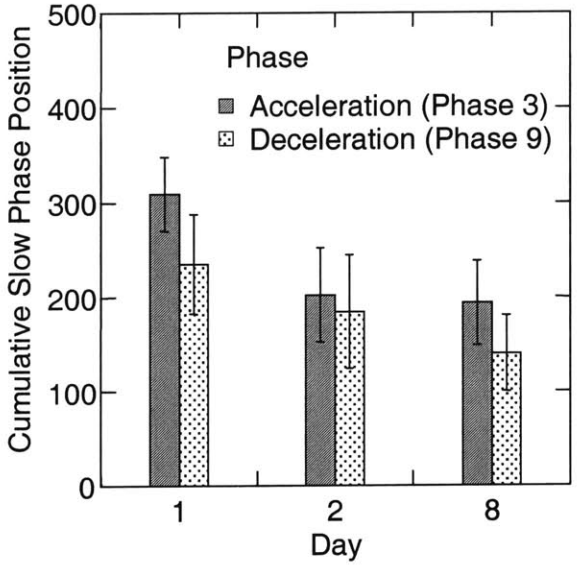
Normalized SPV Subject 11



Normalized SPV Subject 12



Cumulative Slow Phase Position (seven subjects)



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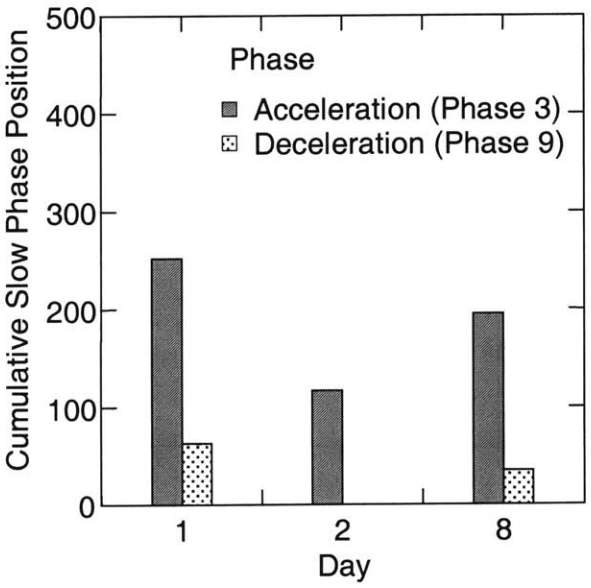
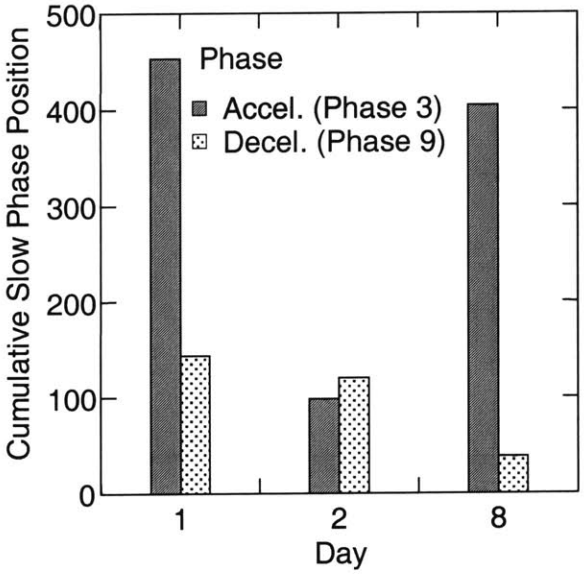
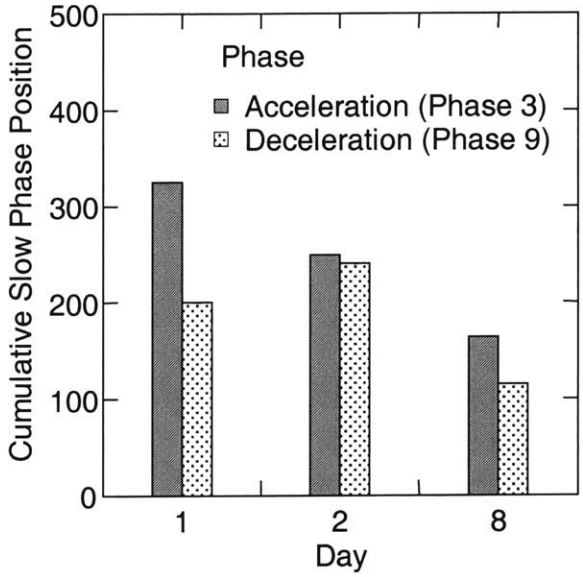


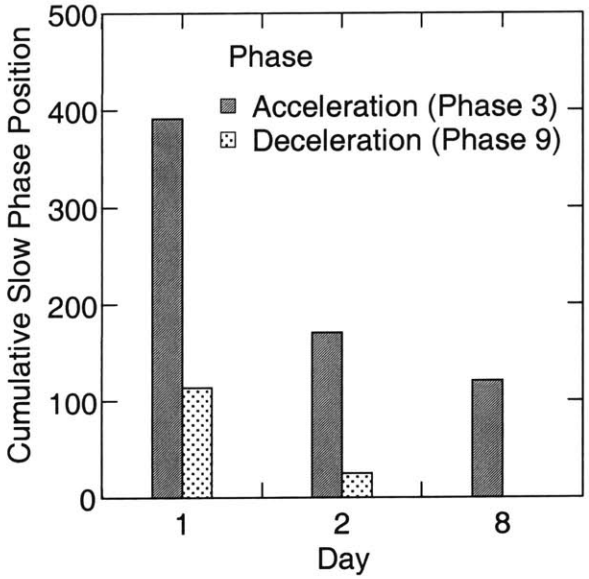
Cumulative Slow Phase Position Subject 4



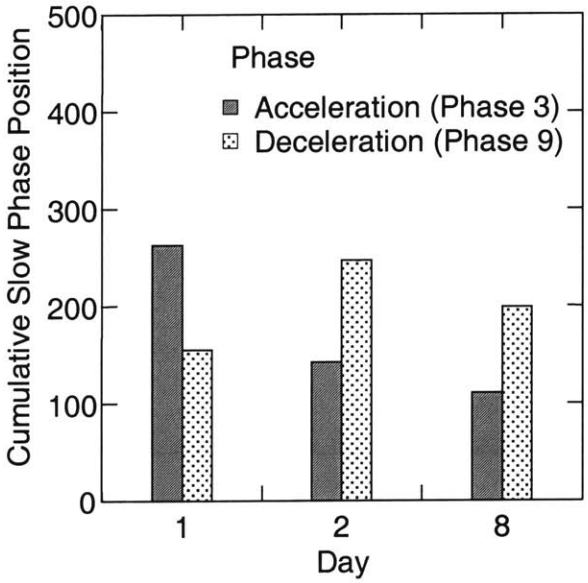
Cumulative Slow Phase Position Subject 6



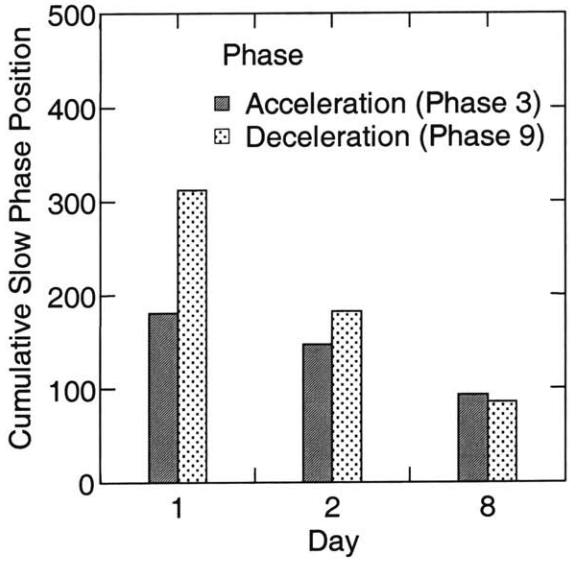
Cumulative Slow Phase Position Subject 7



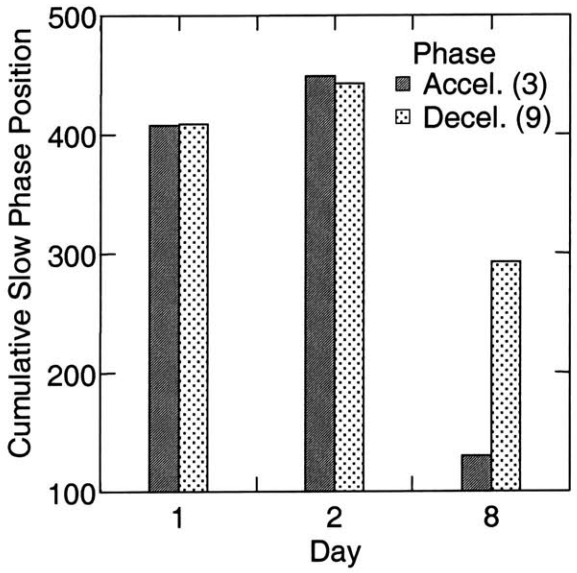
Cumulative Slow Phase Position Subject 9



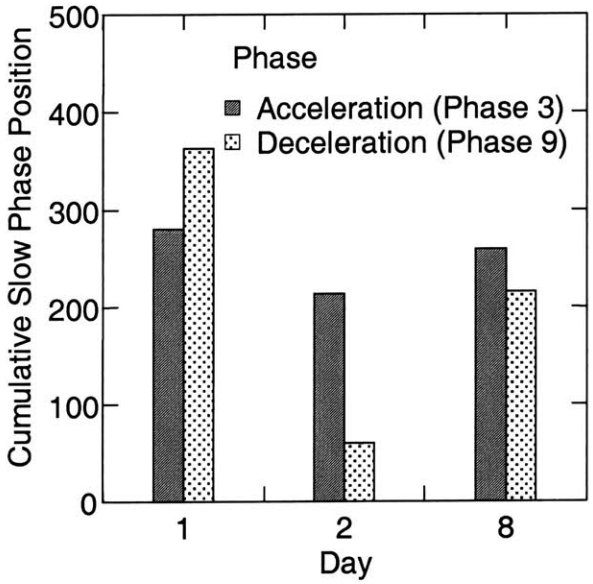
Cumulative Slow Phase Position Subject 10



Cumulative Slow Phase Position Subject 11



Cumulative Slow Phase Position Subject 12



APPENDIX E: RAW DATA

Subject	Day	Phase	Head Pos	Repetition	Head turn (deg)	Head turn (sec)	A	tau	nSPV	Gender
2	1	5	0	1	70	0.5833	61.9814	4.6588	0.478073	1
2	1	5	0	2	92	0.7667	37.1325	2.8146	0.269233	1
2	1	5	0	3	95	0.6667	44.2706	2.2168	0.322003	1
2	1	5	1	1	-84	0.75	-40.1005	8.2716	0.292207	1
2	1	5	1	2	-81	0.5667	-44.0233	5.6538	0.323023	1
2	1	5	1	3	-93	0.5	-72.1106	5.9613	0.523235	1
2	1	8	0	1	103	1.1167	20.8919	4.0194	0.15534	1
2	1	8	0	2	101	1.1167	48.5082	2.1063	0.358026	1
2	1	8	0	3	115	1.8667	2.0239	5.6325E+13	0.358026	1
2	1	8	1	1	-84	0.8833	-73.7611	1.5242	0.537487	1
2	1	8	1	2	-77	0.8167	-44.1731	2.3264	0.328566	1
2	1	8	1	3	-77	0.8833	-19.5747	2.7283	0.1456	1
2	2	5	0	1	76	0.6667	40.4118	3.9623	0.301855	1
2	2	5	0	2	67	0.8333	26.3512	4.0054	0.207494	1
2	2	5	0	3	74	0.8333	17.2691	0.7841	0.130206	1
2	2	5	1	1	-65	0.7	-39.7001	6.3787	0.317507	1
2	2	5	1	2	-58	0.5	-45.4839	4.4126	0.388774	1
2	2	5	1	3	-57	0.5	-62.6722	3.461	0.541685	1
2	2	8	0	1	97	0.7833	24.5543	1.9651	0.179247	1
2	2	8	0	2	98	0.7667	40.7452	0.9745	0.29812	1
2	2	8	0	3	86	0.9333	15.2409	0.4062	0.110717	1
2	2	8	1	1	-71	0.6833	-14.7129	3.8667	0.112783	1
2	2	8	1	2	-84	0.9167	-17.3098	5.248	0.126134	1
2	2	8	1	3	-66	0.8167	-55.2909	2.1771	0.43869	1
2	8	5	0	1	91	0.85	51.314	3.4283	0.371892	1
2	8	5	0	2	91	0.8333	11.8167	5.0892	0.08564	1
2	8	5	0	3	66	0.5	2.6652	26.7654	0.021146	1
2	8	5	1	1	-74	0.6667	-57.4696	6.3487	0.43331	1
2	8	5	1	2	-74	0.7667	-44.5651	5.0281	0.336013	1
2	8	5	1	3	-74	0.9167	-65.702	0.6569	0.495381	1
2	8	8	0	1	105	1.1333	53.5315	5.1213	0.401494	1
2	8	8	0	2	107	1.1333	32.4287	2.9933	0.245657	1
2	8	8	0	3	98	1.0167	45.0813	1.3023	0.329846	1
2	8	8	1	1	-70	0.8667	-69.2801	1.3322	0.534369	1
2	8	8	1	2	-108	1.85	-56.1412	2.033	0.427624	1
2	8	8	1	3	-88	1.4	-18.5535	5.7062	0.134531	1
4	1	5	0	1	50	0.7333	15.1774	17.7823	0.143624	0
4	1	5	0	2	74	0.95	68.2614	5.4464	0.514679	0
4	1	5	0	3	74	0.7833	42.465	3.7307	0.320178	0
4	1	5	1	1	-66	0.7	-53.8699	5.4482	0.427415	0
4	1	5	1	2	-77	0.6333	-53.7744	8.4113	0.399982	0
4	1	5	1	3	-83	0.6333	-74.7209	6.3516	0.545571	0
4	1	8	0	1	81	0.9833	63.1267	5.5305	0.463195	0
4	1	8	0	2	74	0.7	65.994	4.8066	0.497583	0
4	1	8	0	3	73	0.7167	65.4486	6.5528	0.496033	0
4	1	8	1	1	-83	0.8167	-77.0578	4.4287	0.562634	0
4	1	8	1	2	-74	0.5167	-83.2072	3.8428	0.627367	0
4	1	8	1	3	-83	0.7	-68.3869	4.6155	0.499324	0
4	2	5	0	1	67	0.6667	54.4865	6.7611	0.429035	0
4	2	5	0	2	67	0.5	71.4237	5.2442	0.562402	0
4	2	5	0	3	80	0.6167	43.4001	7.5814	0.319385	0
4	2	5	1	1	-76	0.55	-93.8769	5.7821	0.701211	0
4	2	5	1	2	-91	0.7	-101.9736	5.7561	0.739042	0
4	2	5	1	3	-80	0.6	-69.5178	7.9238	0.511587	0
4	2	8	0	1	74	0.8333	21.2778	0.5324	0.160431	0
4	2	8	0	2	64	0.65	6.9056	1.8721	0.055691	0
4	2	8	0	3	67	0.6333	32.8699	0.2535	0.258823	0
4	2	8	1	1	-85	0.7	-28.9784	6.8622	0.210804	0
4	2	8	1	2	-78	0.7333	-3.8858	1.97E+12	0.549402	0
4	2	8	1	3	-75	0.65	-73.221	1.7149	0.549402	0
4	8	5	0	1	79	1	37.2467	0.658	0.274993	0
4	8	5	0	2	88	1.0333	5.2463	2.3655	0.038041	0
4	8	5	0	3	91	1.05	2.514	4.2811E+13	0.038041	0
4	8	5	1	1	-74	0.55	-23.324	11.3671	0.175859	0
4	8	5	1	2	-76	0.7833	-10.166	3.2937	0.075935	0
4	8	5	1	3	-87	0.8333	-42.8363	5.0916	0.310847	0
4	8	8	0	1	77	0.9667	67.7753	4.5937	0.504123	0
4	8	8	0	2	85	1.1	14.8971	7.9846	0.10837	0
4	8	8	0	3	75	0.95	47.4879	2.5688	0.356318	0
4	8	8	1	1	-72	0.75	-64.893	5.5628	0.494541	0
4	8	8	1	2	-77	1.0167	-59.5864	1.6107	0.443213	0
4	8	8	1	3	-72	0.9333	-66.7019	6.5072	0.508327	0

6	1	5	0	1	109	0.8167	79.6073	4.2657	0.609902	0
6	1	5	0	2	101	0.8167	101.6818	4.5565	0.750485	0
6	1	5	0	3	105	0.9167	80.3449	5.3161	0.602598	0
6	1	5	1	1	-90	0.6667	-105.3744	5.1236	0.763583	0
6	1	5	1	2	-76	0.8167	-99.4498	3.4677	0.742837	0
6	1	5	1	3	-70	0.7	-106.5721	3.6741	0.822009	0
6	1	8	0	1	82	0.7167	59.489	4.5456	0.435361	0
6	1	8	0	2	94	1.1333	64.194	4.8551	0.466283	0
6	1	8	0	3	81	1.0667	63.1807	4.7685	0.463591	0
6	1	8	1	1	-65	0.9167	-58.574	3.7889	0.468454	0
6	1	8	1	2	-66	0.75	-77.9965	2.8155	0.618841	0
6	1	8	1	3	-65	0.8	-51.8263	2.2804	0.414488	0
6	2	5	0	1	83	0.8333	67.437	4.6099	0.492388	0
6	2	5	0	2	87	0.95	62.9667	3.9415	0.456925	0
6	2	5	0	3	78	0.7167	78.1523	4.6942	0.579058	0
6	2	5	1	1	-88	0.6333	-104.971	4.4514	0.761144	0
6	2	5	1	2	-65	0.6333	-86.6288	2.8589	0.692826	0
6	2	5	1	3	-67	0.7667	-52.8887	3.0714	0.416454	0
6	2	8	0	1	80	0.9167	73.7864	4.7357	0.543	0
6	2	8	0	2	87	1.1333	60.9687	3.8344	0.442426	0
6	2	8	0	3	81	0.9667	71.9666	4.1077	0.528058	0
6	2	8	1	1	-69	0.9333	-57.0682	2.7725	0.443063	0
6	2	8	1	2	-71	0.9833	-53.1122	2.6985	0.407136	0
6	2	8	1	3	-57	0.8833	-51.4622	3.1965	0.444795	0
6	8	5	0	1	89	0.8	61.8609	4.8486	0.448342	0
6	8	5	0	2	96	0.95	33.7971	6.9401	0.246234	0
6	8	5	0	3	93	1.0167	59.5941	3.7115	0.432415	0
6	8	5	1	1	-77	0.9167	-42.3252	6.2283	0.314822	0
6	8	5	1	2	-84	0.8	-55.569	6.625	0.404924	0
6	8	5	1	3	-71	0.8667	-57.7279	3.5747	0.442518	0
6	8	8	0	1	96	1	46.8833	4.1963	0.341575	0
6	8	8	0	2	100	1.1667	41.9386	4.015	0.308543	0
6	8	8	0	3	100	1.3333	32.4162	3.5129	0.238487	0
6	8	8	1	1	-78	1.1	-20.7065	1.7196	0.153422	0
6	8	8	1	2	-81	1.1167	-7.4502	3.2412E+13	0.2345	0
6	8	8	1	3	-86	1.15	-32.2804	2.4332	0.2345	0
7	1	5	0	1	86	0.7333	80.6825	4.8324	0.586115	1
7	1	5	0	2	107	0.85	62.0387	5.4518	0.469961	1
7	1	5	0	3	109	0.85	54.6961	5.7153	0.419047	1
7	1	5	1	1	-96	0.75	-31.6437	7.9873	0.230545	1
7	1	5	1	2	-95	0.7	-61.0458	7.3341	0.444018	1
7	1	5	1	3	-95	0.7167	-39.2481	3.9922	0.285472	1
7	1	8	0	1	97	1.05	58.0652	4.7544	0.423878	1
7	1	8	0	2	94	1.1	33.0162	6.5994	0.239818	1
7	1	8	0	3	99	0.9333	32.124	6.0732	0.235652	1
7	1	8	1	1	-74	0.5333	-18.2075	8.9109	0.137281	1
7	1	8	1	2	-77	0.5167	-49.0783	2.593	0.365052	1
7	1	8	1	3	-84	0.8	-31.7654	5.7166	0.23147	1
7	2	5	0	1	84	0.6667	42.7536	4.9784	0.31154	1
7	2	5	0	2	95	0.7	24.7309	4.9436	0.179881	1
7	2	5	0	3	93	0.8333	26.0932	2.5868	0.189333	1
7	2	5	1	1	-75	0.4333	-66.2624	0.6693	0.497189	1
7	2	5	1	2	-77	0.6	-36.1301	5.9481	0.268741	1
7	2	5	1	3	-80	0.5	-18.0907	6.5661	0.133131	1
7	2	8	0	1	86	0.6667	39.0855	6.909	0.283935	1
7	2	8	0	2	95	0.5667	14.6902	3.5531	0.10685	1
7	2	8	0	3	86	0.55	8.7391	4.605	0.063485	1
7	2	8	1	1	-75	0.3667	-38.3151	3.7108	0.287491	1
7	2	8	1	2	-81	0.4667	-18.458	3.4601	0.135436	1
7	2	8	1	3	-77	0.45	-35.4899	5.5034	0.263979	1
7	8	5	0	1	86	0.6833	32.9505	2.9354	0.239368	1
7	8	5	0	2	80	0.4667	14.9751	6.9222	0.110203	1
7	8	5	0	3	73	0.35	15.0948	1.0732	0.114403	1
7	8	5	1	1	-78	0.5	-6.3808	5.2607	0.047278	1
7	8	5	1	2	-80	0.55	-9.5594	5.5543	0.070348	1
7	8	5	1	3	-76	0.5833	-0.5182	4.2157E+12	0.070348	1
7	8	8	0	1	79	0.3333	41.1947	3.7681	0.304141	1
7	8	8	0	2	87	0.6333	51.366	0.6021	0.372743	1
7	8	8	0	3	.	.	.	.	0.372743	1
7	8	8	1	1	-83	0.4667	-38.3873	2.0353	0.280283	1
7	8	8	1	2	-91	0.5667	-38.3873	2.0353	0.278207	1
7	8	8	1	3	.	.	.	.	0.278207	1

9	1	5	0	1	104	0.9833	67.9254	3.8237	0.507165	1
9	1	5	0	2	80	0.5167	35.9157	2.327	0.264307	1
9	1	5	0	3	88	0.6667	76.7182	3.9742	0.556283	1
9	1	5	1	1	-77	0.5333	-60.6204	2.1097	0.450904	1
9	1	5	1	2	-83	0.6833	-79.1921	2.7903	0.578218	1
9	1	5	1	3	-81	0.65	-76.3822	5.743	0.560457	1
9	1	8	0	1	86	0.8167	67.9254	3.8237	0.493441	1
9	1	8	0	2	85	0.8	32.3497	1.1577	0.235329	1
9	1	8	0	3	85	0.75	63.0555	3.4922	0.4587	1
9	1	8	1	1	-86	0.8833	-20.7018	1.4008	0.150387	1
9	1	8	1	2	-82	0.8667	-4.8785	4.8345	0.035703	1
9	1	8	1	3	-70	0.9667	-40.1792	0.7101	0.309909	1
9	2	5	0	1	75	0.6833	76.6363	6.7424	0.575028	1
9	2	5	0	2	82	0.7833	81.6829	5.6156	0.597783	1
9	2	5	0	3	87	0.7833	83.2057	5.4965	0.603792	1
9	2	5	1	1	-74	0.6667	-55.1672	8.3843	0.415951	1
9	2	5	1	2	-70	0.75	-54.5956	4.8873	0.421105	1
9	2	5	1	3	-81	0.8333	-60.652	4.4404	0.445036	1
9	2	8	0	1	82	0.85	47.4333	4.552	0.347133	1
9	2	8	0	2	77	0.85	20.9386	7.553	0.155745	1
9	2	8	0	3	82	0.9167	50.5437	3.4712	0.369896	1
9	2	8	1	1	-83	0.7667	-38.303	4.2061	0.279668	1
9	2	8	1	2	-85	0.9167	-44.7166	3.4718	0.325293	1
9	2	8	1	3	-88	0.9167	-30.2568	2.0262	0.219392	1
9	8	5	0	1	62	0.5833	54.777	5.8978	0.449688	1
9	8	5	0	2	59	0.5167	48.638	5.0991	0.411308	1
9	8	5	0	3	63	0.5333	65.5868	4.8593	0.533556	1
9	8	5	1	1	-67	0.5	-38.5798	4.8143	0.303783	1
9	8	5	1	2	-61	0.6	-28.3084	6.4095	0.23461	1
9	8	5	1	3	-73	0.6167	-67.6921	4.1709	0.513037	1
9	8	8	0	1	74	0.8	43.1079	3.4754	0.325026	1
9	8	8	0	2	79	0.9333	34.235	3.825	0.252757	1
9	8	8	0	3	80	0.95	20.6943	3.9054	0.152291	1
9	8	8	1	1	-70	0.6167	-63.8198	3.5876	0.492253	1
9	8	8	1	2	-67	0.6667	-53.2732	2.8384	0.419482	1
9	8	8	1	3	-74	0.7	-24.1477	3.2163	0.182069	1
10	1	5	0	1	91	1.1	65.9926	4.5296	0.478274	0
10	1	5	0	2	85	0.95	81.8732	4.8771	0.59559	0
10	1	5	0	3	83	1	71.3167	4.8426	0.520716	0
10	1	5	1	1	-101	1.1667	-67.1903	5.4584	0.495913	0
10	1	5	1	2	-96	1.3	-85.5477	3.6295	0.62327	0
10	1	5	1	3	-94	1.6667	-49.7658	5.2418	0.361481	0
10	1	8	0	1	82	1.0833	59.0736	5.9455	0.432321	0
10	1	8	0	2	97	1.2167	40.8714	7.0382	0.298362	0
10	1	8	0	3	101	1.4167	23.3845	7.9344	0.172595	0
10	1	8	1	1	-89	1.6667	-37.2049	3.4344	0.269646	0
10	1	8	1	2	-82	1.25	-36.1505	4.164	0.264562	0
10	1	8	1	3	-75	1.6667	-26.6073	5.3521	0.199644	0
10	2	5	0	1	85	1.15	51.917	4.9203	0.377672	0
10	2	5	0	2	76	1.0667	36.436	5.0625	0.272158	0
10	2	5	0	3	77	1	34.4706	5.7569	0.256398	0
10	2	5	1	1	-94	1.8	-44.3547	5.8719	0.322177	0
10	2	5	1	2	-67	1.35	-47.0886	4.9357	0.370783	0
10	2	5	1	3	-78	1.3333	-51.0185	4.8721	0.378014	0
10	2	8	0	1	77	1.15	27.9241	5.9543	0.207704	0
10	2	8	0	2	72	1.0167	43.2926	3.1996	0.329927	0
10	2	8	0	3	74	1.2833	27.5748	4.7563	0.207909	0
10	2	8	1	1	-68	1.7833	-37.7528	5.4726	0.295128	0
10	2	8	1	2	-63	1.4667	-32.0099	3.153	0.260404	0
10	2	8	1	3	-76	1.6667	-53.4693	2.3581	0.399387	0
10	8	5	0	1	84	1.1333	53.641	4.7007	0.390875	0
10	8	5	0	2	75	0.8	38.9121	3.9563	0.291971	0
10	8	5	0	3	80	0.7833	45.9211	4.4715	0.337937	0
10	8	5	1	1	-97	1.7833	-48.0837	5.2227	0.351012	0
10	8	5	1	2	-85	1.4	-40.4205	6.0579	0.29404	0
10	8	5	1	3	-73	0.9667	-49.3545	5.8326	0.374057	0
10	8	8	0	1	73	1.2333	27.1273	7.8782	0.205597	0
10	8	8	0	2	82	1.3333	22.0264	4.9284	0.161197	0
10	8	8	0	3	82	1.25	24.0571	3.5938	0.176058	0
10	8	8	1	1	-64	1.1667	-40.6775	3.6878	0.328046	0
10	8	8	1	2	-69	1.6667	-25.4612	5.7527	0.197674	0
10	8	8	1	3	-86	1.4667	-17.7072	5.8881	0.128633	0

11	1	5	0	1	91	1.2333	48.4967	5.4301	0.351474	0
11	1	5	0	2	98	1.4	31.4696	8.7038	0.230254	0
11	1	5	0	3	125	2.0833	52.9329	3.1222	0.467893	0
11	1	5	1	1	-75	1.3833	-87.1405	13.5467	0.653845	0
11	1	5	1	2	-102	2	-95.6583	7.5922	0.708526	0
11	1	5	1	3	-76	1.6667	-120.8169	10.268	0.902438	0
11	1	8	0	1	90	1.5333	63.5313	2.5927	0.460372	0
11	1	8	0	2	97	1.3	50.6745	3.652	0.369925	0
11	1	8	0	3	83	1	53.8823	3.0375	0.393419	0
11	1	8	1	1	-77	1.2833	-77.5324	7.7923	0.576698	0
11	1	8	1	2	-82	1.3667	-75.2008	6.8363	0.550345	0
11	1	8	1	3	-80	1.1667	-80.1594	7.0557	0.5899	0
11	2	5	0	1	67	0.9167	67.5351	4.9471	0.531782	0
11	2	5	0	2	72	1	72.7852	7.3196	0.554687	0
11	2	5	0	3	69	0.9667	70.7998	6.0034	0.549671	0
11	2	5	1	1	-55	0.8	-44.4691	3.756	0.393516	0
11	2	5	1	2	-70	0.9333	-78.0453	7.8321	0.601977	0
11	2	5	1	3	-55	0.8833	-56.3507	6.5419	0.498659	0
11	2	8	0	1	57	0.9667	46.3943	3.7698	0.400993	0
11	2	8	0	2	61	0.8	71.1212	5.913	0.589428	0
11	2	8	0	3	77	1.5667	31.1304	6.6561	0.231553	0
11	2	8	1	1	-52	0.7833	-44.4691	3.756	0.409075	0
11	2	8	1	2	-54	0.8167	-46.5498	5.4473	0.417092	0
11	2	8	1	3	-73	1.7667	-47.6825	3.9116	0.361384	0
11	8	5	0	1	73	0.9333	51.2092	6.6938	0.388113	0
11	8	5	0	2	80	1.5333	39.4544	2.3394	0.290348	0
11	8	5	0	3	65	0.8667	28.4119	5.1295	0.227228	0
11	8	5	1	1	-70	0.9333	-41.0209	8.5187	0.316401	0
11	8	5	1	2	-55	1.1167	-67.6734	4.6557	0.598856	0
11	8	5	1	3	-62	1.0333	-77.1356	3.8463	0.633239	0
11	8	8	0	1	79	1.1667	73.6057	4.8222	0.543432	0
11	8	8	0	2	94	1.4333	50.4481	4.3409	0.366437	0
11	8	8	0	3	73	1.0333	39.7039	3.1386	0.300915	0
11	8	8	1	1	-62	1.1667	-43.7853	3.7658	0.359452	0
11	8	8	1	2	-47	1.0833	-33.9794	6.9399	0.336804	0
11	8	8	1	3	-60	0.9667	-52.2647	3.5258	0.437454	0
12	1	5	0	1	75	1	43.1596	3.516	0.323841	1
12	1	5	0	2	85	0.9667	40.6952	2.8275	0.296039	1
12	1	5	0	3	75	0.8	44.9336	3.5707	0.337152	1
12	1	5	1	1	-76	0.8167	-61.9831	8.1423	0.462981	1
12	1	5	1	2	-80	0.8833	-36.6444	5.4752	0.269669	1
12	1	5	1	3	-85	0.8	-73.4079	4.9999	0.534009	1
12	1	8	0	1	62	0.9167	47.6599	2.8567	0.39126	1
12	1	8	0	2	57	0.7333	39.7043	4.6154	0.34317	1
12	1	8	0	3	56	0.6667	26.8816	4.7426	0.235043	1
12	1	8	1	1	-65	0.6833	-32.3021	6.5295	0.258341	1
12	1	8	1	2	-65	0.6167	-43.9485	5.4884	0.351484	1
12	1	8	1	3	-63	0.5833	-42.2026	4.6163	0.343323	1
12	2	5	0	1	59	0.95	31.5548	2.3255	0.266844	1
12	2	5	0	2	62	0.8667	18.1655	2.908	0.149128	1
12	2	5	0	3	57	0.9	16.1642	1.8895	0.13971	1
12	2	5	1	1	-66	0.75	-43.9671	5.0177	0.348844	1
12	2	5	1	2	-68	0.6833	-55.6866	6.1537	0.435323	1
12	2	5	1	3	-72	0.75	-60.0923	5.0761	0.457956	1
12	2	8	0	1	62	0.8833	48.8929	3.4101	0.401383	1
12	2	8	0	2	60	0.9833	16.2369	3.5442	0.135902	1
12	2	8	0	3	56	0.8833	23.784	4.731	0.207959	1
12	2	8	1	1	-68	0.6667	-32.9984	2.9092	0.257961	1
12	2	8	1	2	-63	0.65	-8.815	4.8788	0.071711	1
12	2	8	1	3	-67	0.7667	-30.4355	2.7587	0.239654	1
12	8	5	0	1	65	1.2167	34.1518	2.5403	0.273134	1
12	8	5	0	2	56	0.8	21.8335	5.3241	0.190904	1
12	8	5	0	3	69	0.95	24.5472	1.7977	0.190578	1
12	8	5	1	1	-74	0.6833	-43.6077	4.7588	0.328794	1
12	8	5	1	2	-82	0.6333	-48.1792	5.9044	0.352592	1
12	8	5	1	3	-71	0.6	-39.5855	5.4077	0.303446	1
12	8	8	0	1	67	1.25	35.3902	3.7756	0.278668	1
12	8	8	0	2	60	1.2833	41.3199	3.5825	0.345846	1
12	8	8	0	3	58	1.0833	38.3051	5.182	0.327413	1
12	8	8	1	1	-57	0.5667	-16.1621	5.4326	0.139691	1
12	8	8	1	2	-67	0.7333	-27.3833	2.0099	0.21562	1
12	8	8	1	3	-57	0.8	-30.1729	3.7996	0.260789	1

Subject	Day	Run	Area Under Curve
2	1	3	-252
2	1	9	63
2	2	3	-117
2	2	9	0
2	7	3	-195
2	7	9	35
4	1	3	-453
4	1	9	144
4	2	3	-98
4	2	9	120
4	7	3	-404
4	7	9	38
6	1	3	-325
6	1	9	200
6	2	3	-249
6	2	9	240
6	7	3	-164
6	7	9	115
7	1	3	-391
7	1	9	114
7	2	3	-171
7	2	9	25
7	7	3	-121
7	7	9	
9	1	3	-263
9	1	9	155
9	2	3	-143
9	2	9	247
9	7	3	-111
9	7	9	199
10	1	3	-181
10	1	9	312
10	2	3	-147
10	2	9	183
10	7	3	-93
10	7	9	86
11	1	3	-408
11	1	9	409
11	2	3	-449
11	2	9	443
11	7	3	-130
11	7	9	293
12	1	3	-280
12	1	9	363
12	2	3	-214
12	2	9	60
12	7	3	-260
12	7	9	216

APPENDIX F: MATLAB CODE

Matlab Routines and Subroutines

- avg_value.m
- batch_bed.m
- batch_bed_file.m
- batch_eye_channel.m
- bed_classify_phases.m
- convert_bed_file.m
- cum_spv.m
- deblink.m
- deleterow.m
- diff_list.m
- diff_list2.m
- differentiate.m
- edit_alg_diff.m
- expfit.m
- eye.m
- filt_gyro_position.m
- filt_position.m
- get_patient_list.m
- get_PC_bed_path.m
- get_yn.m
- head.m
- init_bed.m
- inlist.m
- interp_blinks.m
- interpolate.m
- make_eye_plot.m
- make_triplot.m
- min_threshold.m
- newAATM.m
- OS_lin2.m
- OS_lin2quad1.m
- PFMH1.m
- PFMH2.m
- review_bed.m
- review_bed_file.m
- review_eye_channel.m
- simple_blinks.m
- thresh_blinks.m
- zero_filter.m

avg_value.m

```
function avg = avg_value(x)

%
% avg_value - returns the average value of 'x', based solely % upon the
% data points that are within one standard deviation % of the mean value,
% so that outlying data points are
% rejected
%

m = sum(x)/length(x);
s = std(x);
if (s > 0),
    num_std = (x - m) / s;
    check = (abs(num_std) < 1);
    avg = sum(x .* check) / sum(check);
else
    avg = m;
end

clear m s num_std check
```

batch_bed.m

```
% batch_bed

close all
clear all

init_bed

batch_mode = TRUE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list

[num_patients,n] = size(patient_list);

for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);  % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
```

```
   end

   convert_bed_file

   for rn=1:num_runs,
      if (rn < 10),
         run_code = [root_file, '_run0', int2str(rn)];
      else
         run_code = [root_file, '_run', int2str(rn)];
      end
      run_file = [data_path, run_code, '.mat'];

      fprintf(['\nProcessing ', run_code, ' ...']);
      load(run_file);

      batch_bed_file

   end
end
```

batch_bed_file.m

```
% batch_bed_file

% create time vector
clear t
t = [0:(num_samples-1)] / sample_rate;

%
% process left vertical eye position data
%
raw_index = LEFT_VERTICAL;
cal_index = LEFT_VERTICAL+num_params;
which_eye = 'Left Vertical';
file_ext = '_LV.mat';

batch_eye_channel

%
% process right vertical eye position data
%
%raw_index = RIGHT_VERTICAL;
%cal_index = RIGHT_VERTICAL+num_params;
%which_eye = 'Right Vertical';
%file_ext = '_RV.mat';

%batch_eye_channel

%
% process left horizontal eye position data
%
raw_index = LEFT_HORIZONTAL;
cal_index = LEFT_HORIZONTAL+num_params;
which_eye = 'Left Horizontal';
file_ext = '_LH.mat';
```

```
batch_eye_channel
%
% process right horizontal eye position data
%
%raw_index = RIGHT_HORIZONTAL;
%cal_index = RIGHT_HORIZONTAL+num_params;
%which_eye = 'Right Horizontal';
%file_ext = '_RH.mat';

%batch_eye_channel
```

batch_eye_channel.m

```
% batch_eye_channel

% free up variable space
clear pos vel spv edited_spv filt_spv fast_start fast_end

% detect blinks using raw data, but make interpolations on
% calibrated data
[pos, num_blinks, perc_blink] = deblink(data(:,raw_index), data(:,cal_index),
0, 0, num_increase);

% filter eye position data to enhance signal-to-noise ratio
%  - one pass of order statistic filter to minimize video quantization,
%       allowing for curved eye movements
%  - two passes of fourth-order phase-less Butterworth low-pass filter
%       with 30 Hz corner frequency, to reduce noise
%  - two additional passes of order statistic filter, to reduce noise
%       and sharpen corners of nystagmus, allowing for curved eye movements
pos = filt_position(pos, sample_rate, 2, 3, TRUE);

% differentiate eye position to get velocity
vel = differentiate(pos, sample_rate);

% classify fast phases in eye velocity data, and interpolate across
[fast_start, fast_end] = bed_classify_phases(vel, num_RMS, num_increase, ...
                                    min_diff_class, sample_rate);
spv = interpolate(vel, fast_start, fast_end);

% no manual editing in batch processing, so no edited_spv
edited_spv = [];

% save data in a Matlab-format file
save_file = [data_path, run_code, file_ext];
parms_list = ' pos vel spv edited_spv fast_start fast_end num_blinks
perc_blink';
eval(['save ', save_file, parms_list]);
```

bed_classify_phases.m

```
function [fast_start, fast_end] = bed_classify_phases(vel, num_RMS, ...
```

```
                            num_increase, min_diff_class, sample)
%
% bed_classify_phases.m  - attempts to detect fast phases in a velocity
% trace 'vel'
%
% The velocity data is filtered by the AATM algorithm, to calculate an
% estimate of SPV.  The difference between the raw eye velocity and the
% AATM velocity is calculated.  Any difference which exceeds a specified
% multiple (num_RMS) of the RMS difference, and which also exceeds a
% specified absolute threshold (min_diff_class), is classified as a "fast" %
point.  A fast phase is defined as a series of consecutive fast points.  % A
specified number of points (num_increase) are added to the beginning
% and end of the fast phase, to allow for transient behaviour,
% particularly due to digital filtering effects. "fast_start" is a vector %
in which each element is the sample number of the start of a fast phase.  %
"fast_end" contains the corresponding sample numbers of the ends of the %
fast phases.
%
% Note: fast phases in the first or last half-second of data will not be
% properly detected
%
% Suggested values for the input parameters are:
%  vel = eye velocity, calculated by differentiating calibrated eye
% position
%  num_RMS = 0.25
%  num_increase = 2
%  min_diff_class = 30
%  sample = 60
%
% Written by: MDB 10/1/99
%

last = length(vel);
AATM_transient = num_increase;

% run AATM filter over data
AATM_spv = newAATM(sample+1, vel);     % one second filter window

% find data points for which velocity and AATM are within 'num_RMS'
i = 1 + AATM_transient;
j = last - AATM_transient;
slow = min_threshold( vel(i:j), AATM_spv(i:j), num_RMS, min_diff_class );
slow = [zeros(AATM_transient,1) ; slow ; zeros(AATM_transient,1)];
fast = ~slow;
clear i j AATM_transient

% increase fast phase duration by 'num_increase' sample
%    in each direction for transients
if (num_increase > 0),
    fast = filtfilt(ones(num_increase+1,1), 1, fast);
    fast = (fast > 0);
end

% find start and end of each fast phase
fast_diff = filter([1 -1], 1, fast);      % two-point difference
fast_start = find(fast_diff > 0);         % 0 to 1 transition
num_start = length(fast_start);
```

```
fast_end = find(fast_diff < 0) - 1;       % 1 to 0 transition
num_end = length(fast_end);
if (num_end < num_start),
    fast_end = [fast_end; last];
    num_end = num_end + 1;
end

clear slow fast num_slow fast_diff num_end num_start

return;
```

convert_bed_file.m

```
%data_path = 'C:\MATLAB\data\watson_data\';
%file_name = 'xllrottest.txt';

fid = fopen([data_path,file_name],'r');

%
% decipher header information
%

% Sometimes, header info is tab-delimited
% In other cases, it is separated by blank spaces
% In either situation, looking for unprintable characters seems to work,
% to find either tab (9) or carriage return (13).
TAB = 9; % tab character seems to be used in header info, instead of blank
space
COLON = 58;
BLANK = 32;

iscan_ver = fgets(fid);    % ISCAN version number, and file format

% discard two lines
inline = fgets(fid);
inline = fgets(fid);

% subject name
inline = fgets(fid);
l = length(inline);
cl = find(abs(inline) == COLON);    % look for ":" in string
str = inline( (cl(1)+1) : l );
tb = find(abs(str) < BLANK);        % look for "tab" or "cr" in sub-string
subject_name = str( (tb(1)+1) : (tb(2)-1) );

% test date
inline = fgets(fid);
l = length(inline);
cl = find(abs(inline) == COLON);    % look for ":" in string
str = inline( (cl(1)+1) : l );
tb = find(abs(str) < BLANK);        % look for "tab" or "cr" in sub-string
test_date = str( (tb(1)+1) : (tb(2)-1) );

% test description
inline = fgets(fid);
```

```
tb = find(abs(inline) == COLON);    % look for "colon" in string
l = length(inline);
if (inline(tb(1)+1) <= BLANK),
   test_descr = inline( (tb(1)+2) : (l-1) );
else
   test_descr = inline( (tb(1)+1) : (l-1) );
end

% discard line
inline = fgets(fid);

% number of runs
inline = fgets(fid);
l = length(inline);
cl = find(abs(inline) == COLON);    % look for ":" in string
str = inline( (cl(1)+2) : l );
tb = find(abs(str) < BLANK);        % look for "tab" or "cr" in sub-string
num_runs = eval( str(1:(tb(1)-1)) );

% total number of points recorded (i.e. number of samples)
inline = fgets(fid);
l = length(inline);
cl = find(abs(inline) == COLON);    % look for ":" in string
str = inline( (cl(1)+2) : l );
tb = find(abs(str) < BLANK);        % look for tab or "cr" in sub-string
total_pts = eval( str(1:(tb(1)-1)) );

% total number of parameters recorded (i.e. number of raw data channels)
inline = fgets(fid);
l = length(inline);
cl = find(abs(inline) == COLON);    % look for ":" in string
str = inline( (cl(1)+2) : l );
tb = find(abs(str) < BLANK);        % look for tab/cr in sub-string
num_params = eval( str(1:(tb(1)-1)) );

% discard three lines
inline = fgets(fid);
inline = fgets(fid);
inline = fgets(fid);

% parse out number of points in each run
run_points = zeros(num_runs,1);     % number of samples in each run
run_rate = zeros(num_runs,1);       % sampling rate for each run
run_start = [];                     % start time for each run
for i=1:num_runs,
   inline = fgets(fid);
   l = length(inline);
   tb = find(abs(inline) == TAB);   % look for "tab" in string
   if (inline(l-1) >= BLANK),
      tb = [0, tb, l];
   end
   run_points(i) = eval( inline( (tb(1)+1) : (tb(2)-1) ) );
   run_rate(i) =  60; %eval( inline( (tb(2)+1) : (tb(3)-1) ) );
   run_start = [run_start; inline( (tb(3)+1) : (tb(3)+9) )];
end

% discard three lines
```

```
inline = fgets(fid);
inline = fgets(fid);
inline = fgets(fid);

% parse information for names of channels, and mean and standard deviation
%    of each channel over length of runs
param_name = [];
name_len = 10;    % allow parameter names up to 10 characters long
all_raw_mean = zeros(num_params,num_runs);
all_raw_std = zeros(num_params,num_runs);
all_cal_mean = zeros(num_params,num_runs);
all_cal_std = zeros(num_params,num_runs);
for i=1:num_params,

   % extract name of parameter
   inline = fgets(fid);
   idx = find(inline == '(');       % look for "(" in string
   pn = inline(2: (idx(1)-2));
   l = length(pn);
   if (l < name_len),               % pad with blanks
      pn = [pn, blanks(name_len - l)];
   else  % truncate length
      pn = pn(1:name_len);
   end
   idx = find(pn < BLANK);
   for k=1:length(idx),             % replace tabs with blank characters
      pn(idx(k)) = BLANK;
   end
   param_name = [param_name; pn];

   % extract mean of raw data from same line
   idx = find(inline == ')');       % look for ")" in string
   str = inline( (idx(2)+1) : length(inline) );
   idx = find(abs(str) < BLANK);    % look for non-numeric in sub-string
   for j=1:num_runs,
      num = eval(str( (idx(j)+1) : (idx(j+1)-1) ));
      all_raw_mean(i,j) = num;
   end

   % extract standard deviation of raw data
   inline = fgets(fid);
   idx = find(inline == ')');       % look for ")" in string
   str = inline( (idx(2)+1) : length(inline) );
   idx = find(abs(str) < BLANK);    % look for non-numeric in sub-string
   for j=1:num_runs,
      num = eval(str( (idx(j)+1) : (idx(j+1)-1) ));
      all_raw_std(i,j) = num;
   end

   % extract mean of calibrated data
   inline = fgets(fid);
   idx = find(inline == ')');       % look for ")" in string
   str = inline( (idx(2)+1) : length(inline) );
   idx = find(abs(str) < BLANK);    % look for non-numeric in sub-string
   for j=1:num_runs,
      num = eval(str( (idx(j)+1) : (idx(j+1)-1) ));
      all_cal_mean(i,j) = num;
```

```
   end

   % extract standard deviation of calibrated data
   inline = fgets(fid);
   idx = find(inline == ')');       % look for ")" in string
   str = inline( (idx(2)+1) : length(inline) );
   idx = find(abs(str) < BLANK);    % look for non-numeric in sub-string
   for j=1:num_runs,
      num = eval(str( (idx(j)+1) : (idx(j+1)-1) ));
      all_cal_std(i,j) = num;
   end

end

% discard three lines
inline = fgets(fid);
inline = fgets(fid);
inline = fgets(fid);
inline = fgets(fid);

num_channels = 2*num_params + 1; % raw and calibrated, plus sample number

idx = find(file_name == '.');
if (isempty(idx)),
   root_file = file_name;
else
   root_file = file_name(1:(idx(1)-1));
end

for i=1:num_runs,

   % input data for run
   num_samples = run_points(i);

   fprintf(['\nConverting ', file_name, ' -- run #', int2str(i), ' (', ...
         int2str(num_samples), ' samples) ...']);

   clear data
   data = zeros(num_samples, num_channels);

   for j=1:num_samples,

if (~rem(j,500)),
   fprintf('\n  finished %d', j);
end

      inline = fgets(fid);
      idx = find(abs(inline) < BLANK); % look for non-numeric in string
      if (idx(1) > 2),
         idx = [1,2,idx];
      elseif (idx(2) > 2),
         idx = [1,idx];
      end

      for k=1:num_channels,
         num = eval(inline( (idx(k+1)+1) : (idx(k+2)-1) ));
         data(j,k) = num;
```

```
      end
   end

   % save data for this run in a separate mat-file
   sample_rate = 60; %run_rate(i);
   start_time = run_start(i,:);
   raw_mean = all_raw_mean(:,i);
   raw_std = all_raw_std(:,i);
   cal_mean = all_cal_mean(:,i);
   cal_std = all_cal_std(:,i);

   if (i < 10),
      out_file = [data_path, root_file, '_run0', int2str(i), '.mat'];
   else
      out_file = [data_path, root_file, '_run', int2str(i), '.mat'];
   end
   param_list = 'data iscan_ver subject_name test_date test_descr num_runs';
   param_list = [param_list, ' total_pts num_params num_samples
sample_rate'];
   param_list = [param_list, ' start_time raw_mean raw_std cal_mean
cal_std'];
   param_list = [param_list, ' param_name num_channels out_file'];

   eval(['save ', out_file, ' ', param_list]);

   % discard one line
   inline = fgets(fid);

end

fprintf('\n');

fclose(fid);
```

cum_spv.m

```
%cum_spv-calculates the cumulative slow phase position based on operator
% input of onset of ramp up/ramp down.  This program begins 7 seconds
% after the initiation of centrifuge acceleration/deceleration as inputted %
and integrates the area under the slow phase velocity curve for 20
% seconds.  Operator should use x1=6.2189 for data collected after
% 2/01/00.

close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list
```

```
[num_patients,n] = size(patient_list);
for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end
   run=input('\nEnter run number: ', 's');
   rn=str2num(run);
      if (rn < 10),
         run_code = [root_file, '_run0', run];
      else
         run_code = [root_file, '_run', run];
      end
   run_file = [data_path, run_code, '.mat'];
   load(run_file);
   run_file = [data_path, run_code, '_LV.mat'];
   load(run_file);
   %-------------------------------------------------------------------------
   Anlog1=data(:,15);                              %Retrieve Analog 1 from
column 15
   Anlog2=data(:,16);                              %Retrieve Analog 1 from
column 16
   x1=1.1646.*Anlog1;   %use x1=6.2189 for subjects 2,4,6,7,9. Use x1=1.1646
for 10,11,12
   x2=1.1646.*Anlog2;   % recalibration factor C
   gyroy=filt_gyro_position(x1);          %Filter Analog 1 (yaw motions
   gyrop=filt_gyro_position(x2);          %Filter Analog 2 (pitch motions
%-------------------------------------------------------------------------
   subplot(2,1,1)
   x=[1:length(spv)];
   plot(x,spv)
   subplot(2,1,2)
   x=[1:length(gyroy)];
   plot(x,gyroy)
 %-------------------------------------------------------------------------
   [x,y,key]=ginput(1);
   beginramp=x;
   beginramp=round(x);
   start=beginramp;
   %[x1,y1,key]=ginput(1);
   %endpoint=round(x1);
   %start=beginramp+3*60;
   start=beginramp+7*60;
   endpoint=start+20*60;
   stuff=spv(start:endpoint);
 %-------------------------------------------------------------------------
  ramp=(endpoint-start)/60
   avg=mean(stuff)
   area=trapz(stuff)/60
  area_under_curve=round(area)
```

```
    end
```

deblink.m

```
function [y, num_blinks, perc_blink] = deblink(x, xcal, low, high,
num_increase)

% detects blinks on position trace "x" using threshold "thresh".
%   low > 0  ==>  use the specified values, call "thresh_blinks"
%   low = 0  ==>  rely on ISCAN zeros for blinks, call "simple_blinks"
%   low < 0  ==>  calculate thresholds based on mean and standard
% deviation and iterate with operator control, call "thresh_blinks"
% "xcal" is calibrated position, while "x" is raw data
%  detect blinks using "x", but make interpolations on "xcal"
%  if "xcal" is empty, assume "x" is calibrated data
% "y" is eye position data with blinks removed by linear interpolation
% "num_blinks" is the number of blinks which were detected in the trace
% "perc_blink" is the percentage of the trace which is defined as a blink
%

if (low == 0),

   [s,e] = simple_blinks(x, num_increase, 100);

elseif (low > 0),

   [s,e] = thresh_blinks(x, num_increase, low, high, 100);

else

   mn = mean(x);
   sd = std(x);
   low = mn - 3*sd;
   if (low < 0),
      low = 0;
   elseif (low > 500),
      low = 500;
   end
   high = mn + 3*sd;
   if (high < 3500),
      high = 3500;
   elseif (high > 4000),
      high = 4000;
   end

   [s,e] = thresh_blinks(x, num_increase, low, high, 100);
   x2 = interp_blinks( x, s, e);
   fig = figure('Name', 'Specification of Blink Threshold');
   h1 = plot(x, 'y');
   hold on
   h2 = plot(x2, 'b');
   xl = get(gca,'XLim');
   h3 = plot(xl, [low low], 'g');
   h4 = plot(xl, [high high], 'r');

   low2 = input('Specify new value for low threshold (-1 to end): ');
```

```
   if (isempty(low2)),
      low2 = 0;
   else
      if (low2 >= 0),
         low = low2;
      end
   end
   high2 = input('Specify new value for high threshold (-1 to end): ');
   if (isempty(high2)),
      high2 = 0;
   else
      if (high2 >= 0),
         high = high2;
      end
   end

   while ((low2 >= 0) | (high2 >= 0)),

      [s,e] = thresh_blinks(x, num_increase, low, high, 100);
      x2 = interp_blinks( x, s, e);
      set(h2, 'YData', x2);
      set(h3, 'YData', [low low]);
      set(h4, 'YData', [high high]);

      low2 = input('Specify new value for low threshold (-1 to end): ');
      if (isempty(low2)),
         low2 = 0;
      else
         if (low2 >= 0),
            low = low2;
         end
      end
      high2 = input('Specify new value for high threshold (-1 to end): ');
      if (isempty(high2)),
         high2 = 0;
      else
         if (high2 >= 0),
            high = high2;
         end
      end

   end

   delete(h4);
   delete(h3);
   delete(h2);
   delete(h1);
   close(fig);
   clear x2

end

if (isempty(xcal)),
   y = interp_blinks( x, s, e);
else
   y = interp_blinks( xcal, s, e);
end
```

```
num_blinks = length(s);
if (num_blinks > 40),
   fprintf('\n    WARNING: dangerously high blink activity (%d blinks)',
num_blinks);
end
perc_blink = 100 * (sum(e - s - 1) / length(x));
if (perc_blink > 3),
   fprintf(['\n    WARNING: dangerously high blink activity (%5.2f%c)'],
perc_blink,37);
end


return;
```

delete_row.m

```
%
%DeleteRow -- W. Kulecz
%

function OutMat = DeleteRow(N,InMat)
% return as output matrix, input matrix with row N removed.
[m,n]=size(InMat);
if N==1
   OutMat=InMat(2:m,:);
elseif N==m
   OutMat=InMat(1:m-1,:);
else
   OutMat=[InMat(1:N-1,:) ; InMat(N+1:m,:)];
end
```

diff_list.m

```
% diff_list
%

function list = diff_list(x1,x2)

% This functions returns a list of ordered pairs, indicating the
% sections in which the vectors x1 and x2 are unequal.  Each
% ordered pair (x,y) corresponds to a segment in which the points
% indexed by 'x' and 'y' are equal in both vectors, but all points
% in between are unequal.
%
%  D. Balkwill   10/25/90

list = [];
l1 = length(x1);
l2 = length(x2);
l = min([l1 l2]);
d = x1(1:l) - x2(1:l);

i = 1;
while (d(i) == 0)
    i = i + 1;
    if (i >= l)
        break;
    end
end

while (i < l)
    start = i - 1;
    while (d(i) ~= 0)
        i = i + 1;
        if (i >= l)
            break;
        end
    end
    finish = i;
    list = [list ; [start finish]];
    while (d(i) == 0)
        i = i + 1;
        if (i >= l)
            break;
        end
    end
end

clear i l l1 l2 start finish d
return;
```

diff_list2.m

```
% diff_list
%

function [s,e] = diff_list2(x,y)

% This functions returns a list of ordered pairs, indicating the
% sections in which the vectors x and y are unequal.  Each
% ordered pair of start (s) and end (e) is such that:
%     x(s-1) = y(s-1)
%     x(i) <> y(i), for all s <= i <= e
%     x(e+1) = y(e)
%
%  D. Balkwill   10/25/90
%  Modified by: MDB, 10/5/99

l = length(x);

d = (x ~= y);     % flag to indicate where values are different

df = diff(d);  % flag transitions from equality to difference
            % df(i) = +1, if x(i) = y(i) and x(i+1) <> y(i+1)
            % df(i) = -1, if x(i) <> y(i) and x(i+1) = y(i+1)
            % df(i) = 0, otherwise

s = find(df > 0) + 1;
if (x(1) ~= y(1)),   % won't be caught otherwise
   s = [1; s];
end
e = find(df < 0);
if (x(l) ~= y(l)),   % won't be caught otherwise
   e = [e; l];
end

clear l d df

return;
```

differentiate.m

```
function xprime = differentiate( x, sample )

% differentiate - returns the first time derivative of 'x'
%
% Written by: D. Balkwill 10/20/93
%

A = 1 / sample;
if (sample == 60),
   B = [0.0077, 0.0714, 0.1078, 0.0870, 0, -0.0870, -0.1078, -0.0714, -
0.0077];
else
```

```
   B = [0.0332, 0.0715, 0.0678, 0.0522, 0, -0.0522, -0.0678, -0.0715, -
0.0332];

end
gain = [4 3 2 1] * B(1:4)' * 2;
B = B / gain;
xprime = zero_filter(B, A, x);

clear A B gain
```

edit_alg_diff.m

```
% edit_alg_diff
%

function edited_spv = edit_alg_diff(t,spv,vel,pos,diffs,colour)

% This is the main algorithm for the manual editing of slow phase velocity %
profiles.
%     sample = sampling rate in Hz
%     spv    = slow phase eye velocity vector
%     vel    = raw eye velocity vector
%     pos    = eye position vector
%     colour = flag for colour monitor
%
% The user now has the capability of over-riding faulty
% interpolations made by the detection process.  The 'diff_list'
% script is called to return a list of regions over which the
% raw velocity and slow phase velocity differ.  The format of
% this list is identical to that of 'flag' in the 'heart' script.
%
% If one wishes to re-edit a previously edited SPV profile, then
% the first line can be deleted so that the 'diffs' list contains
% the differences between raw and *edited* SPV profiles.
%
% If the SPV profile is completely different from the raw
% velocity (due to low-pass or order-statistic filtering for
% instance), then the call to 'diff_list' should be removed.
%
% written by D. Balkwill -- 11/27/90
% some portions ruthlessly and shamelessly stripped from
%    scripts by B. McGrath and W. Kulecz
%
% Modified: D. Balkwill 10/21/93
% Changed 'diffs' to an input parameter, since we already know what
%              what it is from having calculated the SPV

edited_spv = spv;    % don't overwrite spv
%diffs = diff_list(vel,edited_spv);
num_diffs = length(diffs);
highs = [];
num_highs = 0;   % number of regions highlighted
interps = [];
spv_interps = [];
num_interps = 0;   % number of regions interpolated
```

```
l = length(edited_spv);
sample = round(1/(t(2) - t(1)));   % assumes t is periodic

% minimum window height to prevent graph from being dominated by noise
rms = sqrt(sum(edited_spv.*edited_spv)/l);
min_height = 3 * rms;

key = 0;
FINISHED = 27;          % escape
%PAN_LEFT = 28;         % left arrow
%PAN_RIGHT = 29;        % right arrow
%SCROLL_LEFT = 11;      % page down
%SCROLL_RIGHT = 12;     % page up
PAN_LEFT = 107;         % 'k'
PAN_RIGHT = 108;        % 'l'
SCROLL_LEFT = 75;       % 'K'
SCROLL_RIGHT = 76;      % 'L'
ACCEPT = 13;            % carriage return
DELETE_1 = 8;           % backspace
DELETE_2 = 127;         % delete
%ZOOM_IN = 30;          % up arrow
%ZOOM_OUT = 31;         % down arrow
ZOOM_IN = 122;          % 'z'
ZOOM_OUT = 120;         % 'x'
FAST_ZOOM_IN = 46;      % decimal
FAST_ZOOM_OUT = 48;     % zero
COMPLETE_PLOT_1 = 97;   % 'a' key
COMPLETE_PLOT_2 = 65;   % 'A' key
% note: 1, 2, and 3 are reserved for mouse button(s)

num_pick = 0;           % number of points picked
os = 1;                 % offset of start of current trace, in samples
w = l - 1;              % width of trace, in samples
redraw = 1;             % flag for plotting
mf = 1;                 % magnification factor
mag_thresh = 1 / (sample * 10);   % 10 seconds

while (key ~= FINISHED)

    if (redraw == 1)
        df = floor(w/2000);
        if (df < 1)
            df = 1;
        end
        er = edited_spv(os:df:os+w);
        tr = t(os:df:os+w);
        vr = vel(os:df:os+w);
        pr = pos(os:df:os+w);

         % leave some blank space above and below trace for aesthetics
        mxv = max(er);
        if (mxv < 0)
            mx = mxv * 0.9;
        else
            mx = mxv * 1.1;
        end
```

```
        mnv = min(er);
        if (mnv < 0)
            mn = mnv * 1.1;
        else
            mn = mnv * 0.9;
        end
        old = mx - mn;
        if (old < min_height)
            mx = mx + (min_height - old)/2;
            mn = mx - min_height;
        end

         % ensure that position data appears on plot
        pr = pr - min(pr) + mnv;

      cla
        hold off
         % axis([tr(1) tr(length(tr)) mn mx]);
        if (colour == 'y')

            if (mf < mag_thresh)
                plot(tr,er,'k');
            hold on
            set(gca, 'XLim', [tr(1) tr(length(tr))]);
            set(gca, 'YLim', [mn mx]);
            xlabel('black = SPV');
            % h = text(.4,0,'black = SPV','Units', 'Normalized');
            else
                plot(tr,vr,'r-');
            hold on
            plot(tr,pr,'g-');
            plot(tr,er,'k');
            set(gca, 'XLim', [tr(1) tr(length(tr))]);
            set(gca, 'YLim', [mn mx]);
            xlabel('black = SPV,  red = raw velocity, green = eye position');
% h = text(.12,0,'black = SPV','Units', 'Normalized');
% h = text(.4,0,'red = raw velocity','Units', 'Normalized');
% h = text(.7,0,'green = eye position','Units', 'Normalized');
            end

            % plot highlighted regions in green, solid
            hold on
            for i=1:num_highs
                x3 = highs(i,1);
                x4 = highs(i,2);
                plot([t(x3),t(x3)],[mn,mx],'g')
                plot([t(x4),t(x4)],[mn,mx],'g')
                plot([t(x3),t(x4)],[mn,mx],'g')
            end

            % plot picked regions in blue, dash-dotted
            for i=1:num_interps
                x3 = interps(i,1);
                x4 = interps(i,2);
                plot([t(x3),t(x3)],[mn,mx],'b-.')
                plot([t(x4),t(x4)],[mn,mx],'b-.')
                plot([t(x3),t(x4)],[mn,mx],'b-.')
```

```
            plot(t(x3:x4),spv_interps(1:(x4-x3+1),i),'b-')
        end
        % plot currently picked point in blue, dotted
        if (num_pick == 1)
            plot([t1,t1],[mn,mx],'b:')
        end
        hold off

     set(gca, 'XLim', [tr(1) tr(length(tr))]);
     set(gca, 'YLim', [mn mx]);

    else

        if (mf < mag_thresh)
            plot(tr,er)
            text(.4,0,'solid = SPV','sc')
        else
            plot(tr,vr,':',tr,pr,'--',tr,er)
            text(.12,0,'solid = SPV','sc')
            text(.4,0,'dotted = raw velocity','sc')
            text(.7,0,'dashed = eye position','sc')
        end

        % plot highlighted regions in dashed
        hold on
        for i=1:num_highs
            x3 = highs(i,1);
            x4 = highs(i,2);
            plot([t(x3),t(x3)],[mn,mx],'--')
            plot([t(x4),t(x4)],[mn,mx],'--')
            plot([t(x3),t(x4)],[mn,mx],'--')
        end

        % plot picked regions in dash-dotted
        for i=1:num_interps
            x3 = interps(i,1);
            x4 = interps(i,2);
            plot([t(x3),t(x3)],[mn,mx],'-.')
            plot([t(x4),t(x4)],[mn,mx],'-.')
            plot([t(x3),t(x4)],[mn,mx],'-.')
            plot(t(x3:x4),spv_interps(1:(x4-x3+1),i),'-.')
        end
        % plot currently picked point in dotted
        if (num_pick == 1)
            plot([t1,t1],[mn,mx],'-.')
        end
        hold off
    end

  title(['magnification = ',int2str(round(mf)),' X']);
% h = text(.7,.93,['magnification = ',int2str(round(mf)),' X'],...
%  'Units', 'Normalized');
    redraw = 0;

end

[x,y,key] = ginput(1);
```

```
key
if isempty(key),
   key = ACCEPT;
end

    if (key == ZOOM_IN)      % increase magnification factor

        old=mf;
        mf=min(old*2,max(old,floor(1/100)));
        if mf==old            % maximum magnification of 100X
            redraw=0;
        else
            redraw=1;
            w=floor(1/mf);
        end

    elseif (key == FAST_ZOOM_IN)   % fast two-point zoom

         % first point of region to zoom into
        [t3,y,key] = ginput(1);
        if ((key ~= DELETE_1) & (key ~= DELETE_2))

            % bounds check on first point of region
            if (t3 < tr(1))
                t3 = tr(1);
            elseif (t3 > tr(length(tr)))
                t3 = tr(length(tr));
            end
            x3 = 1 + round(t3 * sample);
            t3 = (x3 - 1)/sample;

             % display first point
            hold on
            if (colour == 'y')
                plot([t3,t3],[mn,mx],'r:');
            else
                plot([t3,t3],[mn,mx],':');
            end
            hold off
            redraw = 1;

             % second point of region to zoom into
            [t4,y,key] = ginput(1);

             % allow user to abort zoom via delete key
            if ((key ~= DELETE_1) & (key ~= DELETE_2))

                % bounds check on second point of region
                if (t4 < tr(1))
                    t4 = tr(1);
                elseif (t4 > tr(length(tr)))
                    t4 = tr(length(tr));
                end
                x4 = 1 + round(t4 * sample);
                t4 = (x4 - 1)/sample;

               % display second point
```

```
                hold on
                if (colour == 'y')
                    plot([t4,t4],[mn,mx],'r:');
                else
                    plot([t4,t4],[mn,mx],':');
                end
                hold off

                % swap order of points if needed
                if (x4 < x3)
                    old = x4;
                    x4 = x3;
                    x3 = old;
                end

               % calculate new magnification parameters
                if (x3 ~= x4)
                    os = x3;
                    w = x4 - x3;
                    mf = 1/w;
                end
            end
        end

    elseif (key==ZOOM_OUT)  % decrease magnification

        if (mf == 1)   % already completely zoomed out
            redraw = 0;
        else
            redraw=1;
            old=mf;
            mf=max(floor(old/2),1);
            w=floor(1/mf);
            if (w >= 1)
                 w = 1 - 1;
            end
            if ((os+w)>1)
                os=floor(max(1,1-w));
            end
        end

    elseif ((key == COMPLETE_PLOT_1) | (key == COMPLETE_PLOT_2) | (key ==
FAST_ZOOM_OUT))    % display entire plot

        os = 1;
        mf = 1;
        w = 1 - 1;
        redraw = 1;

    elseif (key==PAN_RIGHT)   % increase offset by quarter-screen

        old=os;
        os=floor(max(1,min(1-w,os+0.25*w)));
        if old==os       % already panned to end
            redraw=0;
        else
            redraw=1;
```

```
        end

    elseif (key==PAN_LEFT)   % decrease offset by quarter-screen

        old=os;
        os=floor(max(1,os-0.25*w));
        if os==old       % already panned to beginning
            redraw=0;
        else
            redraw=1;
        end

    elseif (key==SCROLL_RIGHT)   % jump display one screenful right

        old=os;
        os=floor(max(1,min(os+w,l-w)));
        if os==old       % already panned to end
            redraw=0;
        else
            redraw=1;
        end

    elseif (key==SCROLL_LEFT)   % jump display one screenful left

        old=os;
        os=floor(max(1,os-w));
        if old==os       % already panned to beginning
            redraw=0;
        else
            redraw=1;
        end

    elseif (key==ACCEPT)   % accept fast phase interpolations

        if (num_pick == 0)
            for i=1:num_interps

                % substitute new values into edited SPV
                x1 = interps(i,1);
                x2 = interps(i,2);
                edited_spv(x1:x2) = spv_interps(1:(x2-x1+1),i);

                % add region to list of differences
                if isempty(diffs),    % no previous differences
                   diffs = [x1 x2];
                elseif (x2 < diffs(1,1))   % add to beginning
                    diffs = [[x1 x2] ; diffs];
                elseif (x1 > diffs(num_diffs,2))  % add to end
                    diffs = [diffs ; [x1 x2]];
                else
                    for j=1:num_diffs
                        if (diffs(j,1) > x2)
                            break;
                        end
                    end
                    diffs = [diffs(1:j-1,:) ; [x1 x2] ;
diffs(j:num_diffs,:)];
```

```
            end
            num_diffs = num_diffs + 1;

        end

        % reset appropriate values
        num_interps = 0;
        clear interps spv_interps
        interps = [];
        spv_interps = [];
        num_pick = 0;
        redraw = 1;
    end

elseif ((key==DELETE_1) | (key==DELETE_2))

    if (num_pick > 0)   % wipe out currently picked point
        num_pick = 0;
        redraw = 1;
    elseif (num_highs > 0)   % wipe out highlit regions
        for i=1:num_highs
            x3 = highs(i,1);
            x4 = highs(i,2);
            % copy raw velocity values back in
            edited_spv(x3:x4) = vel(x3:x4);
            index = InList(x3,diffs);
            diffs = DeleteRow(index,diffs);
        end
        num_diffs = num_diffs - num_highs;
        num_highs = 0;
        clear highs
        highs = [];
        redraw = 1;
    elseif (num_interps > 0)   % wipe out last interpolation
        redraw = 1;
        num_interps = num_interps - 1;
        interps = interps(1:num_interps,:);
        spv_interps = spv_interps(:,1:num_interps);
    end

elseif (key==1) | (key==2) | (key==3) % up to three-button mouse input

    if (num_pick == 0)   % this is the first picked point

        % bounds check on picked point
        if (x < tr(1))
            x = tr(1);
        elseif (x > tr(length(tr)))
            x = tr(length(tr));
        end

        % convert time value to sample number
        x1 = 1 + round(x * sample);

        % see if point is in a selected region
        index1 = InList(x1,diffs);
        if (index1 > 0)
```

```
            index2 = InList(x1,highs);
            if (index2 > 0)   % de-highlight region
                num_highs = num_highs - 1;
                highs = DeleteRow(index2,highs);
                redraw = 1;
            else   % highlight region for future deletion
                x1 = diffs(index1,1);
                x2 = diffs(index1,2);
                t1 = (x1 - 1)/sample;
                t2 = (x2 - 1)/sample;
                num_highs = num_highs + 1;
                highs(num_highs,:) = [x1 x2];
                if (colour == 'y')
                    hold on
                    plot([t1,t1],[mn,mx],'g');
                    plot([t2,t2],[mn,mx],'g');
                    plot([t1,t2],[mn,mx],'g');
                else
                    hold on
                    plot([t1,t1],[mn,mx],'-');
                    plot([t2,t2],[mn,mx],'-');
                    plot([t1,t2],[mn,mx],'-');
                end
            end
        else    % point is not already in a selected region
            % display as first point of region being selected
            t1 = (x1 - 1)/sample;
            num_pick = 1;
            hold on
            if (colour == 'y')
                plot([t1,t1],[mn,mx],'b:');
            else
                plot([t1,t1],[mn,mx],'-.');
            end
            hold off
        end
    elseif (num_pick == 1)   % second picked point

        % bounds check on picked point
        if (x < tr(1))
            x = tr(1);
        elseif (x > tr(length(tr)))
            x = tr(length(tr));
        end

        % convert time value to sample number
        x2 = 1 + round(x * sample);
        t2 = (x2 - 1)/sample;

        if (x2 == x1)   % cannot have interval of zero width
            num_pick = 0;
            redraw = 1;
        else
            if (x2 < x1)    % order picked points
                old = x1;
                x1 = x2;
                x2 = old;
```

```
                end
                num_pick = 0;
                hold on
                if (colour == 'y')
                    plot([t2,t2],[mn,mx],'b:');
                else
                    plot([t2,t2],[mn,mx],'-.');
                end

                % interpolate linearly across picked interval
                pick_spv = edited_spv(x1:x2);
                pick_l = length(pick_spv);
                pick_t = t(x1:x2);
                slope = (pick_spv(pick_l) - pick_spv(1)) / (pick_l - 1);
                j = pick_l - 1;
                for i=2:j
                    pick_spv(i) = pick_spv(1) + ((i-1) * slope);
                end
                if (colour == 'y')
                    plot(pick_t,pick_spv,'b-');
                else
                    plot(pick_t,pick_spv,'-.');
                end
                hold off

                % add region to list of interpolated regions, and
                % add interpolated vector to its list, padding the
                % list of interpolated vectors with zeros as needed
                num_interps = num_interps + 1;
                interps = [interps ; [x1 x2]];
                [mm,nn] = size(spv_interps);
                if (pick_l < mm)
                    pick_spv = [pick_spv ; zeros(mm-pick_l,1)];
                elseif (pick_l > mm)
                    if (nn > 0)
                        spv_interps = [spv_interps ; zeros(pick_l-mm,nn)];
                    end
                end
                spv_interps = [spv_interps pick_spv];
            end
        end
    end
end
return;
```

expfit.m

```
function [a, thau, endrange]=expfit(startT,index,spv)
%written by B. Sachler
%modified 1/00 by AG lab group

clf
%Replace with your preferred labels.
XaxisLabel = 'x-values';
YaxisLabel = 'y-values';
```

```
%Range of x-axis
Xmin = -10;
Xmax = 10;

Ymin = 0;
Ymax = 100;

%numXvals = round(size(spv, 1) / 5);
thaus = [];
startXs = [];

%for startX = 1:50:1000,


   startX = startT+index;
   endrange=360;  %1040
   numXvals = startX+endrange;%1500
   spv = spv;
   x =  [1:(numXvals - startX + 1)]' / 60;
   data = [x, spv(startX:numXvals)];

   startParams = [10, 20];
   options = optimset('Display', 'off');
   bestFitVals = FMINSEARCH('expCost', startParams, options, data);
   thau = bestFitVals(1)
   a = bestFitVals(2)
   startXs = [startXs, startX];
   thaus = [thaus, thau];
%end
%thaus
%startXs

curveVals = a * exp(-data(:, 1) / thau);
%cost = sum((data(:, 2) - curveVals) .^ 2);

hold on
plot(data(:,1), data(:,2),...
   'o',...
   'MarkerSize', 4,...
   'MarkerFaceColor', 'k',...
   'MarkerEdgeColor', 'k'...
   );

plot(data(:,1), curveVals,...
   'LineStyle', '-',...
   'Color', 'k',...
   'LineWidth', 0.5);


%axis([Xmin Xmax Ymin Ymax]);
%set(gca, 'XTick', [Xmin Xmin/2 0 Xmax/2 Xmax]);
%set(gca, 'Ytick', [0 25 50 75 100]);
%XLabel(XaxisLabel, 'FontSize', 8, 'FontWeight', 'bold');
%YLabel(YaxisLabel, 'FontSize', 8, 'FontWeight', 'bold');
```

eye.m

```
%eye-allows user to select a specific head movement and subsequently fits
%an exponential decaying curve to the slow phase velocity envelope
%producing values for A and tau.  Also determines goodness of fit
%via the F-test.  Operator should use x1=1.1646 for data collected after
%2/01/00.

close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list
[num_patients,n] = size(patient_list);
for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end
   run=input('\nEnter run number: ', 's');
   rn=str2num(run);
      if (rn < 10),
         run_code = [root_file, '_run0', run];
      else
         run_code = [root_file, '_run', run];
      end
   run_file = [data_path, run_code, '.mat'];
   load(run_file);
   run_file = [data_path, run_code, '_LV.mat'];
   load(run_file);

   Anlog1=data(:,15);                  %Retrieve Analog 1 from column 15
   Anlog2=data(:,16);                  %Retrieve Analog 1 from column 16
   x1=1.1646.*Anlog1;
%use x1=6.2189 for subjects 2,4,6,7,9. Use x1=1.1646 for 10,11,12
   x2=1.1646.*Anlog2;   % recalibration factor C %----------------------
   gyroy=filt_gyro_position(x1);          %Filter Analog 1 (yaw motions
   gyrop=filt_gyro_position(x2);          %Filter Analog 2 (pitch motions
   subplot(2,1,1)
   x=[1:length(spv)];
   plot(x,spv)
   subplot(2,1,2)
```

```
   x=[1:length(gyroy)];
   plot(x,gyroy)
   [x,y]=ginput(1);
   axis([x-200,x+300,-200,600]);
   subplot(2,1,1)
   axis([x-200,x+300,-200,600]);
   subplot(2,1,2)
   %-- look for end of head movement-----have that be startT
   over=10;
   fprintf('Manually change axis until can eye ball end of head peak\n');
   while(over ~= 0)
      %-- while not pressing escape key
      endpoint=input('\nEnter end point: ','s');
      x2=str2num(endpoint);
      axis([x2-5,x2+1*60,-200,280]);
      subplot(2,1,1)
      axis([x2-5,x2+4*60,-200,280]);
      subplot(2,1,2)
      quitting=input('\nEnter 0 if done: ','s');
      over=str2num(quitting);
   end

   start=input('Enter start point: ','s');
   startT=str2num(start);  %-- actually in points, not time
   peakT = 4;
   if y>0
      [peak, index] = max(spv(startT:startT+(peakT*60)));
   elseif y<0
      [peak, index] = min(spv(startT:startT+(peakT*60)));
   end

   [A, tau,endrange]=expfit(startT, index, spv);
   %---------------------- curve fit goodness--------------
   x=[1:endrange+1]/60;
   startpoint=startT+index;
   xspv=spv(startpoint:startpoint+endrange);
   if y>0
      curve=A*exp(-x/tau);
   elseif y<0
      curve=-A*exp(-x/tau);
   end
   lspv=log(xspv);
   lspv=abs(lspv); %---- took abs of lpv to get rid of imaginary parts,
   %--- just takes positive values and mag. of imaginary values.
   lcurve=log(curve);
   figure
   plot(x,lspv);
   hold on
   plot(x,lcurve);
   lave=sum(lcurve)/(length(lcurve));
   residual=lspv-lcurve';
   regress=lcurve'-lave;
   totss=sum((lspv-lave).^2);
%sum of squares of deviations of the individual sample
%points from the sample mean (lave)
   regss=sum(regress.^2); %sum of squares of the regression components
   resss=sum(residual.^2); %sum of squares of the residual components
```

```
   k=1;
%predictor variables in the model-for simple linear regression, k=1
   regms=regss/k; %regression mean square
   n=endrange;
   resms=resss/(n-k-1);
   ftest=regms/resms
   fact=5.15;
   if ftest>fact
      fprintf('satisfies F-test criterion, therefore significant\n')
   else fprintf('not significant\n')
   end
   totss=regss+resss;
   Rsquared=regss/totss
end
```

filt_gyro_position.m

```
function y = filt_gyro_position(x)
sample=60;
num_lpf=2;

%
% filt_position - filters the angular head velocity with a Butterworth
% filter, using 'filtfilt' to remain phase-less
%
% Written by: D. Balkwill 10/20/93
% Modified by: D. Balkwill 8/17/95
%           - added "num_lpf" and "num_OS" parameters for
%             external control of number of filter stages
% Modified by: AGS lab 12/03/99

N1 = sample / 20;
N1 = max(N1, 3);
N1 = min(N1, 10);
N2 = round(1.7 * N1);
N3 = round( (N1 + N2) / 2 );

corner = 30;
[B,A] = butter(2, 2 * corner / sample);   % butterworth filter, fc = 30 Hz
% one stage filter OS2
x = OS_lin2(x, N1, N2);

y = filtfilt(B,A,x);
if (num_lpf > 1),
   for i=2:num_lpf,
      y = filtfilt(B,A,x);
   end
end

clear B A N1 N2 N3 i
```

filt_position.m

```
function y = filt_position(x, sample, num_lpf, num_OS, quad_flag)
```

```
%
% filt_position - filters the eye position with a Butterworth filter,
%                 using 'filtfilt' to remain phase-less
%
% Written by: D. Balkwill 10/20/93
% Modified by: D. Balkwill 8/17/95
%           - added "num_lpf" and "num_OS" parameters for
%             external control of number of filter stages
%

N1 = sample / 20;
N1 = max(N1, 3);
N1 = min(N1, 10);
N2 = round(1.7 * N1);
N3 = round( (N1 + N2) / 2 );

corner = 30;
[B,A] = butter(2, 2 * corner / sample);   % butterworth filter, fc = 30 Hz

% one stage of OS filtering first, to reduce noise
y = OS_lin2(x, N1, N2);
%y = OS_lin2(x, 2*N1, 2*N2);  % filters out some of 16 Hz noise

y = filtfilt(B,A,y);
if (num_lpf > 1),
   for i=2:num_lpf,
      y = filtfilt(B,A,y);
   end
end

for i=2:num_OS,
   if (quad_flag),
       y = OS_lin2quad1(y, N1, N2, N3);
   else
       y = OS_lin2(y, N1, N2);    % order statistic filter
   end
end

clear B A N1 N2 N3 i
```

get_patient_list.m

```
%
% get_patient_codes - input patient codes for batch processing
%
% D. Balkwill 9/28/93
%

check_flag = 1;
code_length = [];
patient_list = [];
[m,n] = size(patient_list);

if (exist([data_path,'patient_list.mat']) == 2),
    eval(['load ',data_path,'patient_list.mat']);
```

```
    fprintf('\nCurrent patient list:\n');
    for i=1:length(code_length),
        fprintf([patient_list(i,1:code_length(i)), '\n']);
    end
    yn = get_yn('Is this the correct patient list','Y');
    if (yn == 'Y'),
        check_flag = 0;
    else,
        code_length = [];
        patient_list = [];
    end
end

while (check_flag == 1),

    % terminate list by entering no patient code
    patient_code = input('Enter Patient Code: ','s');
    if (isempty(patient_code) == 1),
        check_flag = 0;
        break;
    end

    % add run code to patient list, padding with blanks as needed
    l = length(patient_code);
    if (l < n),
        patient_code = [patient_code, zeros(1,n-l)];
    elseif (l > n),
        patient_list = [patient_list, zeros(m,l-n)];
    end
    patient_list = [patient_list; patient_code];
    [m,n] = size(patient_list);
    code_length = [code_length; l];

end

eval(['save ',data_path,'patient_list.mat patient_list code_length']);

clear check_flag patient_code status l m n i yn
```

get_PC_bed_path.m

```
% get_PC_bed_path
%
% This routine searches the MatLab path specification for the main MatLab
% folder (name ends in MATLAB), and looks in that folder for a file named
% research_path, which is to contain a string variable named 'data_path'.
% The contents of 'data_path' is the name of the folder in which the data
% to be analyzed is stored.
%
% Written by: D. Balkwill  10/20/93
% Note: same as 'get_rot_path', but with different file name
% 'research_path'.

%get MatLab path specification
master_path = [matlabroot, '\'];
```

```
% see if rotation path exists,input if it doesn't
status = exist([master_path,'bed_path.mat']);
if (status == 2),
    eval(['load ',master_path,'bed_path.mat']);
else
    data_path = input('Enter bed data folder specification: ','s');
end

% ensure that : is at end of path
l = length(data_path);
if (data_path(l) ~= '\'),
    data_path = [data_path,'\'];
    status = 1;   % force save with back-slashed path name
end

% save path if it hasn't been before
if (status ~= 2)
    eval(['save ',master_path,'bed_path.mat data_path']);
end

clear a b found status mat_path l skip
```

get_yn.m

```
function yn = get_yn( question, default )

%
% yn - asks a yes/no 'question', allowing an answer of 'Y' or 'N'
%      from the user, and returns the capitalized response letter.
%      If the user response is not 'y', 'n', 'Y', or 'N, the response
%      is set to the 'default' value.
%
% Written by: D. Balkwill 9/28/93
%

if ((default >= 'a') & (default <= 'z')),
    default = default - 'a' + 'A';
end

if (default == 'Y'),
    yn = input( [question,' ([Y]/N) ? '],'s');
    other = 'N';
else
    yn = input( [question,' (Y/[N]) ? '],'s');
    other = 'Y';
end

if (isempty(yn)),
    yn = default;
elseif ((yn >= 'a') & (yn <= 'z')),
    yn = yn - 'a' + 'A';
end

if (yn ~= other),
```

```
    yn = default;
end

clear other
```

head.m

```
%head-allows user to select a head movement and outputs the magnitude
%in degrees (integrates the area under the angular rate sensor curve),
%the peak velocity, the time to peak velocity, and the duration
%of the head movement.

close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list
[num_patients,n] = size(patient_list);
for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end
   run=input('\nEnter run number: ', 's');
   rn=str2num(run);
   if (rn < 10),
      run_code = [root_file, '_run0', run];
   else
      run_code = [root_file, '_run', run];
   end
   run_file = [data_path, run_code, '.mat'];
   load(run_file);

   Anlog1=data(:,15);                  %Retrieve Analog 1 from column 15
   Anlog2=data(:,16);                  %Retrieve Analog 1 from column 16
   x1=1.1646.*Anlog1;
%use x1=6.2189 for subjects 2,4,6,7,9.Use x1=1.1646 for 10,11,12
   x2=1.1646.*Anlog2;   % recalibration factor C %----------------------
   gyroy=filt_gyro_position(x1);          %Filter Analog 1 (yaw motions
   gyrop=filt_gyro_position(x2);          %Filter Analog 2 (pitch motions
```

```
   x=[1:length(gyroy)];
   plot(x,gyroy)
   key=0;
   [x,y,key]=ginput(1);
   %-------------------change axis limits ---------------
   axis([x-200,x+200,-200,300]);
   over=10; %-- initializing
   fprintf('Manually change axis until can eye ball start and end of head
peak\n');
   while(over ~= 0)
      %-- while not pressing escape key
      fprintf('\nEnter start point: ');
      [x1,y1,key]=ginput(1);
      fprintf('\nEnter end point: ');
      [x2,y2,key]=ginput(1);
      axis([x1,x2,-200,280]);
      quitting=input('\nEnter 0 if done: ','s');
      over=str2num(quitting);
   end

   start=input('Enter start point: ','s');
   endpoint=input('Enter end point: ','s');

   if y > 0
      upinteg=0;
      start=str2num(start);
      endpoint=str2num(endpoint);
      startpoint=start;

   %  preavezero = x-10*60; %getting 10seconds of time before the
   % headmovment
  %---if error on 1st head movement, set preavezero=1;
      preavezero=1
      earlypoint =  5*60 + preavezero; %aveg over 2 secs
      avezero = sum(gyroy(preavezero:earlypoint))/(earlypoint-preavezero+1);

      for k=startpoint:endpoint
         upinteg=upinteg + (gyroy(k,1)-avezero)*(1/60)
      end
      upinteg
      upinteg=round(upinteg)
      headtime=(endpoint-startpoint)/60
      [peakvel,maxpoint]=max(gyroy(startpoint:endpoint));
      maxtime=(maxpoint)/60
      peakvel=peakvel-avezero
   elseif y < 0
      downinteg=0;
      startlowpoint=str2num(start);
      endlowpoint=str2num(endpoint);

      lowprepoint = startlowpoint-190;
%getting preseconds of time before the headmovment
      lowprepoint2 = startlowpoint-10;
%getting points over which to ave zero
      prelow_avezero = sum(gyroy(lowprepoint:lowprepoint2))/(lowprepoint2-
lowprepoint);
```

```
      for k=startlowpoint:endlowpoint,
         downinteg=downinteg + (gyroy(k)-prelow_avezero)*(1/60)
%find magnitude with changing zero
      end
      downinteg
      downinteg=round(downinteg)
      headdowntime=(endlowpoint-startlowpoint)/60
      [peak_lowvel,maxlowpoint]=min(gyroy(startlowpoint:endlowpoint));
      maxdowntime=(maxlowpoint)/60
      peak_lowvel=peak_lowvel-prelow_avezero
   end
end
```

init_bed.m

```
FALSE = 0;
TRUE = 1;

LEFT_VERTICAL = 2;
%RIGHT_VERTICAL = 3;
LEFT_HORIZONTAL = 4;
%RIGHT_HORIZONTAL = 5;

num_increase = 2;
num_RMS = 0.25;
min_diff_class = 30;
```

inlist.m

```
%
%InList -- W. Kulecz
%

function K = InList(value,list)
% scan a matrix and return row number, K, such that:
%       list(K,1) <= value <= list(K,2)
% return K = 0 if value not in list.
[m,n]=size(list);
if m==0
   K=0;
   return;
end
if n < 2
   error('List matrix must have at least two columns.');
end
K=m;
while K > 0
   if (value >= list(K,1)) & (value <= list(K,2))
      return;
   end
```

```
K=K-1;
end
```

interp_blinks.m

```
function spv = interp_blinks(vel, first, last)

% interp_blinks - Interpolates across eye position blinks by calculating
% new position values to estimate replacement values for blink points.
% New position values are interpolated as first order line segments.
% a zeroth order hold.
%
% Written by: D. Balkwill 11/16/93
%
% Modified from "interpolate.m" by: MDB 10/1/99
%
%

spv = vel;
n = length(first);

% replace old velocities with new ones
delta = last - first + 1;
for i=1:n,
    d = delta(i);
   s = vel(first(i));
   e = vel(last(i));
    spv(first(i):last(i)) = (s * ones(d,1)) + ((e - s) * [0:(d-1)]'/(d-1));
end
```

interpolate.m

```
function spv = interpolate(vel, first, last)

% interpolate - Interpolates across fast phases by calculating new SPV
% values to estimate replacement values for fast phase velocity samples.  %
New SPV is the median of the three SPV values before the fast phase, and %
interpolated as a zeroth order hold.
%
% Written by: D. Balkwill 11/16/93
%

spv = vel;
n = length(first);
vn = length(vel);

if (n == 0),
   return;
end

% variables for calculation of new interpolation values
a = first;
b = last;
m = n;

% eliminate fast phases which are on time boundaries
```

```
start_flag = (first(1) == 1);
end_flag = (last(n) == vn);
if (start_flag),          % first phase is at start of time boundary
    a = a(2:m);
    b = b(2:m);
    m = m - 1;
end
if (end_flag),             % last phase is at end of time boundary
    a = a(1:m-1);
    b = b(1:m-1);
    m = m - 1;
end

% check that there are any fast phases left to interpolate across
if (m > 0),

% construct matrix of velocities before fast phase for speed optimization,
% and calculate new interpolation values as median of previous three
% points
   overlap = find(a < 4);
   if (~isempty(overlap)),
      a(overlap) = 4 * ones(size(overlap));
   end
   overlap = find(b > (vn-3));
   if (~isempty(overlap)),
      b(overlap) = (vn-3) * ones(size(overlap));
   end
   vel_matrix = [vel(a-1), vel(a-2), vel(a-3)];
   start_values = median(vel_matrix')';
   vel_matrix = [vel(b+1), vel(b+2), vel(b+3)];
   end_values = median(vel_matrix')';

% add extrapolation values for fast phases which occurred on time
% boundaries
   if (start_flag),
       i = last(1) + 1;
       v = median(vel(i:i+2));
       start_values = [v; start_values];
       end_values = [v; end_values];
   end
   if (end_flag),
       i = first(n) - 1;
       v = median(vel(i-2:i));
       start_values = [start_values; v];
       end_values = [end_values; v];
   end

% replace old velocities with new ones
   delta = last - first + 1;
   for i=1:n,
       d = delta(i);
       s = start_values(i);
       e = end_values(i);
       spv(first(i):last(i)) = (s * ones(d,1)) + ((e - s) * [0:1/(d-1):1]');
   end

end
```

```
clear a b m n vn start_flag end_flag overlap vel_matrix start_values
end_values i v  delta d s e
```

make_eye_plot.m

```
close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list
[num_patients,n] = size(patient_list);
for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end
   run=input('\nEnter run number: ', 's');
   rn=str2num(run);
      if (rn < 10),
         run_code = [root_file, '_run0', run];
      else
         run_code = [root_file, '_run', run];
      end
   run_file = [data_path, run_code, '.mat'];
   load(run_file);
   run_file = [data_path, run_code, '_LV.mat'];
   load(run_file);

   Anlog1=data(:,15);                  %Retrieve Analog 1 from column 15
   Anlog2=data(:,16);                  %Retrieve Analog 1 from column 16
   x1=6.2189.*Anlog1;
%use x1=6.2189 for subjects 2,4,6,7,9. Use x1=1.1646 for 10,11,12
   x2=6.2189.*Anlog2;   % recalibration factor C %----------------------
   gyroy=filt_gyro_position(x1);          %Filter Analog 1 (yaw motions
   gyrop=filt_gyro_position(x2);          %Filter Analog 2 (pitch motions
   subplot(2,1,1)
   x=[1:length(spv)];
   plot(x,spv)
   subplot(2,1,2)
   x=[1:length(gyroy)];
```

```
plot(x,gyroy)
[x,y]=ginput(1);
axis([x-200,x+300,-200,600]);
subplot(2,1,1)
axis([x-200,x+300,-200,600]);
subplot(2,1,2)
%-- look for end of head movement-----have that be startT
over=10;
fprintf('Manually change axis until can eye ball end of head peak\n');
while(over ~= 0)
   %-- while not pressing escape key
   endpoint=input('\nEnter end point: ','s');
   x2=str2num(endpoint);
   axis([x2-5,x2+1*60,-200,280]);
   subplot(2,1,1)
   axis([x2-5,x2+4*60,-200,280]);
   subplot(2,1,2)
   quitting=input('\nEnter 0 if done: ','s');
   over=str2num(quitting);
end

start=input('Enter start point: ','s');
startT=str2num(start);  %-- actually in points, not time
peakT = 4;
if y>0
   [peak, index] = max(spv(startT:startT+(peakT*60)));
elseif y<0
   [peak, index] = min(spv(startT:startT+(peakT*60)));
end

[A, tau,endrange]=expfit(startT, index, spv);
x=[1:endrange+1]/60;
startpoint=startT+index;
xspv=spv(startpoint:startpoint+endrange);
curve=A*exp(-x/tau);
figure
plot(x,xspv,'k.');
axis([0,6,-10,110]);
hold on
plot(x,curve,'k');
axis([0,6,-10,110]);
xlabel('Time (seconds)');
ylabel('Slow Phase Velocity (degrees/second)');
end
```

make_triplot.m

```
close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
```

```
get_PC_bed_path

% get list of patients to be processed
get_patient_list
[num_patients,n] = size(patient_list);
for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end
   run=input('\nEnter run number: ', 's');
   rn=str2num(run);
      if (rn < 10),
         run_code = [root_file, '_run0', run];
      else
         run_code = [root_file, '_run', run];
      end
   run_file = [data_path, run_code, '.mat'];
   load(run_file);
   run_file = [data_path, run_code, '_LV.mat'];
   load(run_file);

   Anlog1=data(:,15);                  %Retrieve Analog 1 from column 15
   Anlog2=data(:,16);                  %Retrieve Analog 1 from column 16
   x1=6.2189.*Anlog1;
%use x1=6.2189 for subjects 2,4,6,7,9. Use x1=1.1646 for 10,11,12
   x2=6.2189.*Anlog2;   % recalibration factor C %----------------------
   gyroy=filt_gyro_position(x1);       %Filter Analog 1 (yaw motions
   gyrop=filt_gyro_position(x2);       %Filter Analog 2 (pitch motions

   pos1=pos(2650:3600);
   subplot(3,1,1)
   x=[1:length(pos1)]/60;
   plot(x,pos1)
   %axis([2650,3600,-40,30]);
   xlabel('Time (sec)');
   ylabel('Vertical Eye Position (deg)');
   subplot(3,1,2)
   spv1=spv(2650:3600);
   x=[1:length(spv1)]/60;
   plot(x,spv1)
   %axis([2650,3600,-50,200]);
   xlabel('Time (sec)');
   ylabel('SPV (deg/sec)');
   subplot(3,1,3)
   gyroy1=gyroy(2650:3600);
   x=[1:length(gyroy1)]/60;
   plot(x,gyroy1)
   xlabel('Time (sec)');
   ylabel('Ang. Vel. (deg/sec)');
```

```
    end
```

min_threshold.m

```
function same = min_threshold(x, y, mult, minimum)

% threshold - compare two profiles, and reject all points which differ
%           by more than a specified multiple of the rms, and at
%           least by 'minimum' units
% Written by: D. Balkwill 10/20/93
%

d = abs(y - x);
s = sqrt(mean(d .* d));
n = abs(d / s);
same = ((n <= mult) | (d < minimum));
%plot(n)
clear d s n
```

new_AATM.m

```
function spv = newAATM(window, vel)

% matAATM - MATLAB implementation of the "newAATM" C-code, since
%        the C-code could not be run on the PowerMac as yet.
%
% Written by: MDB 1/18/96
%

% initialize parameter values
ALPHA = 0.44;
BETA = 0.12;
MU = 0.4;

% integer number of samples in sliding window
N = floor(window / 2);
L = round(2 * N + 1);
num_samples = max(size(vel));
stop = num_samples - N;

% initialize skewing parameters
Lalpha = round(L * ALPHA);
Lbeta = round(L * BETA);
M = round(L * MU);

% initialize and sort first window of data
spv = vel;
s = sort(vel(1:L));

% check to see if array is sorted
d = s(2:L) - s(1:(L-1));
j = find(d < 0);
if (~isempty(j)),
```

```
   fprintf('Array unsorted initially at indices ');
   j
end

% calculate skewness of first window of data
if (s(L - Lbeta) == s(Lbeta)),
   Sbeta = 0;
else
   Sbeta = (s(L - Lbeta) + s(Lbeta) - 2 * s(N+1));
   Sbeta = Sbeta / (s(L - Lbeta) - s(Lbeta));
end
K = round(- Sbeta * M);

% new value at centre of window is mean of estimated peak of histogram
spv(N+1) = mean( s( (Lalpha + K + 1):(L - Lalpha + K) ) );
%spv(N+1) = mean( s( (Lalpha + K):(L - Lalpha + K - 1) ) );


% for each value
for n = (N+2):stop,

   old = vel(n - N - 1);   % value to be removed from list
   new = vel(n + N);       % value to be inserted into list

   % find index of old value
   k1 = find(s == old);
   if (isempty(k1)),
      disp('ERROR: value not found in vector');
      k1 = 1;
   else
      k1 = k1(1);
   end

if (s(k1) ~= old),
   disp('OLD not found');
end

   %
   % insert new value and remove old value
   %
   if (old == new),        % simple replacement

      s(k1) = new;
      spv(n) = spv(n-1);   % histogram has not changed, so neither has SPV

   else

      % remove old value
      if (k1 == 1),
         s = s(2:L);
      elseif (k1 == L),
         s = s(1:(L-1));
      else
         s = [s(1:(k1-1)); s((k1+1):L)];
      end

      % check for out of bounds of sorted list,
```

```
      %  find insertion index for new value,
      %  and insert new value into list
      if (new <= s(1)),
         k2 = 1;
         s = [new; s];
      elseif (new >= s(L-1)),
         k2 = L;
         s = [s; new];
      else
         k2 = find(s > new);
         k2 = k2(1);
         s = [s(1:(k2-1)); new; s(k2:(L-1))];
      end
%     elseif (new > old),
%        k2 = find(s((k1+1):L) > new);
%        k2 = k2(1) + k1 - 1; % new is to the right of old, shift left
%        s = [s(1:(k1-1)); s((k1+1):k2); new; s(k2+1:L)];
%     else
%        k2 = find(s(1:k1) > new);
%        k2 = k2(1);          % new is to the left of old, shift right
%        s = [s(1:(k2-1)); new; s(k2:(k1-1)); s(k1+1:L)];
%     end

% check to see if array is sorted
d = s(2:L) - s(1:(L-1));
j = find(d < 0);
if (~isempty(j)),
   fprintf(['Array unsorted at iteration # ', int2str(n), ' at indices ']);
   j
end

      % calculate skewness of new window of data
      if (s(L - Lbeta) == s(Lbeta)),
         Sbeta = 0;
      else
         Sbeta = (s(L - Lbeta) + s(Lbeta) - 2 * s(N+1));
         Sbeta = Sbeta / (s(L - Lbeta) - s(Lbeta));
      end
      K = round(- Sbeta * M);

% new value at centre of window is mean of estimated peak of histogram
      spv(n) = mean( s( (Lalpha + K + 1):(L - Lalpha + K) ) );
% spv(n) = mean( s( (Lalpha + K):(L - Lalpha + K - 1) ) );

   end      %else

end      %for

clear s N L K num_samples stop i k1 k2 new old
clear ALPHA BETA MU Lalpha Lbeta M
```

OS_lin2.m

```
function y = OS_lin2(x,N1,N2)
```

```
% This function performs order statistic filtering (first stage
% of Engelken, 1990) on an input signal x to sharpen corners and
% reduce noise.  It uses two windows of length N1 and N2,
% allowing linear root signals.  The new value is therefore
% the median of five values.
%
% D. Balkwill 10/28/90

l = length(x);

% calculate window coefficients for forward filters
h1F = PFMH1(N1);
h2F = PFMH1(N2);

% backward filters have same coefficients, but in reverse
h1B = h1F;
for i=1:N1
    h1B(i) = h1F(N1-i+1);
end
h2B = h2F;
for i=1:N2
    h2B(i) = h2F(N2-i+1);
end

% Use Matlab filter command to maximize speed of execution,
% applying forward and backward windows to appropriate range
% of the input signal.
xF1 = filter(h1F,1,x);
xF1 = [x(1:N1)' xF1(N1:l-1)'];
xB1 = filter(h1B,1,x);
xB1 = [xB1(N1+1:l)' x(l-N1+1:l)'];

xF2 = filter(h2F,1,x);
xF2 = [x(1:N2)' xF2(N2:l-1)'];
xB2 = filter(h2B,1,x);
xB2 = [xB2(N2+1:l)' x(l-N2+1:l)'];

y = median([x xF1 xB1 xF2 xB2]')';

clear xB1 xF1 xB2 xF2 i l h1F h1B h2F h2B
```

OS_lin2quad1.m

```
function y = OS_lin2quad1(x,N1,N2,N3)

% This function performs order statistic filtering (first stage
% of Engelken, 1990) on an input signal x to sharpen corners and
% reduce noise.  It uses two linear windows of length N1 and N2,
% and ones second-order window of length N3, so that linear and
% parabolic root signals are preserved.  The new value is therefore
% the median of seven values.
%
% D. Balkwill 11/19/93
```

```
l = length(x);

% calculate window coefficients for forward filters
h1F = PFMH1(N1);
h2F = PFMH1(N2);
h3F = PFMH2(N3);

% backward filters have same coefficients, but in reverse
h1B = h1F;
for i=1:N1
    h1B(i) = h1F(N1-i+1);
end
h2B = h2F;
for i=1:N2
    h2B(i) = h2F(N2-i+1);
end
h3B = h3F;
for i=1:N3
    h3B(i) = h3F(N3-i+1);
end

% Use Matlab filter command to maximize speed of execution,
% applying forward and backward windows to appropriate range
% of the input signal.
xF1 = filter(h1F,1,x);
xF1 = [x(1:N1)' xF1(N1:l-1)']';
xB1 = filter(h1B,1,x);
xB1 = [xB1(N1+1:l)' x(l-N1+1:l)']';

xF2 = filter(h2F,1,x);
xF2 = [x(1:N2)' xF2(N2:l-1)']';
xB2 = filter(h2B,1,x);
xB2 = [xB2(N2+1:l)' x(l-N2+1:l)']';

xF3 = filter(h3F,1,x);
xF3 = [x(1:N3)' xF3(N3:l-1)']';
xB3 = filter(h3B,1,x);
xB3 = [xB3(N3+1:l)' x(l-N3+1:l)']';

y = median([x xF1 xB1 xF2 xB2 xF3 xB3]')';

clear xB1 xF1 xB2 xF2 xB3 xF3 i l h1F h1B h2F h2B h3F h3B
```

PFMH1.m

```
function h1 = PFMH1(N)

% This calculates the coefficients for a linear order statistic
% window of length N.
%
% D. Balkwill  10/28/90

a = (4*N + 2)/(N*(N-1));
b = 6/(N*(N-1));
h1 = a * ones(1,N) - b * [1:N];
```

```
clear a b ans
```

PFMH2.m

```
function h2 = PFMH2(N)

% This calculates the coefficients for a second-order order statistic
% window of length N.
%
% D. Balkwill  11/19/93

i = [1:N];
h2 = (9 * N * N) + ((9 - 36 * i) * N) + (30 * i .* i) - (18 * i) + 6;
h2 = h2 / (N * (N * N - 3 * N + 2));
%a = (4*N + 2)/(N*(N-1));
%b = 6/(N*(N-1));
%h1 = a * ones(1,N) - b * [1:N];
clear i
```

review_bed.m

```
% batch_bed

close all
clear all

init_bed

batch_mode = FALSE;

% get research data folder name
get_PC_bed_path

% get list of patients to be processed
get_patient_list

[num_patients,n] = size(patient_list);

for patnum=1:num_patients,

   file_name = patient_list(patnum,:);
   idx = find(abs(file_name) > 32);    % printable non-blank characters
   file_name = file_name(idx);

   idx = find(file_name == '.');
   if (isempty(idx)),
      root_file = file_name;
   else
      root_file = file_name(1:(idx(1)-1));
   end

   rn = 1;
   run_code = [root_file, '_run0', int2str(rn)];
```

```
   run_file = [data_path, run_code, '.mat'];

   while (exist(run_file) == 2),

      load(run_file);

      review_bed_file

      rn = rn + 1;
      if (rn < 10),
         run_code = [root_file, '_run0', int2str(rn)];
      else
         run_code = [root_file, '_run', int2str(rn)];
      end
      run_file = [data_path, run_code, '.mat'];

   end
end
```

review_bed_file.m

```
% create time vector
clear t
t = [0:(num_samples-1)] / sample_rate;

%
% process left vertical eye position data
%
raw_index = LEFT_VERTICAL;
cal_index = LEFT_VERTICAL+num_params;
which_eye = 'Left Vertical';
file_ext = '_LV.mat';
```

review_eye_channel.m

```
%
% process right vertical eye position data
%
%raw_index = RIGHT_VERTICAL;
%cal_index = RIGHT_VERTICAL+num_params;
%which_eye = 'right Vertical';
%file_ext = '_RV.mat';

%review_eye_channel

%
% process left horizontal eye position data
%
raw_index = LEFT_HORIZONTAL;
cal_index = LEFT_HORIZONTAL+num_params;
which_eye = 'Left Horizontal';
file_ext = '_LH.mat';
```

```
review_eye_channel

%
% process right horizontal eye position data
%
%raw_index = RIGHT_HORIZONTAL;
%cal_index = RIGHT_HORIZONTAL+num_params;
%which_eye = 'Right Horizontal';
%file_ext = '_RH.mat';

%review_eye_channel

   review_eye_channel
% free up variable space
clear pos vel spv edited_spv fast_start fast_end

% when something is changed in interactive mode, then analysis must be
%    redone from that point on
redo_flag = FALSE;

% review, and allow editing, of despiking algorithm
save_file = [data_path, run_code, file_ext];
load(save_file);
fig = figure('Name', 'Review of Despiking Algorithm');
plot(t, data(:,cal_index), 'r');
hold on
plot(t, pos, 'b');
xlabel('Time (sec)');
ylabel('Eye Position (deg)');
title([run_code, ' -- ', which_eye]);
yn = get_yn('Do you want to redo the despike algorithm','N');
close(fig);
if (yn == 'Y'),
   redo_flag = TRUE;
   [pos, num_blinks, prec_blink] = deblink(data(:,raw_index),
data(:,cal_index), -1, -1, num_increase);
end

% filter eye position data to enhance signal-to-noise ratio
%  - one pass of order statistic filter to minimize video quantization,
%     allowing for curved eye movements
%  - two passes of fourth-order phase-less Butterworth low-pass filter
%     with 30 Hz corner frequency, to reduce noise
%  - two additional passes of order statistic filter, to reduce noise
%     and sharpen corners of nystagmus, allowing for curved eye movements
if (redo_flag),
   pos = filt_position(pos, sample_rate, 2, 3, TRUE);
end

% differentiate eye position to get velocity
if (redo_flag),
   vel = differentiate(pos, sample_rate);
end

% classify fast phases in eye velocity data, and interpolate across
if (redo_flag),
```

```
   [fast_start, fast_end] = bed_classify_phases(vel, num_RMS, num_increase,
...
                                    min_diff_class, sample_rate);
   spv = interpolate(vel, fast_start, fast_end);
end

% allow changing of automated parameters, if desired
fig = figure('Name', 'SPV from Automated Fast Phase Detection');
hold off
plot(t, vel, 'r');
hold on
h2 = plot(t, spv, 'b');
xlabel('Time (sec)');
ylabel('Eye Velocity (deg/sec)');
title([run_code, ' -- ', which_eye]);
yn = get_yn('Do you want to change the fast phase detection parameters','N');
while (yn == 'Y'),
   redo_flag = TRUE;
   new_RMS = input(['    # of RMS levels (', num2str(num_RMS), '): ']);
   if (isempty(new_RMS)),
      new_RMS = num_RMS;
   end
   new_inc = input(['    # of transition points (', int2str(num_increase),
'): ']);
   if (isempty(new_inc)),
      new_inc = num_increase;
   else
      new_inc = round(abs(new_inc));
   end
   new_min = input(['    minimum difference threshold (',
num2str(min_diff_class), '): ']);
   if (isempty(new_min)),
      new_min = min_diff_class;
   else
      new_min = abs(new_min);
   end
   [fast_start, fast_end] = bed_classify_phases(vel, new_RMS, new_inc, ...
                                    new_min, sample_rate);
   spv = interpolate(vel, fast_start, fast_end);
   set(h2, 'YData', spv);
   drawnow
   yn = get_yn('Do you want to change the fast phase detection
parameters','N');
end
close(fig);

% allow manual editing, if desired
yn = get_yn('Do you want to manually edit the SPV data','Y');
if (yn == 'Y'),
   if ((~redo_flag) & (~isempty(edited_spv))),
      yn = get_yn('Do you want to resume previous editing','Y');
      if (yn == 'Y'),      % resume previous editing
         spv = edited_spv;
      else           % discard previous editing
         edited_spv = [];
         [fast_start, fast_end] = diff_list2(vel, spv);
      end
```

```
   end
   fig = figure('Name', ['Manual Editing -- ', run_code, ' -- ', which_eye]);
    ed_spv = edit_alg_diff(t, spv, vel, pos, [fast_start fast_end], 'y');
   close(fig);
   if (isempty(edited_spv)),
      edited_spv = ed_spv;
      [fast_start, fast_end] = diff_list2(vel, edited_spv);
   else
      yn = get_yn('Do you want to save the newly edited SPV data','Y');
      if (yn == 'Y'),
         edited_spv = ed_spv;
         [fast_start, fast_end] = diff_list2(vel, edited_spv);
      end
   end
   clear ed_spv
end

% save data in a Matlab-format file
save_file = [data_path, run_code, file_ext];
parms_list = ' pos vel spv edited_spv fast_start fast_end num_blinks
perc_blink';
eval(['save ', save_file, parms_list]);
```

simple_blinks.m

```
function [blink_start, blink_end] = simple_blinks(pos, num_increase,
min_diff_class)
%
% simple_blinks.m  - attempts to detect the blinks in a position trace
% 'pos'
%
% The ISCAN blink detection algorithm marks "blink" points as zeros.  A
% blink interval is defined as a series of consecutive blink points.  A
% specified number of points (num_increase) are added to the beginning and %
end of the blink interval, to allow for transient behaviour.  In
% addition, the blink interval is extended to include any consecutive
% points that differ by more than a specified threshold (min_diff_class). %
"blink_start" is a vector in which each element is the sample number of % the
start of a blink interval. "blink_end" contains the corresponding
% sample numbers of the ends of the blink intervals.
%
% Suggested values for the input parameters are:
%  pos = raw eye position, uncalibrated
%  num_increase = 2
%  min_diff_class = 100
%
% Written by: MDB 10/1/99
%

[m,n] = size(pos);
if (m > n),     % column vector
   last = m;
   d = [0; abs(diff(pos))];
else         % row vector
   last = n;
```

```
   d = [0, abs(diff(pos))];
end

% flag "blink" points
fast = (pos == 0);

% increase fast phase duration by 'num_increase' sample
%    in each direction for transients
if (num_increase > 0),
    fast = filtfilt(ones(num_increase+1,1), 1, fast);
    fast = (fast > 0);
end

% find start and end of each fast phase
fast_diff = filter([1 -1], 1, fast);          % two-point difference
blink_start = find(fast_diff > 0);            % 0 to 1 transition
num_start = length(blink_start);
blink_end = find(fast_diff < 0) - 1;          % 1 to 0 transition
num_end = length(blink_end);
if (num_end < num_start),
    blink_end = [blink_end; last];
    num_end = num_end + 1;
end

% extend interval until difference is less than threshold
for i=1:num_end,
   s = blink_start(i);
   while (d(s) > min_diff_class),
      s = s - 1;
   end
   blink_start(i) = s;
   e = blink_end(i);
   while (d(e) > min_diff_class),
      if (e < length(d))
         e = e + 1;
%ERROR here is that d(e) index goes higher than length d. This is index
% exceeds matrix dimension
      else d(e) = min_diff_class;
%If difference too high, make it min threshold
      end
   end
   blink_end(i) = e;
end

return;
```

thresh_blinks.m

```
function [blink_start, blink_end] = thresh_blinks(pos, num_increase, ...
                                low_thresh, high_thresh, min_diff_class)
%
% thresh_blinks.m  - attempts to detect the blinks in a position trace
% 'pos' The ISCAN blink detection algorithm marks "blink" points as zeros.  %
In some cases, a blink may be missed by ISCAN, but the value at that
% point may be above or below a specified non-zero threshold.  A blink
```

```
% interval is defined as a series of consecutive blink points with values % <
"low_thresh" or > "high_thresh" in addition to the ISCAN zeros.  A
% specified number of points (num_increase) are added to the beginning and %
end of the blink interval, to allow for transient behaviour.  In
% addition, the blink interval is extended to include any consecutive
% points that differ by more than a specified threshold (min_diff_class). %
"blink_start" is a vector in which each element is the sample number of % the
start of a blink interval. "blink_end" contains the corresponding
% sample numbers of the ends of the blink intervals.
%
% Suggested values for the input parameters are:
%  pos = raw eye position, uncalibrated
%  num_increase = 2
%  min_diff_class = 100
%
% Written by: MDB 10/1/99
%

[m,n] = size(pos);
if (m > n),     % column vector
   last = m;
   d = [0; abs(diff(pos))];
else         % row vector
   last = n;
   d = [0, abs(diff(pos))];
end

% flag "blink" points
fast = ((pos <= low_thresh) | (pos >= high_thresh));

% increase fast phase duration by 'num_increase' sample
%    in each direction for transients
if (num_increase > 0),
    fast = filtfilt(ones(num_increase+1,1), 1, fast);
    fast = (fast > 0);
end

% find start and end of each fast phase
fast_diff = filter([1 -1], 1, fast);          % two-point difference
blink_start = find(fast_diff > 0);            % 0 to 1 transition
num_start = length(blink_start);
blink_end = find(fast_diff < 0) - 1;          % 1 to 0 transition
num_end = length(blink_end);
if (num_end < num_start),
    blink_end = [blink_end; last];
    num_end = num_end + 1;
end

% extend interval until difference is less than threshold
for i=1:num_end,
   s = blink_start(i);
   while (d(s) > min_diff_class),
      s = s - 1;
   end
   blink_start(i) = s;
   e = blink_end(i);
   while (d(e) > min_diff_class),
```

```
      e = e + 1;
   end
   blink_end(i) = e;
end

return;
```

zero_filter.m

```
function y = zero_filter( B, A, x )

% zero_filter
%
% Performs zero phase shift filtering for FIR filters (ONLY!)
%      by padding signal to be filtered with non-zero values at
%      beginning and end of data sequence.
%     Called with the same parameters and order as Matlab filter command.
%
% Written by: D. Balkwill 10/20/93     (slightly modified from D. Merfeld)
%

% check sizes of vectors
nx=max(size(x));
nB=max(size(B));

% get inital condition for delay
x(nx+1:nx+((nB-1)/2)) = x(nx).*ones(((nB-1)/2),1);
[temp,Zi] = filter( B, A, x(1) .* ones(((nB-1)/2),1) );

% derivative filter with initial condition for phase-shift compensation
x = filter(B,A,x,Zi);
y = x(((nB-1)/2+1):nx+((nB-1)/2));

%clear temp Zi nx nB
```