Artificial Gravity: Evaluation of adaptation to head movements during short-radius centrifugation using subjective measures.

By

Lisette Emma Lyne

MSci Physics with Astrophysics (1997)

The University of Birmingham, United Kingdom

Submitted to the Department of Aeronautics and Astronautics
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Signature of Author.. ....
Department of Aeronautics and Astronautics May 12, 2000

Certified by....... ....
Professor Laurence Young
Apollo Professor of Astronautics, Department of Aeronautics and Astronautics

Accepted by.................... ....
Professor Nesbitt Hagood
Chair, Graduate Office

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ABSTRACT

An experiment was performed to determine the ability of humans to adapt, and retain adaptation to out-of-plane head movements made during short-radius centrifugation. The hypothesis for the experiment was as follows: Repeated exposure to a series of yaw head movements made during short-radius centrifugation at 23rpm, (with the subject lying supine and the head on the axis of rotation) will result in a decrease in the magnitude of inappropriate perceived self-motion sensations and severity of motion sickness.

Verbal accounts of perceived pitch, motion-sickness scores and computer animations of subjective sensations were obtained from eight subjects, during three sessions performed at the following intervals: day one, day two and day eight. Verbal accounts of perceived pitch obtained during rotation and post-experiment motion-sickness scores provide clear evidence of adaptation to the stimulus between days one and two, and some retention of adaptation to day eight. Computer animations of subjective sensations obtained after the experiment and motion-sickness scores reported during the experiment do not provide conclusive evidence of adaptation, or retention of adaptation. The validity of these techniques were explored, along with a qualitative analysis of the results.

Thesis Supervisor: Laurence Young
Title: Apollo Professor of Astronautics, Dept. of Aeronautics and Astronautics

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TABLE OF CONTENTS

TABLE OF FIGURES

Humanity will not remain on the Earth forever, but in the pursuit of light and space will at first timidly penetrate beyond the limits of the atmosphere, and then will conquer all the space around the Sun.

-Konstantine Tsiolkovsky, 1911

1. Introduction

Human exposure to long duration weightlessness results in a variety of debilitating effects including cardiovascular de-conditioning, bone loss, and muscle atrophy. Current countermeasures include the penguin suit, fluid loading, diet modification, lower body negative pressure, preflight adaptation training and in-flight exercise. Current countermeasures have proven somewhat successful in a number of areas, however, no countermeasure or combination of countermeasures have been able to preserve bone density. The limited success of current countermeasures has led scientists to consider artificial gravity as a possible solution. Short-term flights and space station missions are unlikely to warrant such an extreme countermeasure, as medical expertise is available on return to Earth. However, for long duration explorations such as a mission to Mars, medical support would not be available on arrival. Provision of artificial gravity during a trip to Mars may enable astronauts to maintain the ability to perform emergency extravehicular activities and avoid bone fractures when exposed to the gravity of Mars.

Provision of artificial gravity can take the form of a large rotating structure or a short-radius centrifuge. Large rotating structures like Von Braun's 125-foot torus spinning at 3rpm would provide continuous artificial gravity with minimal undesirable physiological effects (Young, 1999). Such structures are a complex engineering challenge, and extremely expensive. Short-radius centrifugation would provide intermittent gravity exposure, but would be significantly cheaper and less complex. However, short-radius centrifugation requires large angular velocities to obtain a force of 1G, this results in postural and vestibular disturbances. This report considers short-radius centrifugation rather than large rotating structures as the mechanism to provide artificial gravity.

Vestibular disturbances occur when the head is rotated about an axis which is itself on a device that is rotating about another axis. Out-of-Plane head movements made during short-radius centrifugation, results in stimulation of semicircular canal in planes not usually stimulated when making head turns in a stationary environment. This results in non-compensatory nystagmus, inappropriate perceived self-motion and in some cases motion sickness. In order for short-radius centrifugation to be considered as a viable alternative to current countermeasures, it is essential that astronauts are able to develop and retain adaptation to inappropriate eye reflexes and perceived sensations of self-motion, resulting from head turns during centrifugation. The ability to simultaneously retain two sensory programs, for rotating and non-rotating environments, would enable the astronaut to maintain appropriate spatial orientation and experience low motion sickness levels for active head movements in two different gravity environments. If this is proven not to be the case, a period of disorientation and motion sickness might occur each time the astronaut transitions to and from the short-radius centrifuge. Restricting head movements to avoid such conflicting stimuli is not desirable, as it would be extremely uncomfortable for long and repeated exposures and possibly inconsistent with the need for active exercise on the rotator.

Adaptation is defined as the development of an appropriate new response to a novel environment. This is different from habituation, which results in a reduced response to the conflicting sensory environment upon repeated exposure (Tang and Vidulich, forthcoming late 2000). Dual adaptation is the ability to adapt to a sensory rearrangement more rapidly and/or more completely after repeated experienced with it. Dual adaptation has been found to occur when subjects alternate repeatedly between adapting to the sensory rearrangement and readapting to the normal environment. This repeated alternating exposure fosters the development of a separate adaptation to each situation (Welch, Bridgeman and Williams, 1998). In Welch's experiment, subjects actively made head movements during alternating exposure to a visual-vestibular rearrangement (target/head gain = 0.5) and the normal situation (target/head gain = 0.0). These conditions produced adaptation and dual adaptation of the vestibulo-ocular reflex.

Another study by Welch, Anand and Browman (1993) involved subjects alternating between adapting their visuomotor coordination to a 30-diopter prismatic displacement and readapting to normal vision. In this experiment, dual adaptation was observed by the end of ten alternating cycles. The same paper describes how dual adaptation can be found in everyday situations. For example, after repeatedly donning and removing spectacles, wearers often report disappearance of depth distortions, illusory visual motion and coordination difficulties they had experienced earlier.

In our study, it is hypothesized that with repeated exposure to yaw head movements during short-radius centrifugation at 23rpm (with the subject lying supine and the head on the axis of rotation), adaptation and development of dual adaptation to head movements in the rotating environment will occur. The measures of adaptation were non-compensatory vertical nystagmus, inappropriate perceived self-motion sensations and motion sickness. Evidence exists from current literature to support our hypothesis. Guedry, (1965) found evidence for habituation to vestibular stimulation and retention of adaptation from rotation. Nystagmus and subjective effects were found to decrease after twelve days of rotation, and responses were suppressed compared with initial levels two days and three weeks after rotation. Retention of adaptation to motion sickness has also been found by Senqi and Stern, (1999). That study found that adaptation to motion sickness eliciting stimulation of optokinetic rotation is almost completely retained for one month and partially retained for one year.

2. Background

2.1 Current Countermeasures

The following section provides an outline of the effects of micro-gravity on skeletal muscles, bones and the cardiovascular system. Each section describes the current countermeasures used, and outlines the success or limitations of current techniques. Where applicable, a justification for artificial gravity is given, and the potential benefits described. Further information on this topic can be found from the NASA task force on countermeasures final report, May 1997.

The musculoskeletal system has evolved over millions of years and adapted to the gravity environment of Earth. In microgravity, muscles need no longer perform work against Earth's gravity. Exposure to this state of unloading results in atrophy of primarily slow-twitch muscles (fast-twitch muscles also experience atrophy, but are affected less than slow-twitch muscles), and a reduction in muscle force and power generating properties. Astronauts exposed to prolonged space flight exhibit reduced strength, power and musculoskeletal endurance. Such deficits will undoubtedly impair the astronaut's ability to perform strenuous extravehicular activity and the ability to perform high intensity egress activities. Countermeasures currently used to maintain the skeletal muscle system involve exercise, using treadmills, rowing devices and cycle ergometers. Exercise programs using the devices mentioned above enhance endurance but fail to provide large resistance forces. Ground based experiments have shown that heavy resistance exercises are the most effective at preventing muscle atrophy and loss of muscle strength. Evidence from both the American and Russian space programs indicate that the exercise programs and other countermeasures have been marginally successful in slowing muscle structure and function deficits. Provision of artificial gravity combined with exercise (for example, a human powered short arm centrifuge), would enable astronauts to exercise in a gravity environment, providing both endurance and heavy resistance training.

In the absence of gravitational stresses, bones start releasing calcium salts, the mineral responsible for bone strength. The lost of calcium is measured by testing for increased calcium in urine and post-flight bone density tests. Calcium loss begins slowly in the first week and increases gradually over the next several months. The average whole body loss rate is 0.5% per month, with peak loss rates of 3-5% per month in weight-bearing bones (Churchill, 1997). Unlike other physiologic adaptations, calcium loss did not reach a plateau during the 84 day Skylab mission. Reduction in bone calcium results in decreased bone and muscle strength. This reduction in strength is likely to increase the chance of bone fractures in the event of a fall. Another concern is the rapid increase in urinary calcium, which may increase the risk of kidney stone formation. The mechanism by which bone calcium is lost in microgravity is poorly understood. Current countermeasures include primarily exercise and some dietary measures. Current Mir exercise programs have been unsuccessful in inhibiting flight related bone loss, and nutritional requirements have not been established. Provision of artificial gravity could potentially reduce or eliminate bone loss during spaceflight. However, little is known about the level or duration of artificial gravity required to prevent bone loss.

In spaceflight, blood which is normally pulled to the legs due to gravity moves to the area of least resistance, the venous vessels in the chest. The body interprets this to mean that the body is overfilled and adjusts the mechanical determinants of arterial pressure. The kidneys also excrete extra fluid in the form of urine. Problems occur when astronauts return to a gravity environment, the gravitational pull results in blood pooling from the chest to the legs. The effective circulating volume is considerably smaller, resulting in dizziness or even fainting. This phenomenon is called orthostatic intolerance and is due to the inability to maintain blood pressure. Orthostatic intolerance may seriously affect an astronaut's ability to egress the space vehicle following reentry in the case of an emergency landing. Current countermeasures used to protect orthostatic tolerance include, consuming salt tablets before reentry to restore plasma and blood volume, wearing anti-g suits during reentry to prevent blood from pooling to the legs and in-flight exposure to lower body negative pressure. Provision of artificial gravity in space would replace the physiological stimuli to the cardiovascular system and simultaneously protect aerobic capacity if exercise was performed on the centrifuge.

2.2 Physics of rotating environments

The centrifugal force is an inertial force, which appears if the motion of a particle is analyzed from the standpoint of a rotating reference frame. Centrifugal force is the artificial equivalent (artificial gravity) to the gravitational force on Earth. There are four major features that cause artificial gravity to be different from real gravity. These features fall into two categories, static and dynamic features. Static features include the artificial gravity level (generated by the centrifugal force) and gravity gradients. Dynamic features include Coriolis forces and cross-coupled angular accelerations. The distinction between the two categories lies with the state of the person or object relative to the artificial gravity environment. Forces acting on a human in a large rotating structure have been well documented (Stone, 1970). The following discussion will focus on the forces generated in the particular case of a short-radius centrifuge. The following section discusses the centrifugal force, Coriolis force, gravity gradients and the effect of making head turns in a rotating environment on the semicircular canals (this discussion includes cross-coupled angular accelerations).

2.2.1 Centrifugal force

The centrifugal force is an inertial force that always appears if the motion of a particle is described and analyzed from the standpoint of a rotating reference frame. In order to fully understand the centrifugal force, analysis of the forces acting on a subject on the rotating centrifuge will take place both in the stationary and rotating frames of reference.

(a) Analysis in the stationary frame of reference.

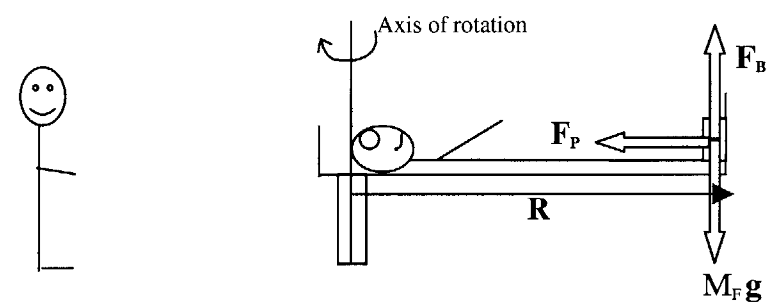


FIGURE 1-FORCES ACTING ON THE SUBJECT'S FEET ON THE ROTATING SHORT-RADIUS CENTRIFUGE, AS VIEWED FROM THE STATIONARY FRAME OF REFERENCE.

Figure 1 shows a subject rotating at constant velocity, on a short-radius centrifuge. The axis of rotation is at the top of the subject's head. The key parameters are defined as follows; ω = Angular velocity, **R** = Radius of Rotation (also equal to the height of the subject), $\mathbf{F_P}$ = Reaction force of foot-plate on the subject's feet, $M_F\,\mathbf{g}$ = Force due to gravity acting on the subject's feet, where M_F represents the mass of the subject's feet, and $\mathbf{F_B}$ = Reaction force of centrifuge on subject's feet. Forces (different magnitudes) act at all points along the subject's body, however for simplicity the following discussion will focus only on the forces acting at the subject's feet. The force diagram in Figure 1 represents the ideal situation where the subject is levitated on the centrifuge, and hence the reaction force is provided solely by the footplate. In reality the person remains at rest due to both the reaction force of the footplate and the frictional force due to the subject lying on the centrifuge.

From the standpoint of the stationary (inertial) frame of reference, the feet have an acceleration ($\omega^2\mathbf{R}$), towards the axis of rotation. The force that causes this acceleration on the feet is $M_F\omega^2\mathbf{R}$. The feet are also being pushed radially by the inertial force from the rest of the body (neglecting the frictional force between the body and the centrifuge), given by $(M_B-M_F)\mathbf{r}'\omega^2$, where M_B is the body mass and $\mathbf{r}'$ is the distance from the axis of rotation to the position of the center of mass of the body minus the mass of the feet. The net force $\mathbf{F}_R$ causing the acceleration towards the axis of rotation is supplied by the reaction force of the footplate on the feet. Therefore

$$\mathbf{F}_R = M_F\,\mathbf{R}\omega^2 + (M_B-M_F)\mathbf{r}'\omega^2 \qquad (1)$$

(b) Analysis in the rotating frame of reference.

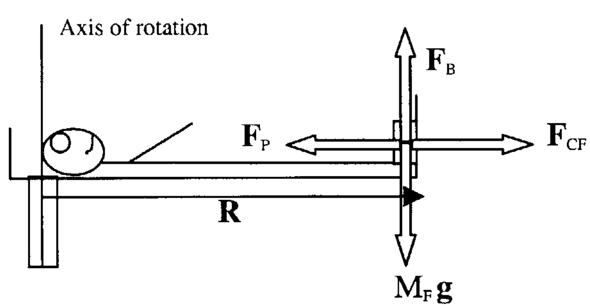


FIGURE 2-FORCES ACTING ON THE SUBJECT'S FEET ON THE ROTATING SHORT-RADIUS CENTRIFUGE, AS VIEWED FROM THE ROTATING FRAME OF REFERENCE.

Figure 2 shows the forces acting on the subject's feet from the standpoint of the frame of reference that rotates with the centrifuge, i.e. the subject's perspective. The acceleration of the subject's feet as viewed by the subject is zero. In order to maintain the validity of Newton's law in the rotating frame of reference, in addition to $\mathbf{F}_R$, the feet experience an inertial force $\mathbf{F}_{CF}$ which is equal and opposite to $\mathbf{F}_R$, and hence directed radially outwards. In the rotating frame of reference, the net horizontal force is given by equation 2

$$\mathbf{F}_{CF} + \mathbf{F}_R = 0 \qquad (2)$$

Hence,

$$\mathbf{F}_{CF} = M_F \omega^2 \mathbf{R} + (M_B - M_F)\mathbf{r}'\omega^2 \qquad (3)$$

where $\mathbf{F}_{CF}$ is the centrifugal force. It is this force which acts radially outwards from the feet that is referred to as artificial gravity. If all the body except the feet were restrained by friction and the feet had no frictional force, only the first term in equation 3 would apply.

The centrifugal force does not act solely at the subject's feet, but along the entire body. However, because the centrifugal force is proportional to the radius of rotation, the centrifugal force decreases in value along the body, until the force is zero at the head. Due to the Earth's gravity vector, the net force experienced will be the resultant of the centrifugal force and weight. In space the gravity component of Earth will be absent and only the centrifugal force will be present.

The centrifugal force creates a gravity gradient along the subject's body. By approximating the human body to a rectangle of suitable dimensions, and approximating the body density to that of water (since humans consist of 90% water), the total net centrifugal force has been calculated by integrating along the body. The various steps in the calculation are outlined below, in addition to a comparison with the net gravitation force exerted by the gravitational pull of Earth.

(a) Consider the body to be a rectangle with the following dimensions

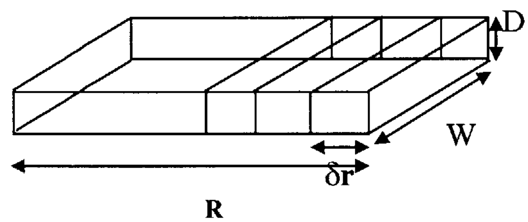


FIGURE 3-A RECTANGULAR BLOCK DIVIDED INTO SECTIONS OF LENGTH δR, WIDTH W AND DEPTH D.

(b) If the body is divided into sections of length **δr**, the total centrifugal force acting on the body is obtained by integrating over the entire length of the body, from 0 to **R**, assuming ρ (density) is not a function of **R** .

$$\mathbf{F}_{CF} = \rho DW\ \omega^2 \int_0^R \mathbf{r\,dr} \tag{4}$$

$$\mathbf{F}_{CF} = \rho DW\ \omega^2(\mathbf{R}^2)/2 \tag{5}$$

More simply, equation 5 represents the centrifugal force of the center of mass acting half way down the body.

(c) If one considers a typical person, with the following dimensions

Width (W) = 0.45m, Depth (D) = 0.2m and Density (ρ) = 1000kg/m^3 (water).

$$\mathbf{F}_{CF} = 45\omega^2\mathbf{R}^2 \tag{6}$$

For a person of typical height 5ft5ins = 1.651m, exposed to 1**g** at the feet (ω = 2.4rads/sec or 23 revs per min), the total centrifugal force is 706N. For the same person standing in the gravity field of Earth, the total force due to the gravitational pull of Earth = **Mg**, where M is the total mass of the person (M = ρ**R**DW), therefore Weight = 1457.66N. Therefore, when the above subject is exposed to the same gravity as on Earth at the foot of the centrifuge, the total centrifugal force acting on the body is 48.4% of that experienced on Earth.

In the general case

- The total integrated centrifugal force = $\rho DW\ \omega^2(\mathbf{R}^2)/2$
- The total force due to the gravitational pull of Earth = **Mg**, where M is the total mass of the person and **g** is the acceleration due to gravity = $\rho DW\mathbf{Rg}$
- The ratio of total centrifugal force to the gravitational pull of Earth

$$\mathbf{F}_{CF}/\mathbf{F}_{FE} = (\rho DW\ \omega^2(\mathbf{R}^2)/2)/\rho DW\mathbf{Rg} \qquad (7)$$

Hence

$$= \omega^2\mathbf{R}/2\mathbf{g} \qquad (8)$$

It can be seen that the ratio is dependent on the variables ω and **R**. In the case where the total centrifugal force is required to be equal to the gravitational force experienced on Earth, the ratio

$$\mathbf{F}_{CF}/\mathbf{F}_{FE} = 1 \qquad (9)$$

Therefore,

$$\omega^2\mathbf{R} = 2\mathbf{g} \qquad (10)$$

Figure 4 shows ω against **R** for this case. Therefore for subjects of varying heights **R**, the corresponding ω reflects the required angular velocity for the subject to experience an overall centrifugal force equal to the gravitational force experienced on Earth.

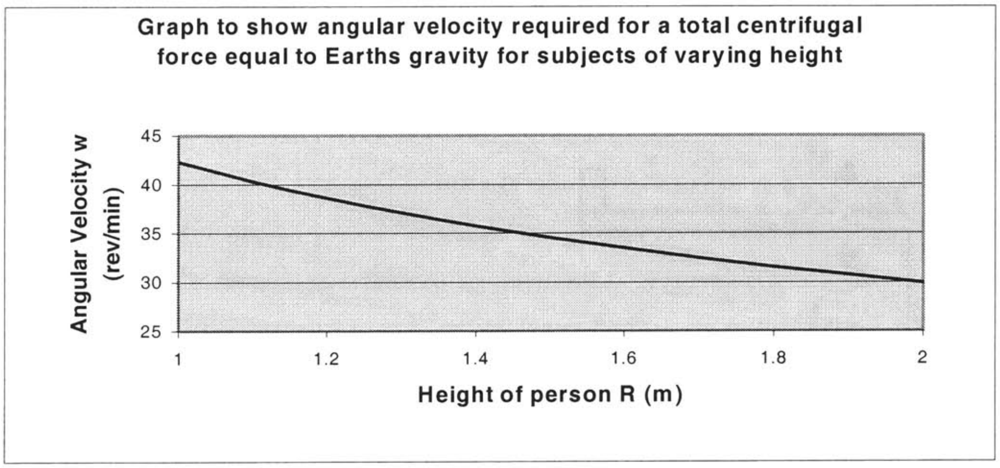


FIGURE 4-ANGULAR VELOCITY REQUIRED FOR A TOTAL CENTRIFUGAL FORCE EQUAL TO EARTHS GRAVITY, FOR SUBJECTS OR VARYING HEIGHT WITH THE CENTER OF ROTATION AT THE HEAD.

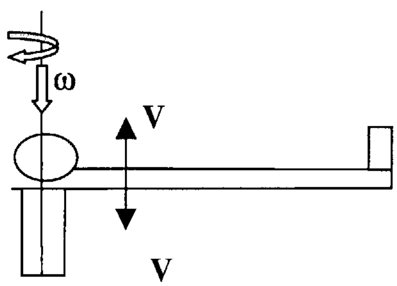
2.2.2 Coriolis force

The Coriolis force is an inertial force, which appears in a rotating environment. The force is applied to an object moving linearly within the rotating environment, and deflects the object at right angles to the direction of motion. The magnitude of the Coriolis force depends on the velocity of the object and not its position. The Coriolis force as observed in the rotating frame of reference is given by

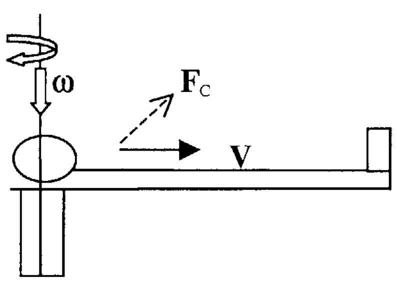
$$\mathbf{F}_C = -2m(\boldsymbol{\omega}\times\mathbf{V}), \qquad (11)$$

Where m = mass of moving object, ω = angular velocity of rotating environment and **V**= linear velocity of particle. It can be seen from equation 11 that any object moving in a direction not parallel to the axis of rotation will experience Coriolis forces. Figure 5 illustrates the direction of the Coriolis force for various hand movements on a short-radius centrifuge, rotating clockwise.

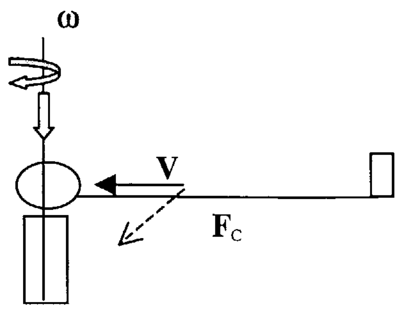
(a) Moving up and down parallel to the axis of rotation, $\mathbf{F}_C = 0$



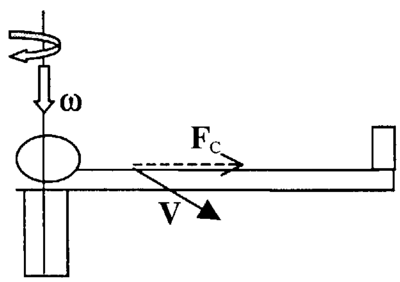
(b) Moving forwards, $\mathbf{F}_C$ left



(c) Moving backwards, $\mathbf{F}_C$ right



(d) Moving to the right, $\mathbf{F}_C$ forwards



(e) Moving to the left, $\mathbf{F}_C$ backwards

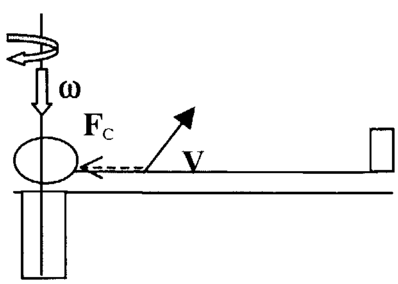


FIGURE 5-DIRECTION OF THE CORIOLIS FORCE FOR VARIOUS HAND MOVEMENTS ON A SHORT-RADIUS CENTRIFUGE, ROTATING CLOCKWISE.

Coriolis forces are likely to cause postural problems when arms and legs move in a non-parallel direction to the axis of rotation.

2.2.3 Gravity gradients

Short-radius centrifugation exposes the body to a 100% gravity gradient, with 0 gravity at the head (providing the head is centered on the axis of rotation) and 100% gravity at the feet. The gravity gradient is due to the dependence of the centrifugal force on the radius of rotation. Large gravity gradients (>1g at the feet) affect the cardiovascular system and cardiovascular parameters. Further details can be obtained from Hastreiter (1997).

2.2.4 Effect of making head turns in a rotating environment on the semicircular canals

Rotation of the head (or whole body) about an axis which is itself on a rotating platform about a different axis, results in instantaneous accelerations about a third axis. Turning the head in such a rotating environment generates cross-coupled angular accelerations that induce motion of the fluid in the semicircular canals. This induced motion is not normally stimulated in the orthogonal direction when making head turns in a stationary environment. In addition to the cross-coupling stimulus, vertical semicircular canals are being brought in and out of the plane of rotation during yaw head movements when lying supine on a centrifuge. This results in a velocity change (either increase or decrease) equal to the angular velocity of the centrifuge, in the plane of the canals. This velocity change causes fluid motion in the vertical semicircular canals, resulting in illusory sensations of self or environmental motion. The vestibular stimulation conflicts with the visual stimulation. This conflict is thought to cause motion sickness (Oman, 1998). In order for the reader to fully understand the effects of making head turns in a rotating environment on the semicircular canals, a detailed description of the vestibular system is given, followed by an explanation of cross-coupled angular acceleration, and the effect on the canals of rotation into and out of the plane of rotation of the centrifuge. The section concludes with a description of the Sensory Conflict Theory of motion sickness.

The Vestibular System

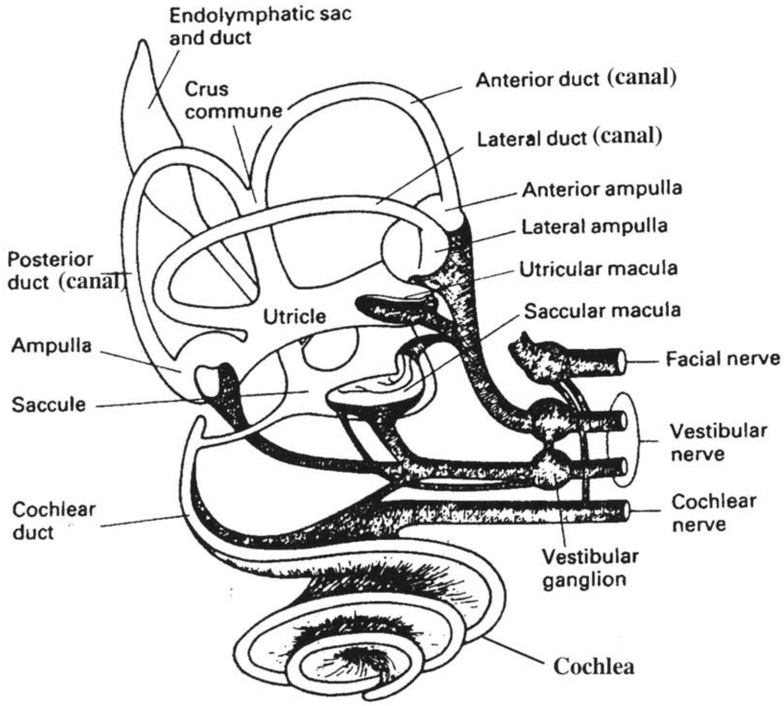


FIGURE 6-THE VESTIBULAR SYSTEM

The inner ear (Figure 6) consists of both the auditory and vestibular systems[1]. The cochlea is the organ of hearing and the vestibular apparatus is the organ of equilibrium. The vestibular organ consists of the semicircular canals and the otolith organs. The three semicircular canals (anterior, posterior and lateral canals) detect angular accelerations, and the otolith organs (saccule and utricle) detect linear acceleration and gravity. Humans have two vestibular apparati, one on each side of the head.

[1] For further details of the vestibular system see Ernstinh, Nicholson and Rainford, 1999

Semicircular Canals

Angular acceleration (magnitude and direction) of the head is detected by the semicircular canals. The three canals are positioned approximately orthogonal to each other, this enables detection of rotation about three axes. The three canals are called the anterior, posterior and lateral canal. When the head is tilted forwards approximately 30-degrees while standing upright, the plane of the lateral canal is horizontal and the plane of the anterior and posterior canals are approximately vertical. The anterior canals project forward and outward by approximately 45-degrees, and the posterior canals project backwards and outwards by approximately 45-degrees. Although the canals do not lie in the roll, pitch and yaw axes of the skull, the brain is able to resolve the rotation detected by the receptors in the canals (into these orthogonal axes). For simplicity, future discussions will equate anterior, posterior and lateral with the head axis, and use the terms roll, pitch and yaw canals. Figure 7 shows the planes of the semicircular canals with respect to the head.

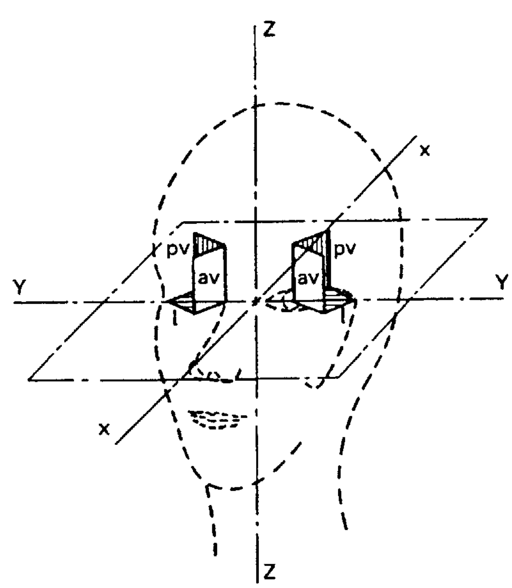


FIGURE 7 – PLANES OF THE SEMICIRCULAR CANALS WITH RESPECT TO THE HEAD. X,Y AND Z ARE THE PRINCIPLE AXES OF THE HEAD. L, AV AND PV REFER RESPECTIVELY TO THE LATERAL (HORIZONTAL), ANTERIOR VERTICAL AND POSTERIOR CANALS.

The canals are filled with a viscous fluid called endolymph. Near the junction of the canals with the utricle, each canal swells to form the ampulla, as shown in Figure 6. The sensory cells are located on the floor of the ampulla, in a saddle-shaped ridge called the crista ampullaris. Extending from the sensory cells is the cupula, which forms a seal across the ampulla. It is the cupula that prevents the endoylmph fluid from freely circulating. Bundles of hair cells called cilia project from each sensory cell in the crista ampullaris, and project up into the cupula. Within each bundle, the longest hair cell is called the kinocilium, with the other hair cells (stereocilia) being graded in length, with the shortest being farthest from the kinocilium. The resting discharge of the hair cells increases when the cilia are deflected towards the kinocilium and decreases when the cilia are deflected away from the kinocilium. Deflection of the cupula, and hence the hair cells, is caused by movement of the endolymph within the canal. This results in transmission of afferent signals to the vestibular nuclei, then the ocular-motor nuclei and then the cerebellum and cerebral cortex. Figure 8 shows a view of the ampulla of a semicircular canal, the sensory cells and the cupula.

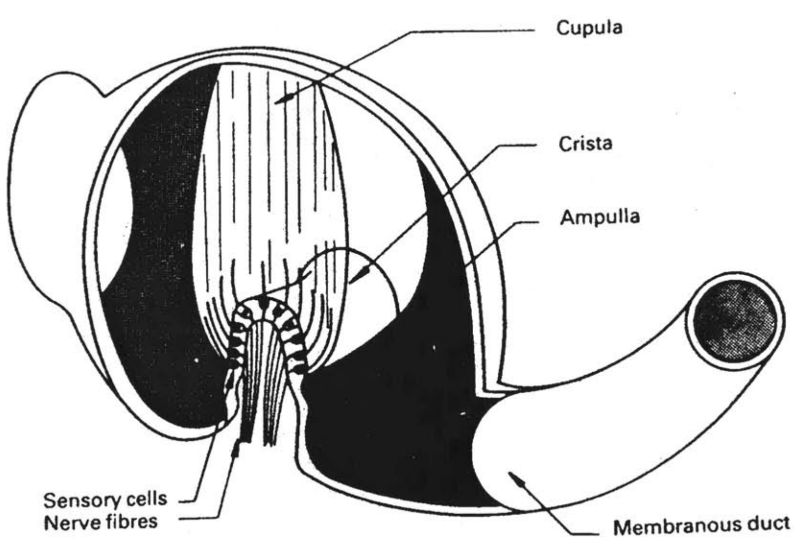


FIGURE 8 – A CUT-AWAY VIEW OF THE AMPULLA OF A SEMICIRCULAR CANAL TO SHOW THE SENSORY CELLS AND CUPULA.

During a head turn the semicircular canals and the whole of the labyrinth move with the head. The endolymph fluid in the canals that lie in the plane of rotation lags behind the movement of the canal walls due to inertia. Thus, during angular acceleration the cupula is deflected in the opposite direction to the head rotation, due to the force between the cupula and the endolymph. The displacement of the cupula changes the afferent firing rate and therefore sends signals to the brain regarding head velocity. Figure 9 shows how the cupula is deflected by an angular acceleration in the plane of the semicircular canal.

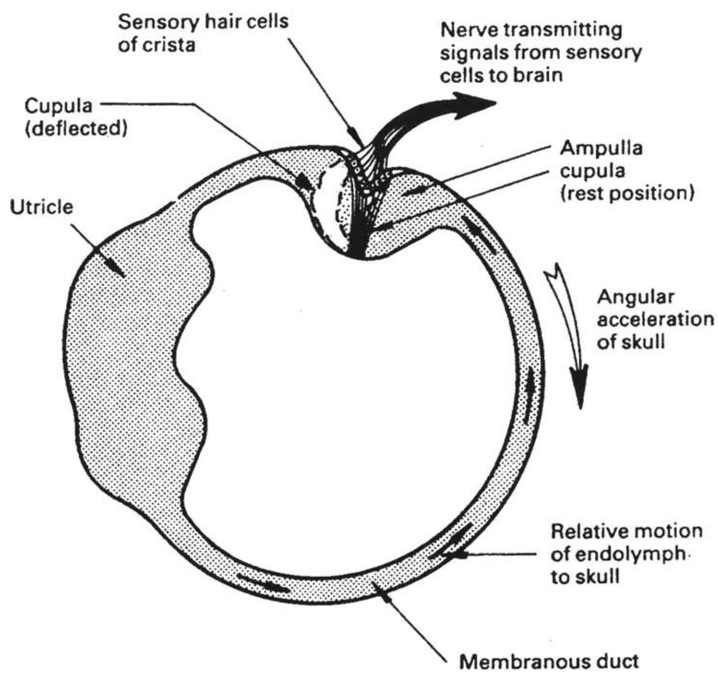


FIGURE 9 – CUPULA DEFLECTION BY AN ANGULAR ACCELERATION IN THE PLANE OF THE SEMICIRCULAR CANAL. THE RING OF ENDOLYMPH RESISTS ANGULAR ACCELERATION BECAUSE OF ITS INERTIA, AND A FORCE IS EXERTED ON THE CUPULA WHICH CAUSES IT TO BE DEFLECTED.

During a normal head movement in a non-rotating frame of reference, angular acceleration is followed immediately by angular deceleration. In this situation the cupula deflection and the associated signals from the sensory cells closely match the angular velocity of the head. This results in the correct sensation of a head turn. If the head continues to rotate at constant velocity, viscous forces between the canal and the endolymph, cause the endolymph to catch up with the canal and the cupula returns to the neutral position with a time constant of approximately 6 seconds (Liefeld, 1993). Continued rotation at a constant rate therefore produces no sensation of angular motion. On cessation of rotation, the fluid pushes against the neutrally positioned cupula and deflects it in the opposite direction. The subject experiences rotation in the opposite direction. The cupula then decays back to its neutral position. The semicircular canals are stimulated by angular acceleration, however, the neural output from the sensory cells represents the angular velocity of the canal. This means that the canal is effectively performing a mathematical integration of the input signal.

Gaze Stabilization[2]

During normal head movements, the gaze of the eyes may remain stabilized on a point in space (even in the dark). This stabilization is achieved by the vestibular system sending signals directly to the muscles that move the eyes. The vestibulo-ocular reflex (VOR) and nystagmus are the two main eye movements that result from activation of the vestibular system. The VOR enables one to maintain unblurred vision during head movements. If the head is turned to the left, information from the semicircular canals causes the eye to turn in the opposite direction, to the right. This compensatory eye movement occurs at the same velocity as the head movement. It is this eye movement reflex which enables the retina to remain fixed in the same point in visual space during head turns.

Nystagmus is an involuntary movement of the eye and consists of a slow phase in one direction and a fast phase (saccade) in the opposite direction. During small angles of head rotation, the compensatory eye movements created by VOR are sufficiently small to remain within the mechanical limits of eye rotation. During large angles of head rotation, the eyeball will reach a large deflection (10-30 degrees) before completion of the head

[2] For more information on vestibulo-ocular reflex and nystagmus, see Balkwill (1992)

movement. In this situation, the eye is rapidly reset back to continue a new cycle of compensatory eye movements. This results in a saw-tooth pattern of eye movements, consisting of alternating slow compensatory eye movements in the opposite direction to the head turn, and rapid resetting eye movements in the direction of the head turn. Three axes of vestibular nystagmus can occur, these consist of horizontal, vertical and torsional.

Head Turns in a rotating environment

Head turns in a rotating environment bring about two effects. When the head is rotated about an axis with angular velocity ω_H, which is itself on a centrifuge that is rotating about another axis with angular velocity ω_C, there is an accompanying orthogonal angular acceleration. The magnitude and direction of this accompanying orthogonal acceleration is given by the cross product of the two angular velocity vectors.

$$\text{Cross-coupled orthogonal acceleration} = -(\omega_C \times \omega_H). \qquad (12)$$

This stimulus is only present during the head turn (which took approximately 1 second in our experiment). The second effect is due to the cupula of the canal in the plane of rotation, returning to the neutral position after several seconds of constant rotation. When a canal is taken out of the plane of rotation, it experiences a change in angular velocity equal to the angular velocity of the centrifuge. Unlike head turns in the stationary environment, the canal does not experience acceleration and then deceleration, which results in the cupula following closely the profile of the angular velocity. Following the head turn, the cupula decays back to the neutral position, with a time constant of 6 seconds. During this time the subject experiences sensations of self-motion, which last for several seconds. This second effect lasts much longer than the cross-coupling effect, and is therefore the dominant sensation. The following discussion considers firstly the effect of the cross-coupled orthogonal acceleration on the semicircular canals during head turns, and secondly the effect of moving canals in and out of the plane of rotation after the cupula has returned to the neutral position.

Cross-coupled angular acceleration

Consider a subject lying supine on a clockwise rotating centrifuge. x, y and z represent the orthogonal axes in the stationary frame of reference, where **i, j** and **k** are the corresponding unit vectors in the x, y and z directions respectively. x', y' and z' represent the orthogonal axes in the rotating frame of reference of the centrifuge, where **i'**, **j'** and **k'** are the corresponding unit vectors in the x', y' and z' directions respectively. Figure 10 shows the rotating and stationary frames of reference with the orthogonal axes labeled.

Rotating frame of reference

Stationary frame of reference

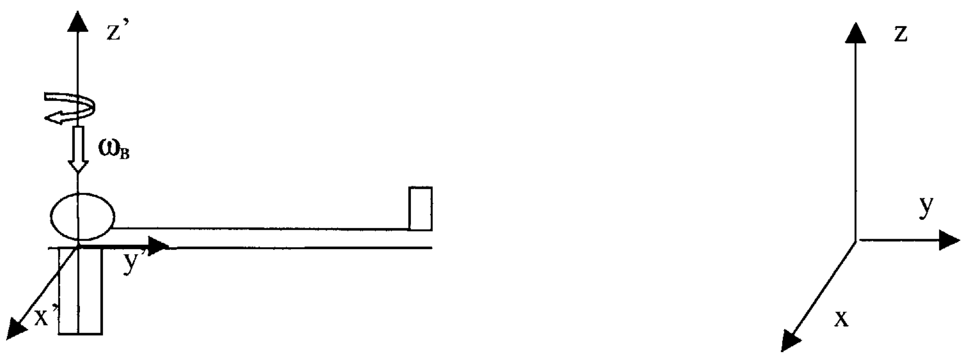


FIGURE 10 – ORTHOGONAL COORDINATE AXES IN THE ROTATING AND STATIONARY FRAMES OF REFERENCE

In the stationary frame of reference, the centrifuge has an angular velocity = $-\omega_C\mathbf{k}$. A yaw head movement from right ear down (RED) to nose up (NU) in the rotating frame of reference, results in a head angular velocity = $-\omega_H\mathbf{j}'$. Analysis of a vector **A**, which is on a rotating centrifuge of angular velocity ω_C, and viewed from a stationary frame of reference lead to the general expression

$$(d\mathbf{A}/dt)_S = (d\mathbf{A}/dt)_{S'} + \omega_C \times \mathbf{A} \qquad (13)$$

where **A** is any vector, S represents the quantities in brackets as observed from the stationary frame of reference, S' represents the quantities in brackets as observed from the rotating frame of reference and ω_C is the angular velocity of the centrifuge. By choosing **A** to be the position vector and linear velocity, results in the general expression for linear acceleration in a rotating environment.

$$\mathbf{a}' = \mathbf{a} - 2(\omega_C \times \mathbf{v}') - [\omega_C \times (\omega_C \times \mathbf{r})] \tag{14}$$

where **a**' is the acceleration as observed in S', **a** is the acceleration as observed in S, $-2(\omega_C \times \mathbf{v}')$ is the Coriolis acceleration acting on a body with linear velocity **v**' (as observed in the rotating frame of reference) and $[\omega_C \times (\omega_C \times \mathbf{r})]$ is the centrifugal acceleration, where **r** is distance from the axis of rotation. A similar analysis can be performed using angular displacement and angular velocity rather than linear displacement and velocity, where the angular velocity on the centrifuge is caused by the subject making yaw head movements. The same analysis in angular terms yields

$$\alpha_H' = \alpha_H - (\omega_C \times \omega_H') - (\omega_C \times \omega_H) \tag{15}$$

where α_H' is the angular acceleration acting on the subjects head as viewed from the rotating frame of reference, α_H is the angular acceleration acting on the subjects head as viewed from the stationary frame of reference, ω_C is the angular velocity of the centrifuge as viewed from the stationary frame of reference, ω_H' is the angular velocity of the head as viewed from the rotating frame of reference and ω_H is the angular velocity of the head as viewed from the stationary frame of reference. The dominant term in equation 15 is the cross-coupling term given by $-(\omega_C \times \omega_H')$, this term represents the magnitude and direction of the cross-coupling acceleration, caused by making head turns about an axis which is different to the axis of rotation of the centrifuge. For more details regarding this derivation see French and Ebison, (1986).

Using the head and centrifuge angular velocity vectors in equation 12 (the cross-coupling term), results in a cross-coupled angular acceleration in the frame of reference of the centrifuge = $\omega_C\omega_H\mathbf{i'}$. Firstly, consider a subject with their head in the RED position. In this position, the pitch canal is not stimulated by the cross-coupled acceleration, which acts about the x' coordinate. As the subject makes a head turn to the NU position, the pitch canal receives maximum stimulation from the cross-coupled acceleration. The magnitude of the cross-coupled acceleration applied to the pitch canal is = $\omega_C\omega_H$, modulated by a sin function to take account of the fact that the pitch canal changes orientation with respect to the stimulation axis. Therefore, the angular cross-coupled acceleration acting on the pitch canal during a yaw head turn from RED to NU,

$$= \omega_C\omega_H(t)\sin(\omega_H(t)t), \qquad (16)$$

where t is time.

The angular velocity profile of the head is a function of time, $\omega_H(t)$ starts at 0 at t = 0, accelerates to peak velocity and decelerates, so the velocity is 0 when the turn angle is 90 degrees. The angular cross-coupled stimulus is modulated by this velocity profile. Just like a normal head movement when angular acceleration is followed shortly by deceleration, the cupula deflection in the pitch canal closely matches the cross-coupled velocity stimulus. The cupula is therefore deflected and returns to the neutral position in approximately the same time taken to complete the 90-degree head turn. This deflection should give a brief pitching sensation, but is probably insignificant compared to the sensation resulting from taking the pitch canal out of the plane of rotation.

The same reasoning can be applied to the roll canal. In the RED position, the roll canal experiences maximum stimulation by the cross-coupled acceleration. As the subject turns to the NU position, the roll canal is not stimulated by the cross-coupled angular acceleration. The cross-coupled angular acceleration acting on the roll canal during head turn from RED to head up is given by

$$= \omega_C \omega_H(t)\cos(\omega_H(t)t), \quad (17)$$

Since the angular velocity of the head consists of acceleration shortly followed by deceleration back to 0, the cupula deflection in the roll canals closely matches the angular velocity of the head. The cupula is therefore deflected and returns to the neutral position in the time taken to complete the 90-degree head turn. This deflection gives a brief sensation of rolling clockwise, but is probably insignificant compared to the sensation resulting from turning the roll canal into the plane of rotation. The yaw canal is unaffected by the angular cross-coupled acceleration during the head turn. Instead, the yaw canal experiences the normal head acceleration and deceleration, which results in the normal cupula response.

Turning canals into and out of the plane of rotation

In addition to the cross-coupling acceleration described above, a second effect occurs when the canals are taken in and out of the plane of rotation, this effect dominates the sensations experienced during such head turns. Consider a subject lying RED on a clockwise rotating centrifuge as shown in figure 11.

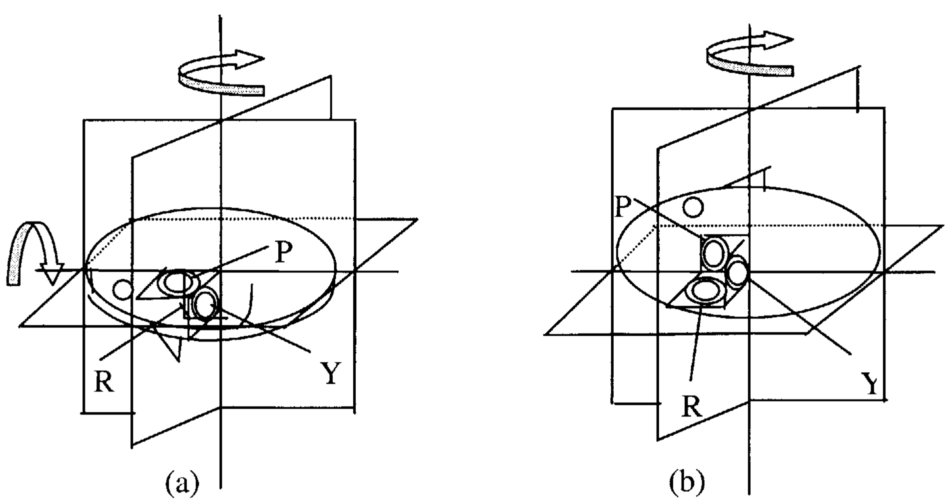


FIGURE 11 – POSITION OF THE SEMICIRCULAR CANALS DURING A 90-DEGREE YAW HEAD TURN FROM (A) RED TO (B) NU, ON A CLOCKWISE ROTATING PLATFORM.

In this position the pitch canal is in the plane of rotation. If the centrifuge rotates at constant velocity, after several seconds the cupula which was initially deflected due to being placed in the plane of rotation, returns to the neutral position. During a head turn from RED to NU, the pitch canal is taken out of the plane of rotation. The pitch canal experiences a change in angular velocity, equal to the angular velocity of the centrifuge (23rpm in our experiment). The endolymph decelerates in the clockwise direction with respect to the canal after the head turn, this should cause the subject to feel a sensation of pitching forwards. Unlike a normal head movement, which consists of a head acceleration closely followed by a deceleration, only a deceleration is present. Rather than the cupula closely following the velocity profile, like in a normal head turn, the absence of an acceleration immediately after the deceleration causes the cupula to decay back to the neutral position with a time constant of 6 seconds. This decay time is much greater than the 1 second cupula deflection due to the cross-coupled angular accelerations experienced during head turns.

The response of the cupula to a change in angular velocity in the plane of the canal can be modeled as a first order system. A modified Young-Oman Laplace transfer function model (Young & Oman, 1969) for rotation in the dark was used to model the cupula response to head turns on the rotating centrifuge. The cupula dynamics are assumed to be a simple exponential decay with a gain K = 1, and time constant Tc = 6 seconds. The adaptation effects are treated as another exponential decay in series with the cupula with a time constant Ta = 80 seconds. Figure 12 shows the modified Young-Oman Laplace transfer function model for the canal dynamics.

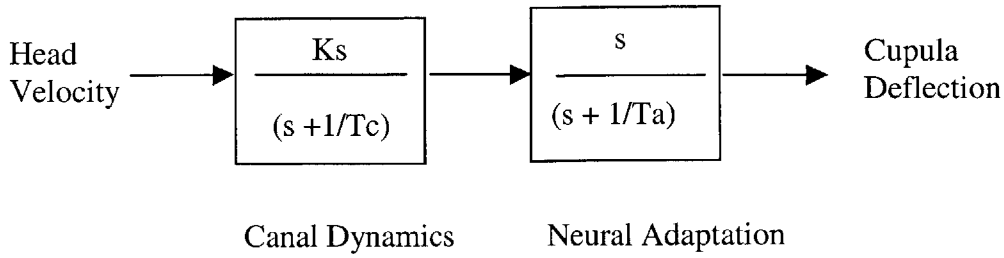


FIGURE 12 - MODIFIED YOUNG-OMAN LAPLACE TRANSFER FUNCTION MODEL FOR THE CANAL RESPONSE TO ROTATION.

Equation 18 represents the open loop transfer function for the system described in figure 12

$$= ks^2/((s+1/Tc)(s+1/Ta)) \quad (18)$$

The change in angular velocity in the plane of the pitch canal was modeled as a ramp change from 23rpm to 0rpm (where 23rpm is the angular velocity of the centrifuge in our experiment). Figure 13 shows the angular velocity in the plane of the pitch canal during a RED to NU head turn, and the response of the cupula.

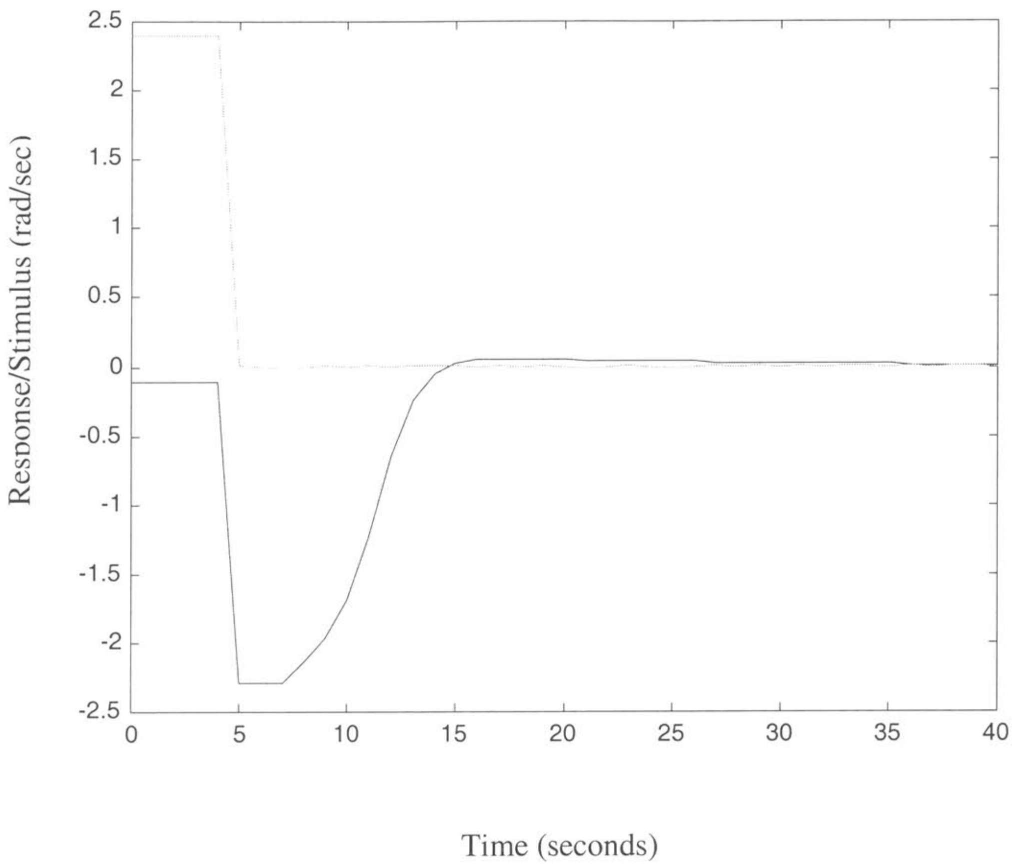


FIGURE 13 - RESPONSE OF THE CUPULA (BLACK) TO A VELOCITY CHANGE OF 23PRMS (2.4 RADIANS/SEC) IN ONE SECOND IN THE **PITCH CANAL** (DOTTED GREY), USING A MODIFIED YOUNG-OMAN LAPLACE TRANSFER FUNCTION MODEL

The roll canal is initially out of the plane of rotation (figure 11), the cupula is therefore in the neutral position. During a head turn from RED to NU, the roll canal is moved into the plane of rotation. The roll canal experiences a change in angular velocity of 23rpm (during the time taken to make a head turn (1 second)). The endolymph accelerates in the counterclockwise direction during the head turn, deflecting the cupula. This should cause the subject to feel a sensation of clockwise roll. Figure 14 shows the angular velocity in the plane of the roll canal during a RED to NU head turn, and the response of the cupula.

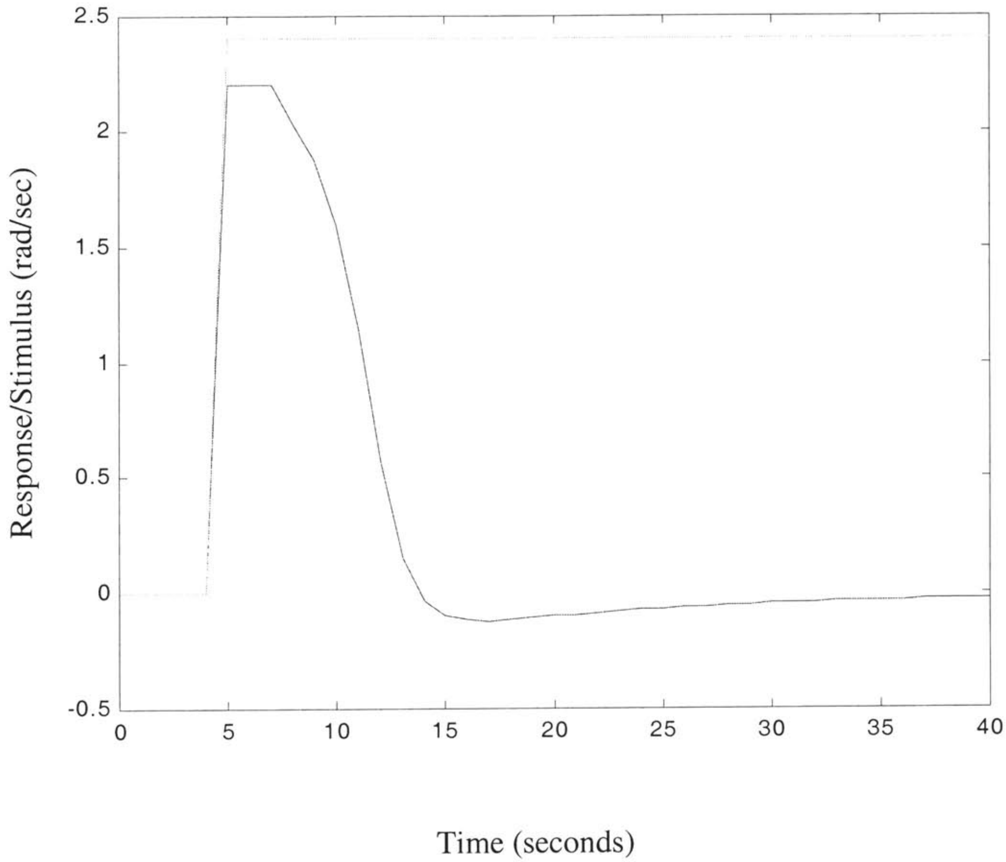


FIGURE 14 - RESPONSE OF THE CUPULA (BLACK) TO A VELOCITY CHANGE OF 23PRMS (2.4 RADIANS/SEC) IN ONE SECOND IN THE **ROLL CANAL** (DOTTED GREY), USING A MODIFIED YOUNG-OMAN LAPLACE TRANSFER FUNCTION MODEL.

The yaw canal is orthogonal to the plane of rotation of the centrifuge, and therefore experiences the normal acceleration and deceleration present during yaw head turns in a stationary environment. The yaw head turn lasts one second and the head rotates through an angle of 90-degrees (peak angular velocity of head = 3.14rads/sec). Figure 15 shows the angular velocity in the plane of the yaw canal during a RED to NU head turn, and the response of the cupula. In this case the cupula closely follows the profile of the angular velocity in the plane of the canal, the subject therefore does not experience any unusual sensations of self-motion in this plane.

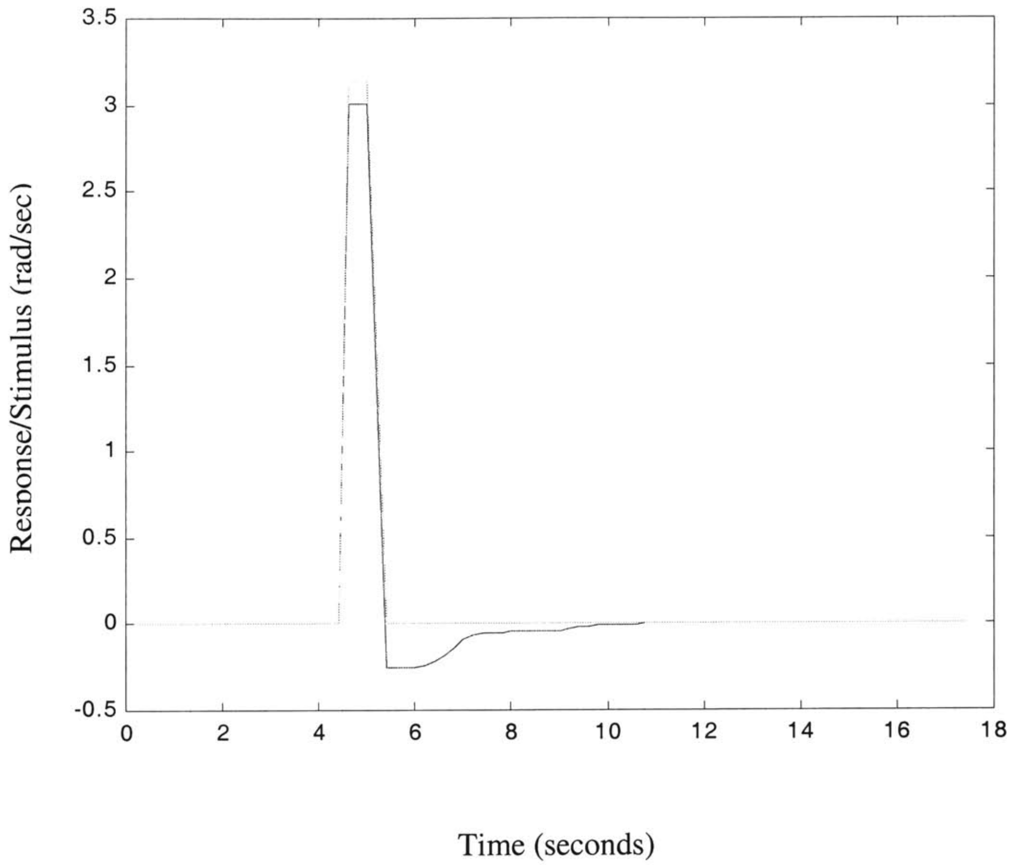


Figure 15 - Response of the cupula (black) in the **yaw canal** to a 90 degree yaw head turn (dotted grey) on a 23prm rotating device, using a modified Young-Oman Laplace transfer function model.

When the reverse head movement is made from NU to RED, the pitch canal is initially out of the plane of rotation, therefore the head movement causes the canal to move into the plane of rotation. This causes the fluid to initially rotate in the counterclockwise direction, the fluid deflects the cupula and should cause a sensation of pitching backwards. The roll canal is initially in the plane of rotation, the head turn causes the canal to come out of the plane of rotation. The fluid which was initially rotating at the same velocity as the canal in the clockwise direction of centrifuge rotation, continues to rotate but decelerates clockwise when the canal is brought out of the plane of rotation, this deflects the cupula and should gives the subject a sensation rolling clockwise.

In addition to the perceived self-motion sensations of pitch and roll, subjects also experience a vertical nystagmus when making yaw head turns. The nystagmus is a result of fluid flow in the vertical semicircular canals and bending of the cupula, for more details see Sienko (2000).

2.3 Motion Sickness

The Sensory Conflict Theory (Oman, 1998) is one approach to explaining the cause of motion sickness. The major factors contributing towards motion sickness consist of conflicts between visual, vestibular and proprioceptive inputs, and comparison of inputs with expectations from previous experience. There are two approaches to generating motion sickness in a controlled environment, the first consists of vestibular stimulation such as the Coriolis effect caused by head rotation in a rotating environment, and the second visual stimulation. Signs and symptoms of motion sickness include nausea, pallor, headache, dizziness and in the extreme case, vomiting. In the example given in the previous section, where yaw head movements are made on a rotating centrifuge, the subject experiences unexpected self-motion in the directions described. This perceived self-motion conflicts with the visual input, and the expected internal model associated with performing yaw head turns. This motion is therefore likely to induce motion sickness.

3. Methods

3.1 Design

This study was designed to determine the ability of humans to adapt, and retain adaptation to out-of-plane head movements made during short-radius centrifugation. The hypothesis for the experiment was as follows: Repeated exposure to a series of yaw head movements made on a short-radius centrifuge will result in a decrease in: non-compensatory vertical nystagmus, inappropriate perceived self-motion sensations and motion sickness. Decreases in non-compensatory vertical nystagmus and inappropriate perceived self-motion sensations are expected both during the experiment and with repeated exposures, demonstrating both habituation and adaptation. Motion-sickness scores are also expected to decrease with repeated exposures.

Measures of adaptation included non-compensatory vertical nystagmus, motion-sickness scores during centrifugation, post-experiment motion-sickness scores, verbal reports of spatial orientation and computer animations of perceived self-motion. This report focuses on measurements of perceived self-motion and motion sickness. A detailed report of non-compensatory vertical nystagmus as a measure of adaptation can be found in Sienko (2000).

The study involved exposing eight subjects to three sessions of centrifugation, each lasting approximately twenty minutes. The sessions were performed on the following days: day one, day two and day eight. The centrifugation sessions were divided into three phases comprising: pre-adaptation, adaptation and post-adaptation. Subjects were required to make yaw head turns during all three phases of the experiment. Both pre- and post-adaptation phases were performed in darkness, during which eye data was collected. The adaptation phase lasted ten minutes and was performed in the light. Evidence exists (Guedry,1964) to support the theory that habituation to Coriolis stimulation is more effective with visual cues that in darkness (It is thought that when a visual reinforcement of a still fixation is provided during the habituation series, nystagmus decline may be attributable to competition between visual and vestibular systems, with vision gaining dominance). The experiment is therefore designed to measure the subject's initial reaction to the stimulus in the dark, and again in the dark after ten minutes of head movements in the light, during which adaptation is expected to occur. The design was driven by the requirement of non-compensatory vertical nystagmus measurements to be performed in darkness, due to suppression of nystagmus in the light.

3.2 Equipment

The main experimental apparatus consisted of the MIT short-radius centrifuge, an ISCAN infrared eye imaging system, Watson angular rate sensors, two 300Hz emachine computers, and a variety of tools to capture motion sickness and perceived self-motion sensations (motion-sickness surveys, verbal reports and computer animation software and hardware).

3.2.1 MIT short-radius centrifuge

The MIT short-radius centrifuge has a 2-meter radius and is designed to rotate a subject about an axis through the head. The centrifuge was built and designed by Peter Diamandis in 1988. The centrifuge is driven by a 1hp electric motor through a 50:1 gear reduction. We operated the centrifuge at 23 rpm, which created a1G force at the feet of a 1.67m tall subject. Counter weights were used at the head of the centrifuge to balance the moment arms, and an adjustable footplate accommodated subjects of different heights. A 32-channel slip ring located in the center of the tube support structure was used to transmit data from the centrifuge to the data acquisition system. A number of safety features were included in the centrifuge design, including side railings, a safety belt and an emergency stop button. A windshield canopy was also built by Diamandis to protect subjects from winds generated at high velocities. An on-board RCA color video camera was mounted to one end of the centrifuge and wired through the slip ring. Further details regarding the centrifuge design can be found in Diamandis, (1988). A picture of the MIT short-radius centrifuge is shown in Figure 16.

A series of modifications were carried out on the centrifuge in order to perform this study. The centrifuge velocity controller was converted from manual control to computer control. LabVIEW software (version 5.1) was used to generate velocity profiles and control the velocity of the centrifuge. A Hewlett Packard optical encoder (256CPR) was mounted to the worm gear to provide accurate velocity readings. ISCAN eye imaging goggles and Watson angular rate sensors were powered by on-board batteries and wired through the slip ring. (The ISCAN eye-imaging system was used to measure the displacement of the corneal reflection and hence measure the non-compensatory vertical nystagmus. The Watson angular rate sensors were used to measure the angular rate of the subject's head about the yaw and pitch axes. For more details on these systems see Sienko, (2000)). Three 6V battery powered lights were attached to the centrifuge for use during the light adaptation phase. The windshield canopy was darkened with black cloth to prevent light cues during pre- and post-adaptation phases. A 300Hz emachine etower computer was used for ISCAN data collection, two televisions and a VCR were used to view and record eye movements. A television was used to view the subject during centrifugation from the on-board video camera, and a VCR recorded head movements during light adaptation. To enable clear communication with the subject during the experiment, three Motorola TalkAbout two-way radios were used, one for the subject and two for the operators. A schematic diagram of the MIT short-radius centrifuge is shown in Figure 17.

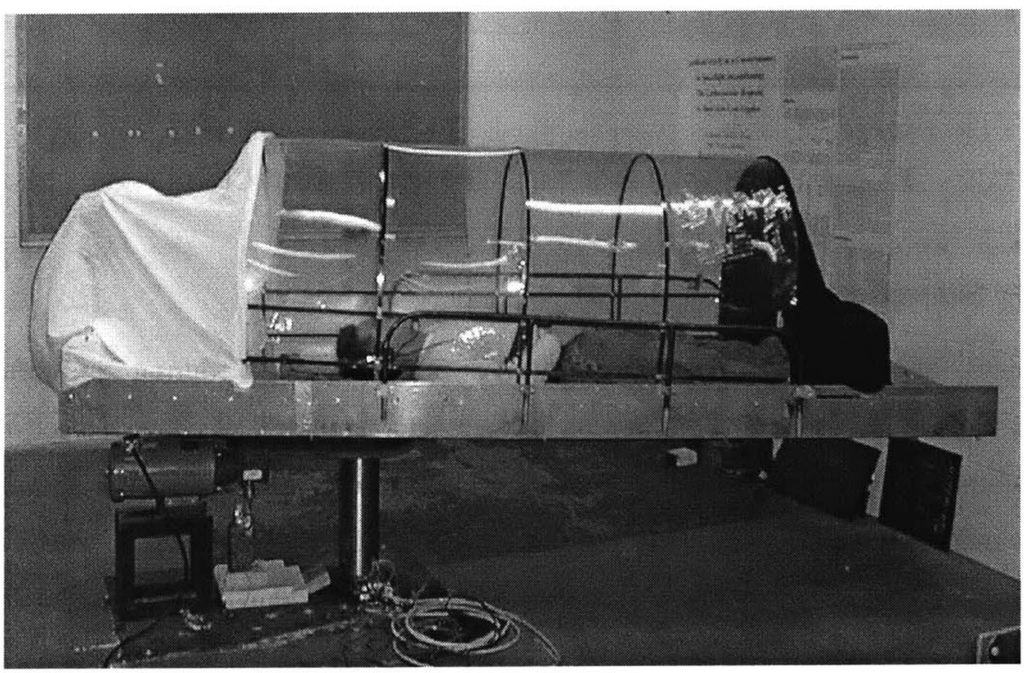


FIGURE 16-THE MIT SHORT-RADIUS CENTRIFUGE

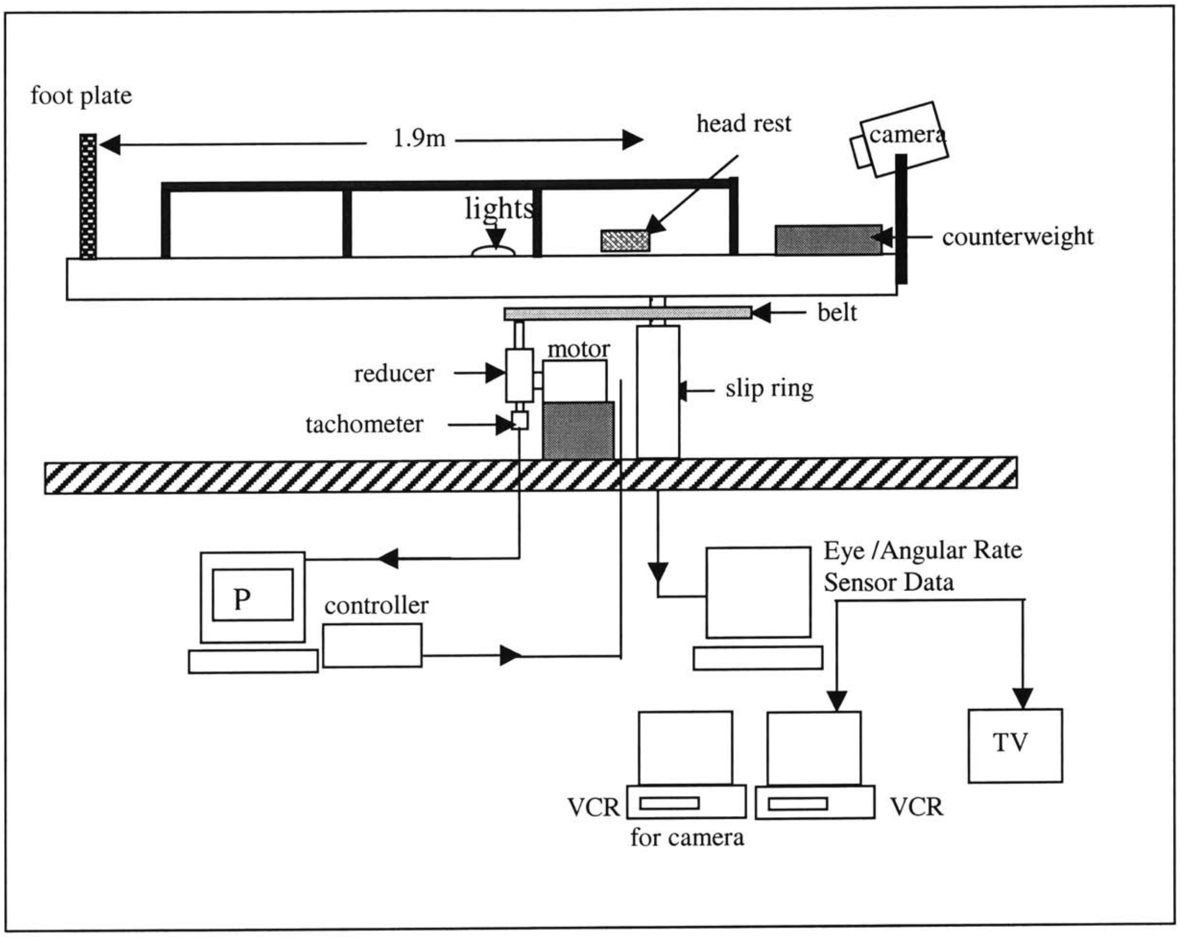


FIGURE 17-SCHEMATIC OF THE MIT SHORT-RADIUS CENTRIFUGE

3.2.2 Subjective measurement tools

A series of subjective measurements were performed both during and after the experiment to assess the level of motion sickness and magnitude of perceived self-motion sensations. The measurements consisted of: Pensacola motion-sickness score, post-experiment motion-sickness scores (using a 0-20 scale), motion-sickness scores during the experiment (using a 0-20 scale), verbal reports and Worldup computer animations of perceived self-motion. The measures are discussed in detail in the following section.

Pensacola Motion-Sickness Survey

The Pensacola Diagnostic Index Method (Graybiel, Wood, Miller & Cramer, 1968) was used to score the subject's overall motion sickness immediately after centrifugation. The symptom scoring definitions devised by Oman, Rague and Rege (1987) were used. The observer and subject graded the subjective intensity of eight different classes of symptoms. The classes consist of nausea, temperature, pallor, sweat, salivation, drowsiness, headache and dizziness. The symptom intensities of each of the classes were classified according to three levels of intensity (slight, moderate and severe). The symptoms were assigned a numerical weighted score and summed to obtain an overall severity level. The severity levels are: slight malaise (1-2), moderate malaise B (3-4), moderate malaise A (5-7), severe malaise (8-15) and frank sickness ($\geq$16). There is no relationship between the numbers assigned using the Pensacola scale and the 0-20 scale, which is described below. Appendix A shows the Pensacola scoring system and symptom definitions.

Post-experiment motion-sickness scores (using a 0- 20 scale)

Post-experiment motion-sickness scores were collected every thirty minutes after centrifugation until the subjects went to sleep, and one additional value was recorded the following morning. Subjects were instructed to use a 0-20 objective magnitude estimation scale to represent their overall feeling of discomfort, where 0 represents "I am feeling fine" and 20 represents vomiting.

Motion-sickness scores during the experiment (using a 0-20 scale)

Motion-sickness scores were collected at the start of the experiment, at regular intervals during pre- and post-adaptation phases, and every minute during light adaptation. Figure 18 shows when the motion-sickness scores were collected. Subjects were instructed to use a 0-20 scale to represent their overall feeling of discomfort, where 0 represents "I am feeling fine" and 20 represents vomiting. The scores enabled operators to monitor the well being of subjects during the experiment. If subjects reached a score at or above 15, subjects were asked to stop making head movement until their score decreased to 12. Subjects communicated with the operator via two-way radios.

Verbal Reports

Verbal reports describing the sensations experienced during head turns were obtained during the forth set of yaw head movements made in the dark while rotating, during both pre- and post-adaptation phases, and after 5 minutes of light adaptation. Figure 18 shows when the verbal reports were collected. Reports were obtained after turning 90-degrees from RED to NU and again after turning 90-degrees from NU to RED. A pilot study showed that pitch sensations were the most dominant during head turns, hence subjects were asked to quantify if appropriate, the direction and number of degrees of pitch experienced. Subjects communicated with the operator via two-way radios. At the end of the experiment, subjects were asked to explain in detail their sensations and clarify any ambiguous reports obtained during centrifugation.

Worldup Computer Animation

Worldup is a real-time graphical simulation software package developed by Sense8 Corporation. The package enables users to create complex geometries and view the object as a simulation in the simulation editor. Scripts define the behavior of an object when the simulation is being run, they consist of script files containing basic script language. All components of a simulation are stored in a universe file, the file contains the simulation content, reference models and scripts etc. Objects can be moved using a mouse or variety of supported trackers. This movement can be recorded and replayed using the path browser.

A demo version of Worldup (saving disabled) and tutorials were downloaded from the internet (http://www.sense8.com/products/wupdemo.html). A computer model of a head (courtesy of D.Parker, University of Washington) was imported and the system configured to interface with a 2-degree of freedom space-ball. After completing the protocol, subjects used the space-ball (yaw and pitch) to manipulate the position of a computer-generated head on a screen, to represent how their head felt during head movements in the dark on the rotating centrifuge. Subjects moved the space-ball to reenact their sensations when turning 90-degrees from RED to NU, repositioned the head, and reenacted their sensations when turning 90-degrees from NU to RED. Subjects were given time before the start of the first day of testing to play with the tracker and computer generated head. Animations were recorded using the path browser, and were played back to the subjects to verify that the animation was a true representation of their sensations. Subjects were given the opportunity to repeat the recording and amend the animations as appropriate. Appendix B describes the procedure for assembling the Worldup software and tracker.

3.3 Subjects

Eight subjects (4 male, 4 female) were selected from the MIT Department of Aeronautics and Astronautics student population. Applicants completed a questionnaire (Appendix C) and were screened for disqualifying medical conditions (Appendix D) (including symptoms of vestibular abnormalities), and previous artificial gravity training. Selected subjects were in the age range 19 to 25yrs (mean age 22.9 +/-2.2), with mean height 173.2+/-11.8 inches and weight 151.8+/-25.7 lbs. Subjects were selected according to the following criteria: 18-30 years old, 4 females and 4 males, height range 5'0'' – 6'2'', weight less than 200lbs, partake in some form of exercise>2 hours a week, ability to perform necessary motor tasks, good communication skill (ability to relate experiences verbally) and tolerance to severe motion sickness. Subjects were instructed to abstain from consuming caffeine and alcohol for 24 hours preceding the experiment.

3.4 Experimental procedure

All eight subjects performed the same protocol on day one, day two and day eight. Eye movement data and subjective measurements were acquired on all days. The experiment was divided into three sections: 1) Training, instrumentation and pre-experiment data collection 2) Data collection 3) Post-experiment data collection. A copy of the pre-test briefing and the data collection sheets can be found in Appendix E.

3.4.1 Training, instrumentation and pre-experiment data collection

The operator described the experimental protocol to the subject and informed them of their right to terminate. Subjects were instructed to read the consent form (Appendix F), and sign on agreement of the terms and conditions. A detailed pre-test briefing for verbal and motion sickness reporting was given, this included definitions of yaw, pitch and roll movements, an explanation of the 0-20 motion-sickness scale and instructions of when to report. Subjects were asked to make as many head movements as possible during light adaptation, and to inform the operator if they reach a stage when they cannot make any more head movements. Subjects were also asked to inform the operator if they experienced any specific symptoms, for example hot, cold sweaty. The operator documented the reported symptoms.

Subjects were instructed how to use the space-ball and Worldup software. Five minutes were allocated to playing with the tracker and the computer generated head. Subjects were asked to choose one of the following categories to describe their overall wellness: extremely good, slightly better than normal, normal, slightly worse than normal or extremely poor. Subject's height and weight were measured prior to the experiment. The height was required for adjustment of the centrifuge footplate, and the weight was required for appropriate placement of counterweights. The ISCAN eye imaging goggles and fabric cap mounted with angular rate sensors were placed on the subject's head and adjusted to fit. Subjects were positioned supine on the centrifuge and necessary adjustments made to the footplate and counterweights in order to balance the centrifuge. Subjects were secured to the centrifuge with the safety belt, and instructed how to use the emergency stop button.

Subjects were instructed how to use the battery operated lights for use during light adaptation and the two-way radios for communicating. Demonstrations were given on how to make 90-degree yaw head turns, from RED to NU and from NU to RED. Subjects practiced the head movements until the operator was satisfied. An eye calibration test was performed using an adjustable stand positioned 71cm above the subject's eyes. Five dots, at equal spacing were painted on the stand, positioned in the center, horizontally and vertically. Subjects were required to look center, up, down, right and left. The ISCAN acquisition software was used to perform the calibration. A wind canopy covered in black cloth was placed over the subject and secured using Velcro and clips. The centrifuge was manually rotated once to check for obstacles and obstructions.

3.4.2 Data collection

Eye reflex data, motion-sickness scores and reports of subjective sensations were obtained at various phases during the main experiment. Figure 18 shows the eleven phases of the experiment. A motion-sickness score was obtained at the start of the experiment. Three operators were required to run the experiment, the main duties were divided as follows: operator 1: eye data collection, operator 2: subjective sensations and motion-sickness data collection and operator 3: timeline recording. This section describes each of the phases in detail.

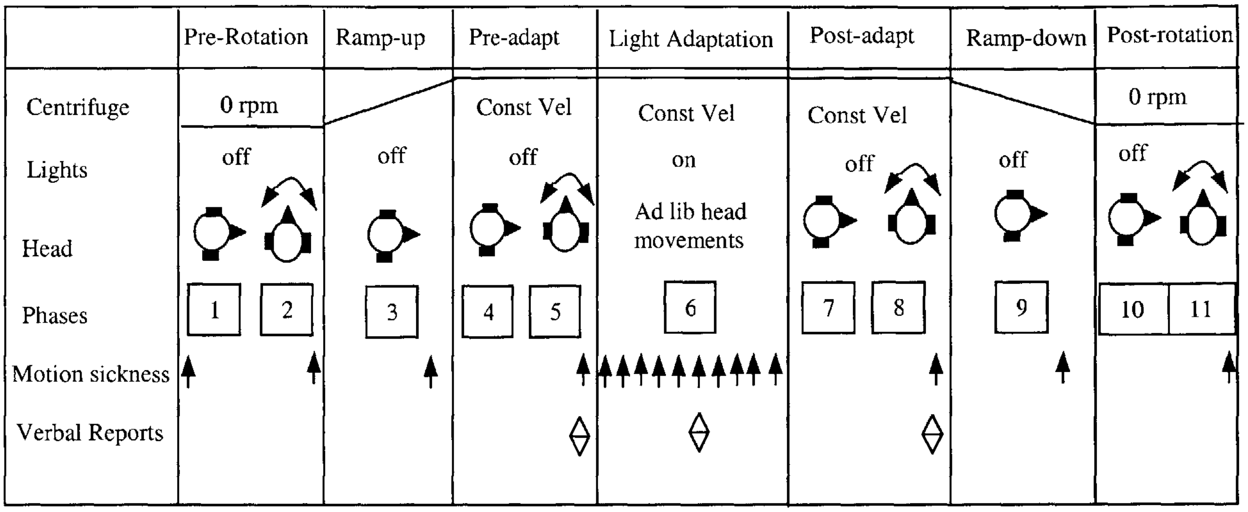


FIGURE 18-ELEVEN PHASES OF THE MAIN EXPERIMENT, INCLUDING CENTRIFUGE ROTATION STATUS, LIGHTING CONDITIONS, HEAD POSITION, LOCATION OF MOTION-SICKNESS SCORES AND LOCATION OF VERBAL REPORTS.

Phase 1: Pre-rotation baseline data collection with head stationary.

Subjects were positioned RED in the dark, with the centrifuge stationary. Baseline eye reflex data was collected with the head stationary for 30 seconds.

Phase 2: Pre-rotation baseline data collection with head movements

Subjects were positioned RED in the dark, with the centrifuge stationary. Subjects made three sets of yaw head movements as instructed by the operator. A set of head movements consisted of a 90-degree yaw head turn in 1 second from RED to NU, followed by a 20-second pause in the NU position, and a 90 degree yaw head turn in 1 second from NU to RED, again followed by a 20-second pause. Baseline eye reflex data was collected during the head turns, and a motion-sickness score was given after three sets of head movements.

Phase 3: Ramp-up

Subjects remained stationary in the RED position in the dark, while the centrifuge followed a constant acceleration profile to 23rpms. Subjects reported a motion-sickness score after acceleration to constant velocity.

Phase 4: Pre-adaptation with head stationary

Subjects remained stationary in the RED position in the dark, while the centrifuge rotated at constant velocity. Eye reflex data was recorded for 30 seconds.

Phase 5: Pre-adaptation with head movements

Subjects were positioned RED in the dark, while the centrifuge rotated at constant velocity. Subjects made a set of three yaw head movements, as instructed by the operator (as described in phase 2). Eye reflex data was recorded during the head turns, and a motion-sickness score was given after three sets of head movements. A fourth sets of head movements were made, during which subjects were asked to give a verbal report of their sensations. Subjects who experienced a pitch sensation were asked to quantify the pitch sensation in degrees. Separate verbal reports were obtained for RED to NU and NU to RED.

Phase 6: Light Adaptation

Subjects were instructed to manually turn on the on-board lights and remove the fleece eye goggle cover (designed to eliminate light cues). Subjects were instructed to make self-regulated yaw head movements, and were encouraged to make as many head movements as tolerable. Motion-sickness scores were recorded every minute during the ten minutes of light adaptation. Verbal reports of subjective sensations were given after five minutes of light adaptation. After ten minutes, subjects were instructed to turn off the lights, replace the eye cover, and return to the RED position.

Phase 7: Post-adaptation with head stationary

Subjects remained stationary in the RED position in the dark. Eye reflex data was recorded for 30 seconds.

Phase 8: Post-adaptation with head movements

Subjects made three sets of yaw head movements in the dark, as instructed by the operator. Eye reflex data was recoded during the head turns, followed by a motion-sickness score. A fourth set of head movements was made, during which subjects were asked to give a verbal report of their sensations.

Phase 9: Ramp-down

Subjects remained stationary in the RED position in the dark, while the centrifuge decelerated at a constant rate until stationary. Eye reflex data was recorded during deceleration for 30 seconds, followed by a motion-sickness score.

Phase 10: Post-rotation with head stationary

Subjects remained stationary in the RED position in the dark, with the centrifuge stationary. Eye reflex data was recorded for 30 seconds.

Phase 11: Post-rotation with head movements

Subjects made three sets of yaw head movements in the dark, with the centrifuge stationary. Eye reflex data was recorded during the head movements, followed by a motion-sickness score.

Following phase 11, the wind-canopy, ISCAN goggles and angular rate sensors were removed. The subject was instructed to remain supine on the centrifuge.

3.4.3 Post-experiment data collection

A series of self-motion reports, motion-sickness surveys and general questions were performed after the main experiment. The operator and subject worked together to determine motion-sickness scores for each of the symptom categories using the Pensacola motion-sickness scoring system. Subjects were asked to describe in detail the sensations experienced when making yaw head turns from RED to HU and NU to RED, during both pre- and post-adaptation phases. Subjects were asked a series of general questions to understand their overall well-being and their experiences. The questions can be found in Appendix E.

Subjects were then escorted to the virtual reality room where they were asked to recreate their sensations during head turns, using the space-ball and computer-generated head. Animations were recorded using the path browser and were played back to the subjects to verify that the animation was a true representation of their sensations. Subjects were given the opportunity to repeat the recording and amend the animations as appropriate. Subjects were asked to rate the accuracy of the recorded animation and the difficult of the task on a 0-10 scale, and specify the technique which best enabled them to describe their sensations (verbal or computer animation). Subjects were asked to use the 0–20 scale to document their overall feeling of discomfort every thirty minutes after the experiment, until retiring for bed and assign one value in the morning. Statistical analysis was performed using Systat and SAS software packages.

4. Results

4.1 Pensacola Motion-Sickness Survey

Pensacola motion-sickness scores (Appendix G) were obtained immediately after centrifugation for all eight subjects on each of the three test days. Motion sickness was reduced with repeated exposure, and the decrease was retained over the following five days (indicating retention of adaptation). Figure 19 shows the Pensacola motion-sickness scores by day. The median values decreased from ten on day one, to four on day two, and to three on day eight. A Friedman test [3] showed that this decrease was significant over all three days [$\chi^2_{(2)} = 8.313$, $p = 0.016$]. A sign test showed that the greatest decrease occurred between days one and two [$p = 0.125$], compared to days two and eight [$p = 0.289$].

The box plots used throughout the document have the following format: The solid line marks the median of the sample for eight subjects, the height of each box shows the range within which the central 50% of the values fall, with the box edges at the first and third quartiles. The whiskers indicate the extent of the nearest points that are not considered outliers and the asterisk represents the outlier.

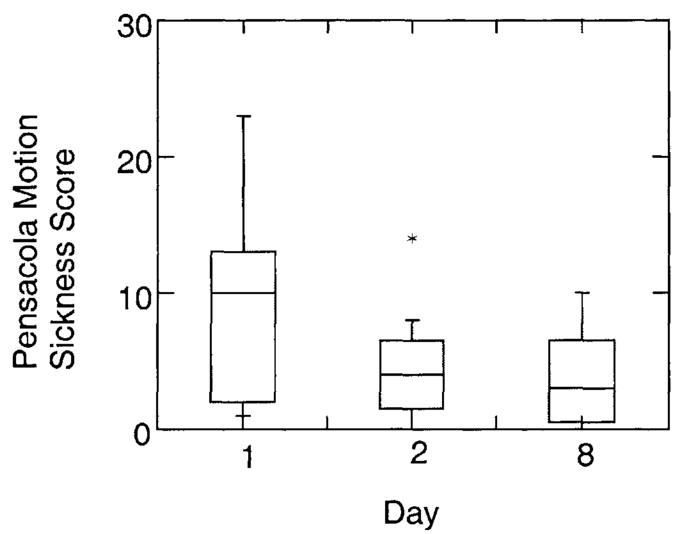


FIGURE 19-PENSACOLA MOTION-SICKNESS SCORE BY DAY.

The number of subjects who experienced the various motion-sickness symptoms at some point during the three test days are shown in Figure 20. The most common motion-sickness symptoms were pallor, drowsiness and nausea. Salivation was only reported by one subject, in fact two subjects reported experiencing mouth dryness. Nausea received

[3] A Friedman test is a non-parametric test based on ranking the measurements, this test does not assume a normal distribution. The Friedman statistic is approximately distributed as chi squares.

the highest average weighted symptom score [3.326, N = 5] where N is the number of subjects, followed by pallor [1.52, N=7] and then drowsiness [1.44, N=6)]. This implies that although nausea was not the most common symptom amongst subjects, the effects of nausea were the most severe. The weighted scoring system used in the Pensacola Index uses a 1-16 range for nausea compared with a 2-8 scale for pallor and drowsiness. The nausea scale enables the subjects to reach a higher score for a lower severity level than in the case of pallor and drowsiness, which may bias the outcome of the result. However, symptoms of pallor and drowsiness do not tend to be as uncomfortable as sensations of nausea. One may argue therefore that the scores are comparable because the sensations of nausea deserve a higher numerical weight (due to the discomfort factor), than symptoms of pallor and drowsiness.

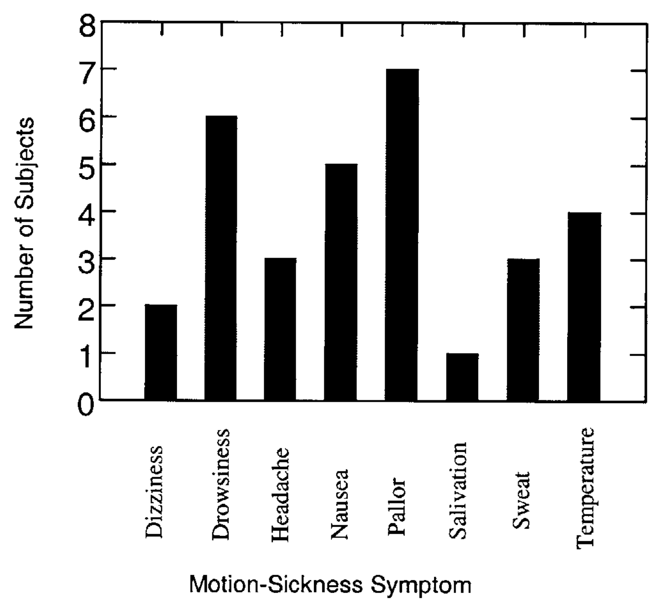


FIGURE 20-NUMBER OF SUBJECTS (N=8) WHO EXPERIENCED THE MOTION-SICKNESS SYMPTOM LISTED, AT SOME POINT DURING THE THREE TEST DAYS.

4.2 Post-Experiment Motion-Sickness Scores

Post-experiment motion-sickness score sheets (Appendix H) were collected from the subjects the day after centrifugation. The time taken to return to a motion-sickness score of zero was calculated for each subject. In cases where subjects did not reach a motion-sickness score of zero by the following morning, the motion-sickness scores were extrapolated using a line fit. In the case where the extrapolated time to zero was smaller than the time of the morning score, the extrapolated value was used, otherwise the time of the morning score was used. No subjects gave a morning motion-sickness score greater than zero. Of the eight subjects tested, two did not report any post-experiment motion-sickness symptoms, and one subject did not provide a value for day eight. These subjects were removed from the subsequent statistical analysis. The time taken to return to a motion-sickness score of zero decreased with successive test days, as shown in Figure 21.

The median times to loose all motion sickness symptoms decreased from three hundred and forty-five minutes on day one, to one hundred and twenty minutes on day two, and to ninety minutes on day eight. A Friedman test was performed on the time taken to return to a motion-sickness score of zero for the remaining five subjects. The decrease in time taken over all three days was found to be significant [$\chi^2_{(2)} = 6.3$, p=0.043]. A Sign test showed that the greatest decrease occurred between days one and two [p = 0.062], compared with days two and eight [p = 1.000]. The decrease was therefore retained over the five rest days.

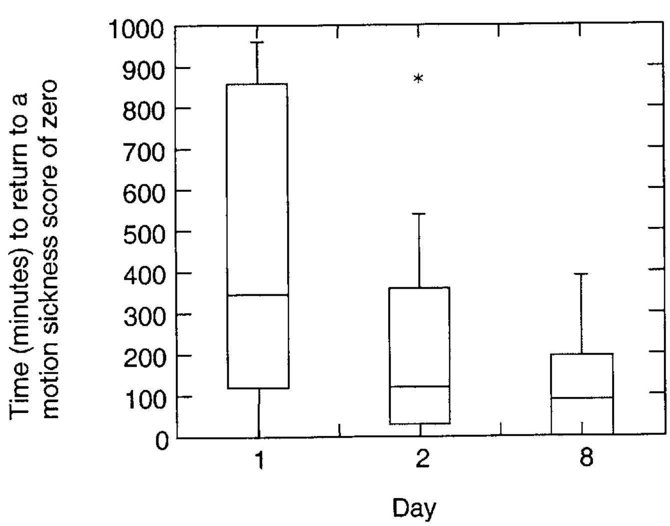


FIGURE 21-TIME (MINUTES) TO RETURN TO A MOTION-SICKNESS SCORE OF ZERO BY DAY, FOR EIGHT SUBJECTS.

4.3 Verbal Reports

The reported pitch magnitudes and directions were extracted from the verbal reports (Appendix I). All subjects experienced a pitch sensation during head turns, although one subject experienced a tumbling sensation of several revolutions rather than a discrete pitch value, and one subject experienced damped pitching oscillations. One subject was unable to quantify the pitch sensation was excluded from the analysis. In order to account for individual differences and to include the subject who experienced tumbling (360 and 720 degrees), the data was standardized to a mean of 1 and a standard deviation of 0.3.

A repeated measures ANOVA was performed on the reported magnitude of the perceived pitch sensation with three factors, day (three levels), pre-adaptation vs. post-adaptation (two levels), and direction of head turn (two levels). The analysis revealed no significant difference between the degrees of pitch experienced and the direction of head turn [$F(1,6) = 1.38$, $p = 0.285$], as a result the pitch magnitudes were combined for the two directions. All statistical results outlined below have been performed on the combined RED to NU and NU to RED data.

Figure 22 shows the degrees of perceived pitch (raw data) for each pre- and post-adaptation session when turning from RED to NU. Figure 23 shows the degrees of perceived pitch (raw data) for each pre- and post-adaptation session when turning from NU to RED. A main effect for pre- and post-adaptation head turns was found [$F(1,6) = 11.89$, $p = 0.014$], indicating that the experienced pitch sensation decreased significantly between pre- and post-adaptation session. This is evidence for habituation. A main effect was found for day, indicating that the experienced pitch sensation decreased significantly between days one and two [$F(1,6) = 33.87$, $p = 0.0011$] [4]. Retention of adaptation to day eight was found to be marginally significant, a comparison of day one to eight gave [$F(1,6) = 5.92$, $p = 0.051$]. No interactions showed significant results.

[4] Since the data may not be normally distributed, a sign test was conducted which verified the result $p = 0.016$.

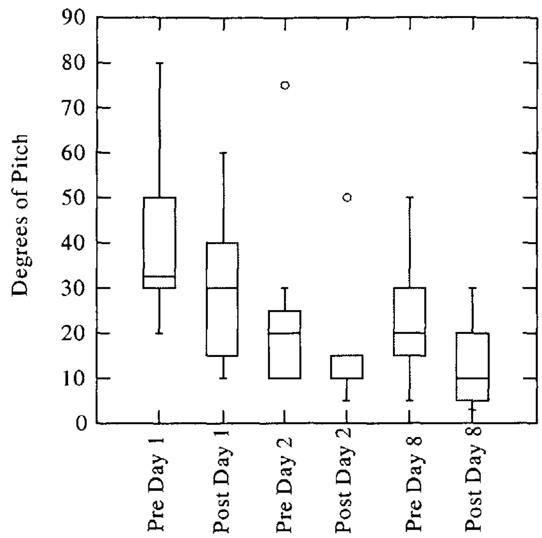


FIGURE 22-BOX PLOT OF THE REPORTED PERCEIVED PITCH SENSATION EXPERIENCED DURING PRE- AND POST-ADAPTATION **RED TO HU** HEAD TURNS, FOR SIX SUBJECTS. ONE SUBJECT WHO EXPERIENCED A TUMBLING SENSATION HAS BEEN OMITTED FROM THE PLOT FOR SCALING PURPOSES.

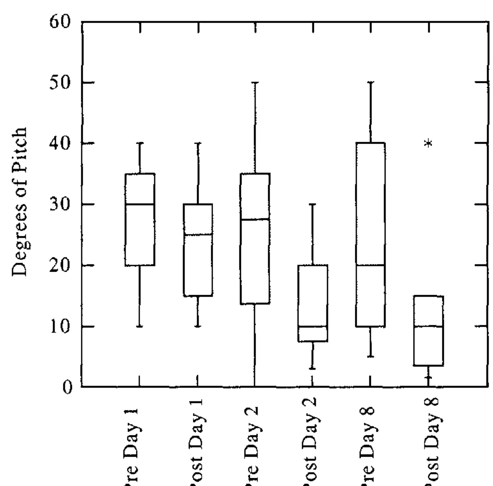


FIGURE 23-BOX PLOT OF THE REPORTED PERCEIVED PITCH SENSATION EXPERIENCED DURING PRE- AND POST-ADAPTATION **HU TO RED** HEAD TURNS, FOR SIX SUBJECTS. ONE SUBJECT WHO EXPERIENCED A TUMBLING SENSATION HAS BEEN OMITTED FROM THE PLOT FOR SCALING PURPOSES.

4.3.1 Magnitude and direction of pitch sensation

The semicircular canal model predicts that subjects feel a pitching forwards sensation when turning from RED to NU and a pitching back sensation when turning from NU to RED. During the verbal reports, one subject commented that the pitch sensation reflected the motion of his head (rather than his body), and four subjects described the pitch as a whole body sensation. The remaining three subjects did not differentiate between head and body motion, hence it was assumed that the motion reported reflected whole body sensations. Figure 24 shows a table of the directions of pitch experienced by the subjects, the average pitch angle and standard deviation in pitch angle (The average values were calculated from the pre- and post- adaptation verbal reports, for the three test days) for subjects who experienced a discrete pitch, and the number of degrees of tumble for the subject who experienced tumbling. (The average pitch angle includes the subject who experienced damped pitching oscillations, the initial magnitude of the pitch sensation was used).

Pitch Direction	**RED to NU**	**NU to RED**
Forwards	5	2
Backwards	1	4
Mixed	2	2
Average pitch angle (subjects who experienced a discrete pitch)	24.95 +/- 19.20	21.162 +/- 14.36
Degrees of tumble (subject who experienced tumbling)	540 +/- 197.18	600 +/- 185.90

FIGURE 24-PERCEIVED PITCH DIRECTION WHEN TURNING FROM RED TO NU AND NU TO RED.

Five subjects felt the expected sensation of pitching forward when turning from RED to NU, and one subject experienced the opposite direction. Four subjects felt the expected sensation of pitching back when turning from NU to RED, and two subjects experienced the opposite direction. Two subjects experienced a mixture of both pitching forward and backward in both directions. Examples of subjects in this category include the subject who felt pitching oscillations both forwards and backwards, and a subject who did not consistently feel pitching in one direction during repeated head turns. These inconsistencies became the focus of a large population study, see Cheung (2000). The average pitch angle experienced for the RED to NU turn was 24.95 +/- 1920, and 21.162 +/- 14.36 for the NU to RED turn. The average number of degrees experienced by the subject who reported tumbling rather than a discrete pitch was 540 for the RED to NU turn and 600 for the NU to RED turn.

5. Comparisons

5.1 Comparison of the Pensacola motion sickness scores to the time taken to return to a post motion sickness score of zero

The subjects who receive a larger score on the Pensacola scale, (which was performed immediately after centrifugation) were expected to take longer to return to a motion-sickness score of zero (using the 0-20 scale) after the experiment. The two subjects who did not score above zero on the 0-20 post motion-sickness survey, also scored low (≤ 4) for all three days using the Pensacola scale. One subject scored low (≤ 2) on all three days using the Pensacola scale but did not reach a post motion-sickness score of zero until the following morning on days one and two. For the remaining five subjects, all five subjects showed a decrease in Pensacola scores from days one to two, and also showed a decrease in the time taken to reach a post motion-sickness score of zero from days one to two. A comparison of days two and eight for the same five subjects showed opposite trends for three subjects, either a decrease in Pensacola and an increase in time or an increase in Pensacola and a decrease in time. Only one subject showed a decrease in both Pensacola and time.

A Pearson correlation analysis performed on the Pensacola motion-sickness scores and the time taken to return to zero for all days [r=0.586, p=0.0033, N=23] was significant.

Another Pearson correlation analysis was performed on the difference between times on day one and two and the difference in Pensacola score between days one and two [r = 0.64957, p = 0.0813, N=8]. The same analysis was performed for days two and eight [r= -0.47294, p=0.2837, N=7]. Only the differences between days one and two are correlated. This implies that for the first two days of testing, a decrease in the Pensacola score taken immediately after centrifugation is likely to result in a quicker recovery time, whereas after five days of no exposure, this relationship is no longer valid.

5.2 Comparison of the Pensacola motion sickness score to the 0-20 scale

A comparison was made between the scores from the two motion-sickness scales to test whether one scale captured the same information as the other. The Pensacola scores, which were obtained immediately after the experiment (after removal of the canopy), were compared with the 0-20 score taken at the end of the experiment (before the canopy was removed). A Pearson correlation analysis [r=0.6083, p=0.0016, N=24], showed a significant correlation between the two scoring systems. This means that a simple rating scale such as 0-20 reflects a significant part of the subject's overall feeling of discomfort. Figure 25 shows a scatter plot of the Pensacola motion-sickness scores, against the 0-20 motion-sickness score reported after centrifugation, for eight subjects on three test days. Inspection of the data shows that while there is a definite positive correlation, there are a considerable number of data points where the reported motion-sickness score is zero using the 0-20 scale and greater than zero using the Pensacola scale. Nine out of twenty-four motion-sickness scores were reported to be zero using the 0-20 scale. Out of the nine cases, two corresponding Pensacola scores were also zero and seven were greater than zero. Only one report was given where the Pensacola score was zero and the corresponding 0-20 score was greater than zero.

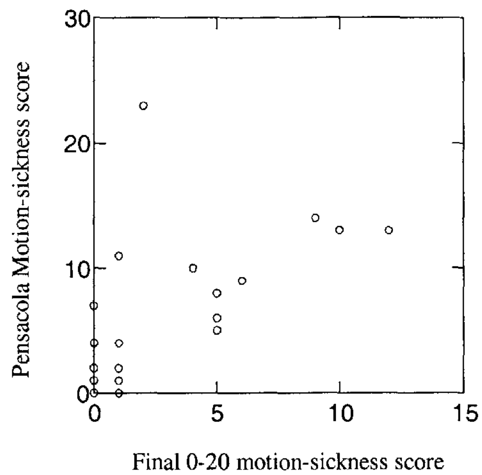


FIGURE 25-SCATTER PLOT OF PENSACOLA MOTION-SICKNESS SCORES AGAINST THE 0-20 SCALE MOTION SICKNESS SCORE REPORTED AFTER CENTRIFUGATION, FOR EIGHT SUBJECTS ON THREE TEST DAYS.

This implies that the Pensacola scale seems to be measuring symptoms of motion-sickness at low motion-sickness levels that are not captured by the 0-20 scale. One explanation could be that the Pensacola scale measures symptoms such as Pallor, headache and sweating, which people may not necessarily associate with motion sickness. Hence, the Pensacola scale may capture symptoms which fail to score on the 0-20 scale.

5.3 Comparison of motion sickness and subjective sensation retention

While adaptation to motion sickness was retained over the five rest days, subjective sensations were retained with only marginal significance. An interesting comparison can be made with a study by Guedry,(1965) whose subjects were rotated at ten rpm counterclockwise for twelve days. Subjective sensation and nystagmus tests were conducted on a rotating chair both before and at the following intervals after the twelve day exposure, one hour, forty-eight hours, three weeks and three months. Subjective sensations produced by head movements during the accustomed direction of rotation were found to diminish markedly after the twelve day exposure. During the three week post exposure test, subjects reported a return of sensations in both counterclockwise and clockwise rotation. However, subjects who experienced motion sickness during the initial test reported no feelings of nausea or stomach awareness during later testing. This supports the findings in our study where adaptation to subjective sensations was only marginally retained over the five day rest period, where as reduced motion-sickness scores were retained. Motion sickness reduction appears to be retained more after a period of rest than subjective sensations. This finding has interesting implications for motion sickness conflict theories. If motion sickness is caused by visual/vestibular conflict, and the visual/vestibular conflict is still present as evident by the subjective sensations, then one would expect motion sickness to occur. However, results from our experiment and Guedry, (1965) seem to imply that the subjective sensations occur without the expected motion-sickness symptom levels. This may suggest that some form of dissociation occurs between motion sickness and visual/vestibular conflict after adaptation to the stimulus.

6. Discussions and Recommendations

6.1 Retention of adaptation

Severity and duration of motion-sickness symptoms clearly decrease with repeated exposure to the stimulus. The greatest decrease in both symptom severity and duration occurs from day one to day two, and this adaptation is retained over the five rest days. Limitations of the current study include a small sample population, one exposure schedule (consisting of two consecutive days of exposure followed by five rest days, and re-exposure on the eighth day), and a specific adaptation protocol during rotation. A variety of parameters could be varied in order to explore adaptation and retention to adaptation. Suggested parameters include the number of centrifuge exposures, number of rest days before re-exposure, duration of centrifugation and adaptation protocol. This section provides an outline of future experiments to explore the dependence of the number of rest days on the severity and duration of post motion-sickness symptoms on the final test day, the role of visual tasks on habituation and transfer of adaptation.

The current protocol involved two sequential days of testing, five rest days and re-exposure on the eighth day. The motion-sickness data collected showed that subjects maintain a similar level of motion sickness on day eight to that on day two. Increasing the number of rest days would establish upper limits for the maximum number of rest days before the severity and duration of post motion-sickness symptoms become greater than those experienced on day two.

Increasing retention times while maintaining low motion-sickness symptoms may be dependent on the degree of adaptation obtained prior to the period of rest. Senqi and Stern, (1999) compared the retention of adaptation to motion-sickness eliciting stimulation after one month and one year. Subjects repeatedly viewed an optokinetic rotating drum until they had no feelings of nausea. Subjects were re-exposed to the optokinetic drum either after one month or one year. The mean ratings of nausea for subjects who were re-exposed after one month (using a 0-10 scale) were 9.23 for the initial exposure and 0.94 for the re-exposure session. The mean ratings of nausea for the subjects who were re-exposed to the drum after one year were 8.94 for the initial exposure and 6.88 for the re-exposure session. These results indicate that adaptation to the motion-sickness eliciting stimulation of optokinetic rotation is almost completely retained for one month and only partially retained for one year. However, they used an inappropriate t-test and the one-year effect seems questionable. It is not known whether the retention mechanism for optokinetic adaptation is the same as for Coriolis adaptation. The relationship between the mechanisms is discussed below.

Eyeson-Annan and Peterken, (1996) showed that visual information is more important than vestibular input in causing motion-sickness symptoms when the stimuli are presented in isolation. However, in conditions where both visual and vestibular information are present, cross-coupling appears to occur between the visual effect and the Coriolis effect, as the two conditions are not significantly different in producing motion-sickness symptoms. This indicates that the stimulus for motion sickness may be essentially the same for both the Coriolis effect and the visual effect. If the stimulus for the two mechanisms is the same then one could speculate that the retention mechanism may be the same. If this is true, then the retention times for Coriolis adaptation may be greatly increased by pre-adapting subjects until no motion-sickness symptoms are experienced before taking rest days. This experiment proposes adapting subjects until no motion-sickness symptoms are experienced (or below some threshold), and re-exposing different subject groups to the provoking Coriolis stimulation after different rest periods.

6.2 Habituation using visual tasks

Our results clearly show that there is a significant decrease between the perceived pitch sensation pre- and post-adaptation. The adaptation period consisted of subjects making self-regulated yaw head movements in one quadrant, in the light. Retention of adaptation to the perceived pitch sensation was only marginally significant compared with motion-sickness scores, which showed retention. Modifications in the adaptation protocol may enhance habituation and may in turn increase retention of adaptation. Guedry,(1964) found that a habituation series in the light, consisting of head movements, resulted in pronounced reductions in nystagmus and subjective effects when a visual task was used. In addition, he found that subjects who used a visual task were relatively free of motion sickness, this enabled them to make one hundred head movement cycles during the adaptation period (significantly more than the number of self-regulated head movements made by subjects in our study). It was noted by personnel engaged in Pensacola experiments, that increased mental activity and interest in a task seem to suppress nausea and malaise. Future studies may wish to consider using a visual task to enhance reductions in nystagmus, subjective sensations and reduce motion-sickness symptoms. A reduction in motion sickness will enable subjects to make more head movements, which in itself may lead to enhanced habituation and retention of adaptation.

6.3 Transfer of adaptation

To date, our experiment has only considered adaptation to head turns in one quadrant and centrifuge rotation in the clockwise direction. An interesting question to ask is whether adaptation achieved in one quadrant transfers to head movement in a different quadrant. Some interesting insights can be obtained from Guedry,(1965). In this experiment, subjects were rotated at ten rpm in a counterclockwise direction for twelve days. Recording of nystagmus and subjective sensations were taken before and after the twelve day exposure on a ten rpm rotating chair. Voluntary movements were performed in the light during the twelve days of habituation. Tests before and after the twelve-day exposure consisted of lateral head tilts towards the right shoulder and a return movement to upright, followed by a similar sequence towards the left shoulder. Before the twelve day exposure, subjects performed head tilts on the rotating chair, rotating both counterclockwise and clockwise. Reactions resulting from the head movements were found to be of about equal intensity, irrespective of the direction of rotation. Tests performed one hour after the twelve day exposure found that seven out of eight subjects reported no subjective reactions to head tilts during counter clockwise rotation (The forth subject reported very weak sensations). However, six out of eight subjects felt that sensations were as strong as or stronger than those experienced during clockwise rotation prior to the twelve day run (The other two subjects reported sensations to be slightly less than those experienced during the initial test). Tests performed forty-eight hours after the twelve day exposure found that seven out of eight subjects experienced a slight return of sensation during counterclockwise rotation compared to post one hour rotation, but weaker than prior to the twelve day exposure. During the clockwise rotation, six out of eight subjects experienced sensations much weaker than those experienced during post one hour or initial tests.

The large subjective responses experienced during post-rotation one hour testing in the clockwise direction, may imply that transfer of habituation has not taken place. However, this is inconsistent with the post forty-eight hour testing, which shows a decrease in clockwise rotation sensations and a slight increase in the counterclockwise rotation, compared with post one hour tests. One suggestion is that the large sensations experienced during clockwise rotation may be due to the presence of compensatory reactions rather than a lack of transfer of habituation. In addition, at the time of the post forty-eight hour test, the compensatory reactions were no longer evident in the static condition. The results suggest a more general response suppression, which persists after compensatory reactions have disappeared. Future experiments testing transfer of adaptation may wish to consider the following points. When adapting subjects in one direction, tests to determine transfer of adaptation may wish to be performed after compensatory reactions have been extinguished, this will help to differentiate between adaptation transfer and compensatory reactions. Also, if transfer of adaptation is not observed, it would be interesting to see whether adaptation occurs quicker for the same stimulus but a different head movement directions.

6.4 Tumbling sensation verses discrete pitch

All subjects experienced a pitch sensation during yaw head turns from RED to NU and NU to RED. However, while 6 subjects experienced a discrete pitch, 1 subject experienced a tumbling sensation of several revolutions and one subject experienced damped pitching oscillations. When the pitch canals are rotated out of the plane of rotation there is a sudden cupula deflection, the cupula then returns to the neutral position with a time constant of 6 seconds. During this time, the pitch canal signals a continuous but slowly decaying pitch velocity. If only the signals from the pitch canal are considered, it is expected that subjects would feel a tumbling sensation in the pitch direction. However, other sensory organs provide cues, which conflict with the information generated by the pitch canal. Dichgans, Held, Young and Brandt (1972) reported that when observers viewed a wide-angled display rotating around the observer's line of sight, both visual and postural orientation measures yield tilts of the apparent vertical. The paper explains that the sensation is caused by a paradoxical illusion of continuous motion of the body and the visible target, combined with limited sensed displacement of both, in the continuous direction of motion. The authors suggest that the limitation of displacement maybe provided by the vertical graviceptive information given by the otoliths and pressure receptors. In our experiment, it is expected that subjects receive graviceptive information from the otoliths, tactile cues in the form of pressure cues to the skin (provided by the support surface of the centrifuge on the subject's back) and kinesthetic information about body orientation (from internal kinesthetic sources such as muscle spindles), all of which fail to confirm the tumbling sensation signaled by the canals. These additional conflicting cues are expected to result in the subjects experiencing a sense of steady pitch rather than continuous tumbling.

An interesting comparison can be made with Hecht, Kavelaars and Cheung (2000) [manuscript submitted for publication], who performed a large population subjective report study on the same rotating centrifuge as our study. Twenty subjects were asked to generate reports of perceived self-motion during yaw head turns on the rotating centrifuge. A total of 40 reports were generated, consisting of 30% tumbling sensations, 37.5% discrete pitch sensations and 32.5% no reports of pitch sensations. The proportion of subjects who experienced a tumbling sensation in the large population study is significantly greater than in our study [where12.5% experienced a tumbling sensation]. It is clear in the large population study that the tumbling sensation is as prevalent as the discrete pitching sensation. The sensory signals of continuous tumbling from the canals appears to dominate in some subjects while other sensory cues such as otolith, tactile and kinesthetic cues appear to suppress the continuous tumbling sensation resulting in a discrete pitch for other subjects. Unlike the large population study, our study shows that the majority of subjects suppress the canal signals with other sensory cues resulting in a discrete pitch sensation.

7. Additional Results and Discussion part one

7.1 Worldup computer animation

Pitch and yaw components of subjective motion were extracted from the Worldup software, and converted from quaternions into degrees. Appendix J shows the matlab code used to extract the Worldup output and convert it into degrees. The magnitude of the peak pitch value in degrees (minus the baseline) was taken as the measure of adaptation. The 90-degree head turns from RED to NU and NU to RED were recorded separately, and peak pitch magnitudes were extracted for each direction. Appendix K shows the Worldup pitch and yaw axis output in degrees for all subjects on all three days. Appendix L shows peak pitch magnitudes in degrees (minus the baseline) for all subjects on all three days.

No significant difference was found between the peak pitch magnitudes and direction of yaw head turn, therefore the average peak pitch value was calculated for each head turn. No significant decrease in the peak pitch magnitude was found with day [F(2,14) =0.999, p = 0.393] for eight subjects. Figure 26 shows the peak worldup pitch magnitudes for eight subjects by day. This result is opposite to the verbal reports, where a significant decrease was found between days one and two, and retention of adaptation to day eight.

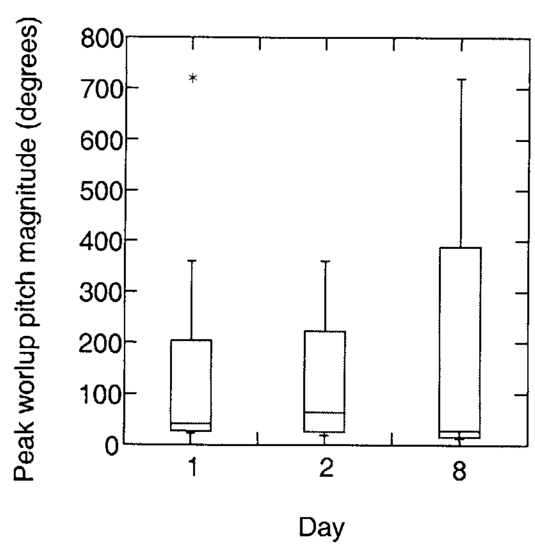


FIGURE 26-PEAK PITCH MAGNITUDES IN DEGREES BY DAY FOR EIGHT SUBJECTS. PITCH MAGNITUDES WERE COLLECTED USING WORLDUP, A COMPUTER ANIMATION SOFTWARE PACKAGE.

At the end of each test period, and after completing the Worldup computer animation, subjects were asked the following questions:

1. On a scale of 0-10, how accurately does the Worldup animation recreate the sensations you experienced (0 = not very accurately and 10 = very accurately)?

2. On a scale of 0-10, how difficult is it to use Worldup to recreate your sensations, (0 = not very difficult and 10 = very difficult)?

The purpose of the questions was to gain an understanding of how accurately the subjects felt that the computer animation resembled their true sensations, and the difficulty of the task. The mean accuracy was 5.409 +/- 1.817, and the mean difficult was 5.205+/-2.472. No significant difference was found for accuracy with day [F(2,10) = 0.077, p = 0.927] for six subjects. Figure 27 shows the subjective accuracy score (0-10) by day for six subjects with scores for all three days, and two subjects with scores for days one and eight only. No significant difference was found for difficulty with day [F(2,10) = 1.808, p = 0.214] for six subjects. Figure 28 shows the difficulty scores (0-10) by day for six subjects with scores for all three days, and two subjects with scores for days one and eight only.

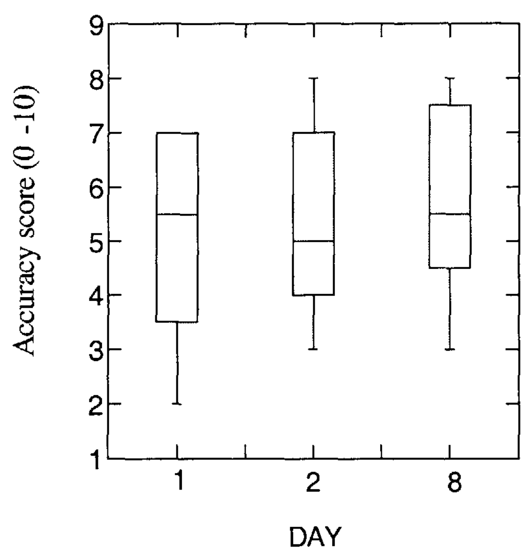


FIGURE 27-WORLDUP ACCURACY SCORES BY DAY FOR EIGHT SUBJECTS

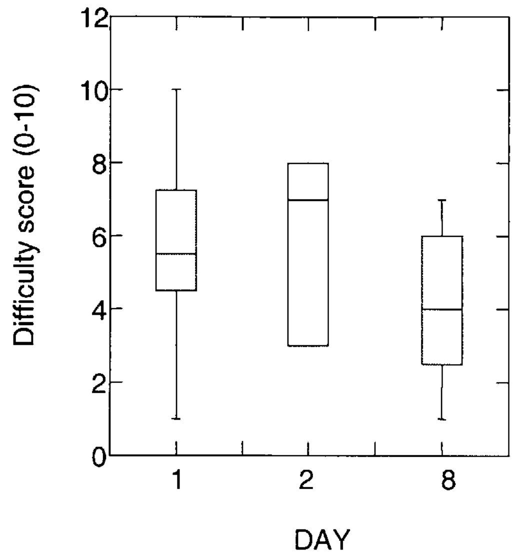


FIGURE 28-WORLDUP DIFFICULTY SCORES BY DAY FOR EIGHT SUBJECTS

7.2 Validity of Worldup results

The peak pitch magnitudes acquired using the Worldup computer animation software, clearly show that there is no decrease in the perceived pitch sensation with day. This is contrary to the conclusions drawn from the verbal reports generated at various stages during the experiment. The verbal reports clearly show that adaptation occurs between days one and two, and that this adaptation is retained through to day eight. There are two pieces of evidence which suggest that more weight should be given to the verbal reports than the Worldup animations. Subjects were asked to name the technique which best enabled them to describe their sensations during head movement on the rotating centrifuge, the choices were verbal reports and Worldup computer animation. Seven out of eight subjects said that they could best describe their sensations verbally. Only one subject said that he could best describe his sensations using Worldup. Secondly, the mean accuracy score was 5.409, where 10 is very accurate and 0 is not very accurate. These results imply that more value should be given to the verbal scores as the majority of subjects felt that they could describe their sensations better verbally than using Worldup. Also, the low mean accuracy score implies that the Worldup animations were not a very accurate representation of the subject's sensations.

7.3 Evaluation of Worldup as a tool for capturing subjective sensations

Accuracy scores and post-assessment questions indicate that Worldup did not accurately capture the subject's perceived sensations. A variety of factors may have contributed to this result. This section discusses some of these factors. Timing of reporting may affect the accuracy of the final result. The verbal reports were acquired immediately after making a head movement, the sensations were therefore fresh in the subject's mind when the report was given. The subject was also lying in the same position, which may have prevented confusion when recalling directions of the perceived sensation. The Worldup computer animations were performed approximately ten minutes after completion of the experiment. This time lapse may have resulted in memory degradation of the perceived sensations, resulting in inaccurate recollections. In addition, during the Worldup animations, subjects were positioned sitting upright in a chair, in a different room. This environment and orientation change may have contributed to changes when recalling the perceived sensations.

Subjects generally experienced a very complex set of motions, consisting of roll, pitch and yaw components. Some subjects also experienced a tumbling sensation rather than a discrete pitch or roll. The space-ball, used by the subjects to move the computer generated head was limited to yaw and pitch motion and therefore did not have the capability to capture all aspects of the complex sensations experienced. Subjects may have found it difficult to isolate those sensations that the computer could capture from the complete complex set of motions. This may have contributed to the ambiguous result.

Accuracy and difficult scores for the Worldup animation showed no improvement with repeated trials. One would expect that the process of translating perceived self-motion onto a computer-generated head would become less difficult and more accurate with practice. However, it is clear from the results that no increase in accuracy or decrease in difficulty was seen. This means that the failure of Worldup to accurately capture perceived sensations is not a training/practice issue, but rather an intrinsic problem with the technique or limitations of the technique.

7.4 Recommendations

In order to accurately capture complex perceived self-motion, it is important to obtain the measure or report immediately after the stimulus has taken place. This will avoid erroneous reports through memory loss. In order to correctly recall the sensations, it is important that the subject remains in the same position. For example, the subject should not be asked to stand and give the report if the sensation was experienced while the subject was lying supine. A change in orientation and/or environment may cause confusion in directions of the perceived self-motion. Subjects appear to find it easier to act out the sensations and describe them verbally, the verbal preference was evident from the post-assessment question results. Subjects seemed to find it difficult to translate their sensations onto another object, such as the Worldup computer generated head. One solution may be to attach a tracker to the subject's head while on the rotating centrifuge. This would enable subjects to reenact their sensations while lying in the same position, using their own head. The tracker should be able to capture six degrees of freedom, consisting of three translational and three rotational components. This would avoid the problem of subjects having to isolate certain components of the complex self-motion. One disadvantage of this technique is that continuous tumbling sensations cannot be captured by a head nod. An alternative could be for the subject to hold the tracker instead of mounting it to the head

8. Additional Results and Discussion part two

8.1 Motion Sickness scores reported during the experiment

Motion-sickness scores obtained during the experiment were extracted from the data collection sheets. The time of each score was reported, as extracted from the timeline. Head movement videos recorded by the on-board camera were replayed and the number of head movements during light adaptation counted. Appendix M shows the motion-sickness scores reported during the experiment, the time each score was reported, cumulative number of head turns, motion-sickness scores/No. of head turns, No. of head turns till peak motion-sickness score, time till peak motion-sickness score and peak motion-sickness score.

No significant difference was found for the peak motion-sickness score with day for eight subjects [$F(2,14)=2.445$, $p=0.123$], although a decrease in scores can be seen with day. Figure 29 shows peak motion-sickness scores for eight subjects by day.

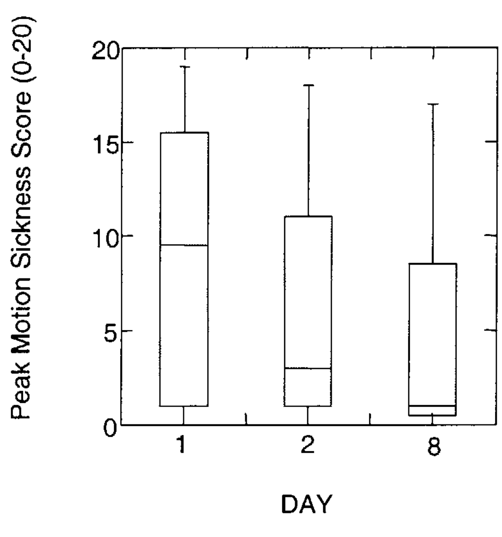


FIGURE 29-PEAK MOTION-SICKNESS SCORES (0-20) FOR EIGHT SUBJECTS, BY DAY.

During the adaptation period, subjects were instructed to make self-regulated head movements. The number of head movements therefore varied between subjects, and between days. The number of head movements made in the dark during pre- and post-adaptation phases were the same for each subject. No significant difference was found for the total number of head turns made during the adaptation period with day, for eight subjects [$F(2,14) = 0.034$, $p = 0.967$]. A 90-degree yaw head turn was counted as one head movement. Figure 30 shows the total number of head movements made during light adaptation for eight subjects by day, the average number of head movements for all subjects per day and the standard deviation.

Subject No.	Day 1	Day 2	Day 8
2	57	58	96
4	82	175	190
6	42	19	26
7	62	97	69
9	28	43	50
10	66	28	27
11	18	32	39
12	218	138	50
Average	71.625	73.750	68.375
Standard Deviation	62.710	57.256	54.251

FIGURE 30-TOTAL NUMBER OF HEAD MOVEMENTS MADE DURING LIGHT ADAPTATION FOR EIGHT SUBJECTS BY DAY, THE AVERAGE NUMBER OF HEAD MOVEMENTS FOR ALL SUBJECTS PER DAY AND THE STANDARD DEVIATION.

The time taken to reach the peak motion-sickness score was extracted from the recorded data and timeline. Zero time was taken to be the beginning of the light adaptation period. No significant difference was found for the time to peak motion sickness with day, [$F(2,8) = 3.102$, $p = 0.101$], although a decrease in time can be seen with day. Only five subjects have been included in the analysis as one subject consistently had a motion-sickness score of zero and two subjects experienced zero motion sickness on one of the three days. Figure 31 shows the time (seconds) to peak motion-sickness score by day for seven subjects. The subject who scored zero motion sickness on all three days has been omitted from the plot.

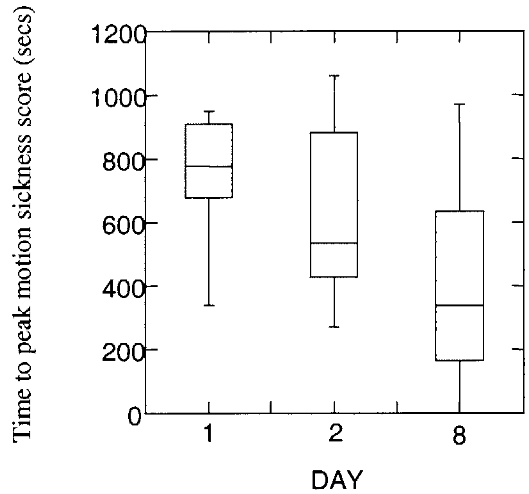


FIGURE 31-TIME TO REACH A PEAK MOTION SICKNESS SCORE (SECONDS) FOR SEVEN SUBJECTS, BY DAY.

In order to understand at what point in the experiment most subjects experienced the greatest motion-sickness symptoms, each of the subject's exposures were assigned to the appropriate category where the peak motion-sickness symptoms occurred. The categories consisted of: pre-light adaptation, post-light adaptation and one to ten minutes during light adaptation. Figure 32 shows the number of cases when peak motion-sickness scores were reached at that point during light adaptation. A case is defined as one exposure to the centrifuge, each subject was exposed three times. Nineteen out of twenty-four cases are shown in Figure 32, the remaining five cases have been omitted due to subjects experiencing zero motion-sickness symptoms.

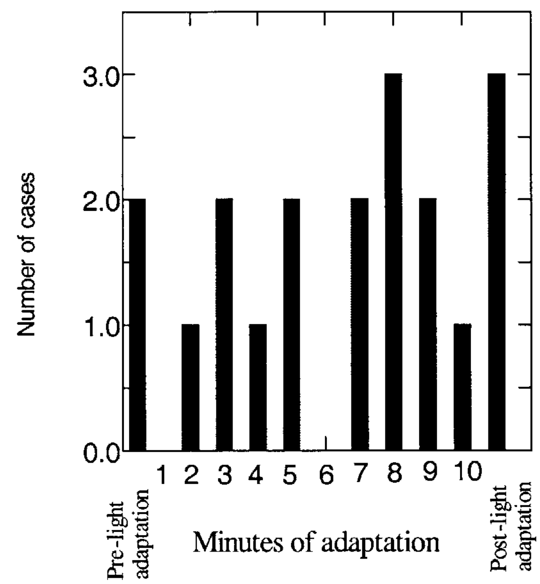


FIGURE 32-DISTRIBUTION OF NUMBER OF CASES WITH PHASE OF EXPERIMENT, DURING WHICH PEAK MOTION-SICKNESS SYMPTOMS OCCURRED.

8.2 Qualitative evaluation of peak motion-sickness scores and number of head turns

Peak motion-sickness scores recorded during the experiment do not show any significant difference with day. If subjects adapt and retain adaptation with repeated exposure, then one would expect a decrease in the peak motion-sickness score between days one and two, and retention of this adaptation to day eight. However, subjects were allowed to make self-regulated head movements during light adaptation. Since the number of head movements during this period was not consistent for each case, it is difficult compare motion-sickness scores. For example, does an increase in motion-sickness score result from the subject making more head movements which masked the effect of adaptation? Or does a decrease in motion-sickness scores result from the subject making less head movements rather than adaptation? Although a statistically rigorous analysis is not appropriate in this situation due to the small data sample with mixed results, valuable insights can be obtained from a qualitative analysis.

Inspection of the cumulative number of head movements show that five subjects increased head movements during light adaptation from day one to day two. Three of the five subjects showed a decrease in peak motion-sickness scores, one subject maintained the same motion-sickness score of two, and one subject showed a slight increase from zero to one, both of these can be considered as negligible motion sickness. The other three subjects all showed a decrease in head movements between days one and two. Two of these subjects reported an increase in peak motion-sickness scores and the other subject did not experience any motion-sickness symptoms. The interesting point to note is that subjects who showed an increase in head movements showed a corresponding decrease in peak motion-sickness (excluding the subjects who showed negligible motion-sickness scores). Whereas subjects who showed a decrease in the number of head turns also experienced an increase in peak motion-sickness symptoms (excluding the subjects who showed negligible motion-sickness scores). This rules out the hypothesis that peak motion-sickness scores decrease due to subjects making fewer head movements and peak motion-sickness scores increase due to subjects making more head movements.

The results imply that subjects who increase head movements during the adaptation phase from day one to day two, are able to do so because they adapt to the stimulus enough that the peak motion-sickness symptoms decrease despite the additional stimulus caused by extra head movements. Subjects who reduce head movements from day one to day two appear not to be able to adapt to the stimulus during the experiment, as the peak motion-sickness scores increase despite the decrease in stimulus. There appear to be three distinct groups of subjects, consisting of 1). Subjects who reduce head movements from day one to two, and show increased levels of motion sickness. This group appears not to be able to adapt to the stimulus during the experiment with repeated exposure. This is verified by the peak motion-sickness scores of day eight which are comparable to days one and two. 2). Subjects who increase head movements from days one to two and show a decrease in peak motion-sickness scores. This group appears to be able to adapt to the stimulus during the experiment and reduce motion-sickness symptoms, despite the additional stimulus from the increased number of head movements. This is verified by the lower peak motion-sickness scores for all subjects in this category for day eight. 3). Subjects who show very low motion-sickness scores <2 during all three days. These subjects do not appear to be affected by the stimulus during the experiment. However, no clear conclusion can be drawn from this discussion due to the small sample of subjects tested.

Recommendations for future experiments include standardizing the protocol to ensure all subjects perform the same number of head turns during light adaptation. This will enable direct comparison of the motion-sickness scores, which can then be used as a measure of adaptation. One disadvantage of using this technique is that subjects tolerate different numbers of head movements, therefore a standard protocol which may be suitable for one subject may cause severe motion-sickness symptoms for another subject. If this approach is used, subjects may have to be pre-selected to ensure similar tolerance for motion sickness. A larger sample of subjects would enable a more rigorous statistical analysis of this data, this would enable the suggestion that three distinct types of subjects exist to be verified or disproved.

8.3 Time to reach peak motion sickness

No significant difference was found for the time taken for subjects to reach a peak motion- sickness score with day. This is a surprising result, as one would expect the time to increase with repeated exposure. Figure 32 shows that there is a relatively even distribution of the number of cases with phase of experiment during which peak motion-sickness symptoms occurred. Therefore, there is no common phase in the experiment where subjects typically experienced peak motion sickness. The phases of the experiment can be grouped into light and dark phases. The dark phase consisted of pre- and post-adaptation, and ten minutes of light adaptation. 58% of cases during which peak motion-sickness symptoms occurred were during light adaptation, 21% were during the dark phase, and no motion-sickness symptoms were experienced during 21% of cases.

Sensory conflict theory of motion sickness (for an overview see Oman, 1998) predicts that motion sickness is caused by a conflict, resulting from a comparison of information provided by different sensory modalities. This suggests that motion sickness should be more severe during light adaptation when visual information conflicts with vestibular information. In the dark, visual information is not present and therefore does not contribute towards the conflict. The results suggest that the majority of cases during which peak motion-sickness symptoms occur were during light adaptation, where visual conflicting signals were present. However, other factors in the design of the protocol may be responsible for this result. Light adaptation was the longest section of the protocol and involved more head movements than pre-and post-adaptation. Therefore, achieving peak motion sickness during light adaptation may have been due to making more head movements over a long period of time, rather than the visual conflict. Future studies may wish to investigate the role of visual cues on motion sickness and compare motion sickness-scores in the light and dark.

9. Conclusion

Verbal accounts of perceived pitch, motion-sickness scores and computer animations of subjective sensations were obtained from eight subjects. Verbal accounts of perceived pitch obtained during rotation and post-experiment motion-sickness scores provide clear evidence of adaptation to the stimulus between days one and two, and some retention of adaptation to day eight. Computer animations of subjective sensations and motion-sickness scores obtained during the experiment do not provide conclusive evidence of adaptation or retention of adaptation. The validity of these techniques were explored, along with a qualitative analysis of the results.

The results show that subjects do adapt to making head turns during short-radius centrifugation with repeated exposure, and are able to retain most of this adaptation for five days. The results therefore support the hypothesis that adaptation is achieved after two centrifuge sessions, and that adaptation is retained or partially retained (depending on the measure of adaptation) for five days. However, the number of days over which adaptation can be retained is unknown. Assuming that the same mechanisms for adaptation occurs in microgravity as in Earth's gravity, the results provide evidence for the ability of humans to develop adaptation to head movements during short-radius centrifugation in weightlessness. Future studies may wish to investigate the ability of humans to transfer adaptation achieved to head movements made during short-radius centrifugation on Earth, to the same rotating environment in weightlessness. If this is proven, then astronauts may be able to become pre-adapted to the rotating environment before the mission. This will enable them to transition between the rotating and non-rotating environments without any perceived self-motion or motion sickness. The results therefore provide evidence of adaptation and retention of adaptation, which supports the efficacy of short-arm centrifugation as a possible countermeasure to the debilitating effects of the zero gravity environment on the human body.

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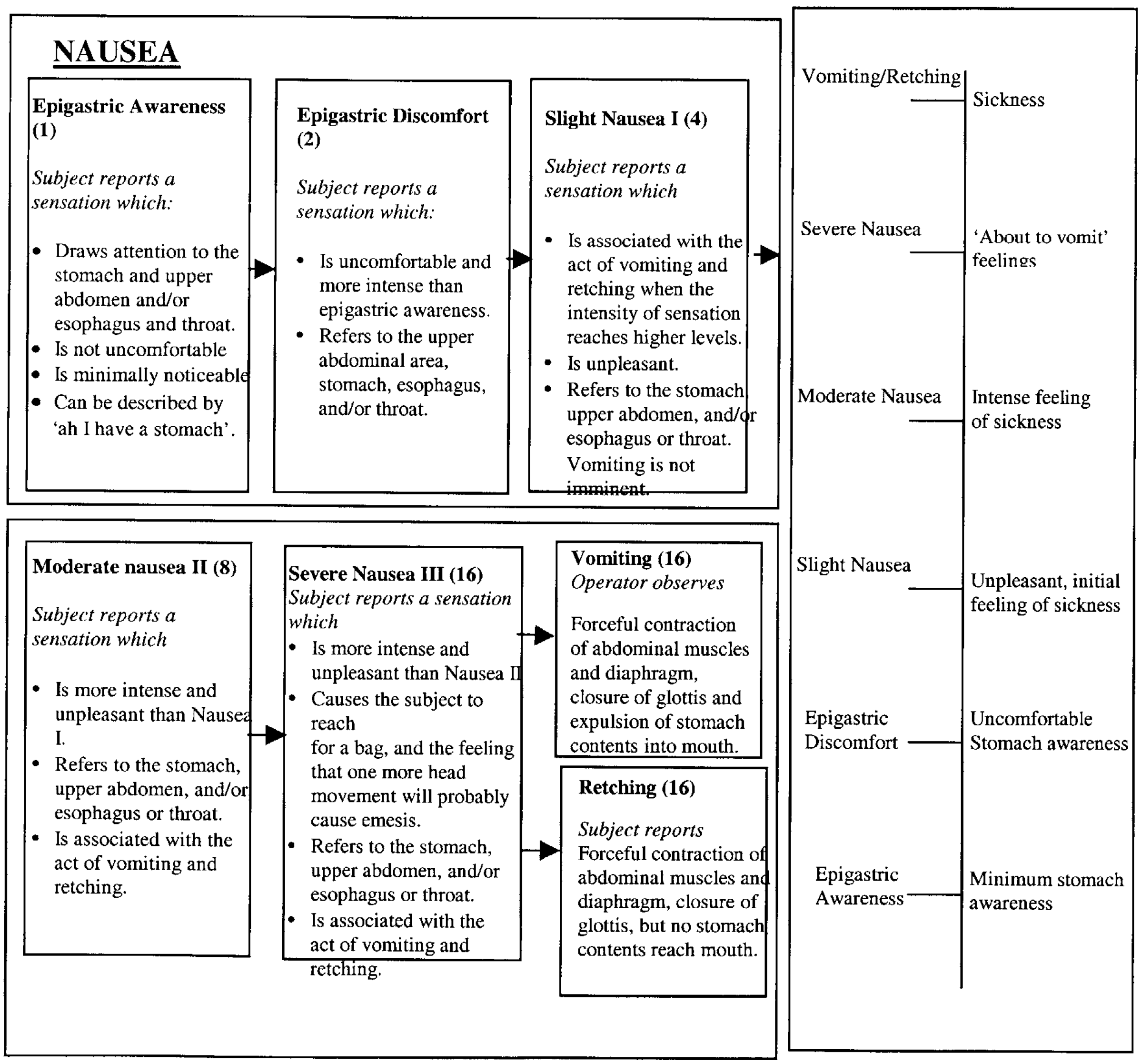
APPENDIX A - Pensacola diagnostic index method for scoring motion-sickness symptoms

The numbers in brackets indicate the score assigned to the motion-sickness symptom severity level.



TEMPERATURE

Moderate Flushing/subjective warmth II (1)

Flushing
Operator observes

- Increased reddening of skin, usually starting on the face and neck.

Subjective warmth
Subject Reports

- A gradual or sudden sensation of increased warmth of the surface of the body. The warmth may also be localized to the chest, back, under arms or thighs. (either of the two symptoms experienced separately or together constitutes one point).

→

Severe Flushing/subjective warmth III (1)

Flushing

Operator reports
- Same definition as II but more severe.

Subjective Warmth

Subject Reports
- Same definition as II but more severe.

PALLOR

Slight Pallor I (2)

Operator Observes

- Noticeable blanching or whitening (paling) of the skin color on the face. (It may not involve the entire face, but be limited to small areas such as around the nose and mouth or the ear lobes.

→

Moderate Pallor II (4)

Operator observes

- Loss of color to the subject's entire face, and possibly
- ears, neck, and upper chest.
- Blotchy appearance.
- More noticeable effects than Pallor I.

→

Severe Pallor III (8)

Operator observes

- Complete loss of color to the Subject's face and upper torso.
- White or green skin.
- 'White as a ghost' subject
- More noticeable effects than Pallor II

SALIVATION

Slightly increased salivation I (2)

Subject reports

- Noticeable increases in the amount of saliva accumulating in his/her mouth, and consequently an increased need to swallow.

→

Increased Salivation II (4)

Subject reports

- An increase in the amount of excess saliva accumulating in the his/her mouth more than I.
- Increased frequency of swallowing.

→

Increased Salivation III (8)

Operator observes

- Copious amounts of saliva.
- Drooling from the mouth.

SWEAT

Slight Sweat I (2)

Subject reports

- Awareness of a light amount of sweat on the forehead, upper torso or under arms.
- A mild clammy or sticky feeling before the actual appearance of beads of sweat.
- Cold skin due to sweat evaporation.

→

Moderate Sweat II (4)

Subject reports

- A generalized body sweat that feels cool due to evaporation.

Operator observes

- Small beads of perspiration, typically on the forehead and face.
- Dampening of tight clothing.

→

Severe Sweat III (8)

Subject reports

- A profuse whole body sweat.

Operator observes

- Sheets or rivulets of sweat on exposed parts of the subjects body, especially the face and neck.
- Noticeable damp clothing, particularly on the chest, under arms and back.

DROWSINESS

Slight Drowsiness I (2)

Subject reports

- A slight decrease in mental alertness.
- The feeling of being slightly sleepy.
- Boredom, apathy and/or fatigue.

→

Moderate Drowsiness II (4)

Subject reports

- The feeling of easily being able to fall asleep.

Operator observed

- The subject's desire to fall asleep.

→

Severe Drowsiness III (8)

Operator observes

- The subject literally falling asleep during the test.
- Inability of the subject to perform the required tasks, even when prompted.

HEADACHE

Moderate headache II (1)

Subject reports:

- A moderate headache which was not present prior to the test, and which the subject feels is a symptom.

→

Severe Headache III (1)

Subject reports:

- A severe headache which was not present prior to the test, and which the subject feels is a symptom.

DIZZINESS

Moderate dizziness II (1)

Subject Reports:
- Dizziness
- Feathers in the head
- Vertigo
- Spatial disorientation
- wobbliness
- Unsteadiness

(at moderate levels)
(Any of the above sensations should be present at moderate levels and persist beyond several seconds after the subjects head stops moving, in order to score).

→

Severe Dizziness III (1)

Subject reports:
- Dizziness
- Feathers in the head
- Vertigo
- Spatial disorientation
- wobbliness
- Unsteadiness

(all at severe levels)
(Any of the above sensations should be present at severe levels and persist beyond several seconds after the subjects head stops moving, in order to score)

Appendix B - Human Interface Technology Laboratory Technical Report

Draft 3/22/99

Human Interface Technology Laboratory Technical Report No. xxxx

A Procedure for using Real-Time Computer-Generated Animations to Assess Self-Motion Perception.

D. E Parker[1] and L. E. Lyne[2]

[1] Department of Otolaryngology - Head & Neck Surgery and Human Interface Technology Laboratory, University of Washington, Seattle, WA 98195-7923
[2] Department of Aeronautical and Astronautical Engineering and Manned Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge, MA

Introduction

In a paper entitled "Self-Motion Perception: Assessment by Real-Time Computer-Generated Animations", Parker and Phillips described a new procedure for assessing complex self-motion perception. The abstract for that presentation is included in Appendix 1.

The purpose of this Technical Report is to facilitate use of the real-time computer-generated animations in other laboratories.

Apparatus and Procedure

The apparatus and procedure used by Parker & Phillips were as follows. Subjects "reported" real and illusory self-motion by moving doll head in which Polhemus 3Space® Fastrak® 6 degree-of-freedom sensor was embedded. Movement of the sensor produced corresponding motion of a virtual head displayed on a computer monitor using a Pentium Pro® 200 MHz processor and a Matrox Millennium 4 MB graphics accelerator. "Real-time" virtual head motion was generated using WORLD UP© (Sense 8) at 24 frames per sec. Virtual head movement data were saved for later analyses using the virtual video recorder built into the WU Path Browser.

Complex self-motion was evoked by cross-coupled angular acceleration. Subjects manipulated the real doll head so that the virtual doll head displayed on the monitor moved in a manner that corresponded to their own perceived head motion during the cross-coupled angular acceleration stimulus. Only rotations were displayed; translations were disabled to simplify the task. Primary emphasis was on directions of head movement; accurate representation of time-course was not stressed. After the subjects were satisfied that their manipulation corresponded to their perceptual experience, the animation was saved using the virtual video recorder for later analysis.

Implementation

Implementation of the procedure described by Parker & Phillips requires WORLD UP© (WU, see http://www.sense8.com/ or call Brad Swift, 415 339-3232) Release 3.

(Release 2 can be used but requires a "patch" so that the motion link from the tracker to the head can be set to "parent" as described below.) WU supports a variety of trackers including the Polhemus Fastrak, Flock of Birds and Intersense.

Files Needed

Four files can be downloaded from this web site to get you started.

Barbaranew.up. This is the basic WU) file to support the procedure. It should be placed in the Worlds folder.

Barbaranew.nff. This is the virtual head whose motion is driven by the tracker. It should be placed in the Models folder.

01.mat. This is the materials table for the Barbaranew head. It should also be placed in the Models folder.

reset.ebs. Attach the reset script to an object "The Universe" under the Universe Type. (Use the WU tutorial to learn how to create objects.)

Reset Script

As above, attach the reset script to an object "The Universe" under the Universe Type. As can be determined by reading the script, typing a "1" returns the Barabaranew head to its initial position and orientation if a disturbance occurs in the "object select" mode; typing a "2" returns the head to its initial position and orientation if the disturbance occurs in the "navigate" mode. The window in which the head is displayed must be "active" for the reset script to work properly. If the Path Browser window is active, the reset script won't work. "Click" on the window in which the head is displayed to activate it.

Motion Links

Create a motion link (motion link 2) from the tracker object (e.g., Fastrak-1) to the Barbaranew head. The reference frame for that link should be "Parent", not "Local" (see the Motion Link properties box).

Tracker Control of Head

The Barbarahead should be movable using either a mouse of the tracker. Check the WU manual regarding mouse control of head motion.

The tracker baud rate should be set to 19200 and the output configured for 1 tracker. Connect the tracker to the computer's COM2 port with null modem cable.

Set the serial port to COM2 in Fastrak properties box and create a Fastrak-1 object.

Locate transmitter and receiver in same relative positions they will be used in for recording before turning on the apparatus.

Create a motion link from Fastrak-1 to Barbaranew.

The defaults in the current WU release may require the tracker to be rotated 90 degrees in yaw to produce the appropriate correspondence between tracker and Barbaranew head motion.

Fastrak permits control of head motion in 6 degrees-of-freedom. To simplify the subject's task we suppress translatiional; motion by setting the Fastrak sensitivity property to 0.

For self-motion reporting, we orient the virtual head to that the observer sees it from the rear. They can then make the head yaw rightward by moving the tracker rightward, etc. This avoids making the subject perform coordinate transformations.

Path Recording

In the Path Browser, create a new path. Double click the Pth-1 to open a properties box that allows you to link the Pth-1 to Barabaranew. Note that the "record from" window also indicates Barbaranew.

Recording and playback can be accomplished using the virtual VCR which is built into the Path Browser.

To work properly with WU defaults, apparently you need to save path files in the Models folder.

If you import a saved *.pth file into the Path Browser, double click the path name to open a window, and link the path to Barbaranew. You should then be able to play the previously recorded path.

Saved path files can be read and plotted using Excel. Path files can be deciphered by "brute force and ignorance": simply record various motions and determined what was recorded by reading the path file into Excel .

Appendix C – Medical Questionnaire

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

Appendix D - Medical disqualifying conditions

- Experiences with the rotating centrifuge 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 trouble

Appendix E - Data collection and subject briefing sheets

Artificial Gravity Study

Subject Identification:

Experiment Number:

Date:

Session:

Date of Previous Sessions:

Filename:

Files Created and Location:

1. Explain the various stages of the experiment to the subject

Subject Guidelines

<u>Pre-test Briefing</u>

- Consent Form
- Explanation of protocol
- Subjective briefing

↓

<u>Preparation for Centrifuge</u>

- Medical Checks
- Explanation of equipment / safety features
- Angular Rate Sensors
- Eye goggles/Calibration
- Explanation of head movement protocol
- Practice yaw head movements

↓

<u>Centrifuge Experiment</u>

- Rotation in dark with head movements
- Rotation in light with head movements
- Rotation in dark with head movements
- Subjective reports

↓

<u>Post Centrifuge</u>

- Motion sickness and self-motion sensation data collection

2. Consent Form

Give subject consent form and obtain signature

3. Pre-test briefing

a. Verbal report of sensations experienced during yaw head turn

During the forth set of yaw head movements, both pre-and post-adaptation, you will be asked to give a verbal account of your sensations when making head turns from RED to NU and NU to RED. Listed below are some terms, which may be of use when describing the sensations. Reports will also be taken after 5 minutes of light adaptation.

Pitch: Rotation of your head as though you were bowing. Pitch may be forwards or backwards.
Yaw: Sideways motion of the head, for example looking right and looking left, while keeping the head vertical.
Roll: Tilting of the head from side to side, while still looking forward.

b. Motion-sickness score (using the 0-20 scale)

During the experiment you may experience symptoms of motion sickness, similar to those experienced during sea-sickness. As a result you will be asked to give a rating on a 0 to 20 scale to represent your overall feeling of discomfort. A score of 0 represent 'I am fine' and a score 20 represents vomiting. The operator will say 'please give me a score 0-20' to which you must reply with a value as soon as possible. During the light adaptation phase the frequency of surveying will increase to one every minute. During the light adaptation phase you need to make as many head movements as possible, it is important to tell the operator if you reach the stage when you cannot make anymore head movements. Also, inform the operator if you experience any specific symptoms, for example sweaty, hot, cold etc.

c. Worldup computer animation training

Sense 8 Worldup software has been configured in the VR lab to enable subjects to recreate using computer animation their sensations during yaw head movement in the dark. You will practice using the tracker and become familiar with using the software. After completing the protocol on the centrifuge, you will then use the software to reenact how your head felt during yaw head movement made in the dark on the rotating centrifuge.

e. General medical questions

Choose one of the following categories to describe how you feel today

Extremely good (full of energy)	
Slightly better than normal	
Normal	
Slightly worse than normal	
Extremely poor	

f. Mount subject on the centrifuge

g Calibrate I-Scan

h. General instructions for operating equipment on the centrifuge

i. Instructions for making head turns

j. Put Canopy on centrifuge

4. Centrifuge data collection

Record 0-20 motion sickness scores and verbal reports at the following positions indicated in the protocol. Note any comments made by the subject, for example 'I am feeling warm'

Time	**Position during trial**	**Score (0-20)**	**Comments**
	Before experiment starts		
	After 3 yaw head movements (non-rotating)		
	After acceleration to 23rpm		
	After 3 yaw head movements (rotating)		
	RED-HU (4^{th})(Verbal Description)		
	Confirm no. of degrees of pitch, if reported		
	HU-RED (4^{th})(verbal Description)		
	Confirm no. of degrees of pitch, if reported		
	After 1 min (adaptation)		
	After 2 min		
	After 3 min		
	After 4 min		
	After 5 min		
	RED-HU (Verbal description)		
	Confirm no. of degrees of pitch, if reported		
	HU-RED (Verbal description)		
	Confirm no. of degrees of pitch, if reported		
	After 6 min		

	After 7 min		
	After 8 min		
	After 9 min		
	After 10 min		
	After 3 yaw head movements (rotating)		
	RED-HU (4th) (Verbal description)		
	Confirm no. of degrees of pitch, if reported		
	HU-RED (4th) (Verbal description)		
	Confirm no. of degrees of pitch, if reported		
	After dec to 0		
	After 3 yaw head movements (non-rotating)		

5. Post-experiment data collection

a. Verbal reports

Verbal report describing the sensations experienced during yaw head turns from RED to NU and NU to RED on the rotating platform in the dark, before adaptation.

RED - HU

HU-RED

Verbal report describing the sensations experienced during yaw head turns from RED to NU and NU to RED on the rotating platform in the dark, after adaptation.

RED-HU

HU-RED

6. General questions part 1

a. Did you experience any roll component during yaw head turn in the dark?
If so, approximately how many degrees and in what direction?

b. Did the yaw component feel like a full 90-degree turn, from RED to NU?

c. Are you experiencing any strange visual illusions or sensations?

d. At what point did you feel the most discomfort during centrifugation?

7. Pensacola motion sickness survey

Category	Score
Nausea	
Temperature	
Pallor	
Sweat	
Salivation	
Drowsiness (persistent feeling – long after stopped moving head)	
Headache	
Dizziness	
Total Score	
Severity level	

8. Worldup computer animation

Recreate the sensation experienced using the Worldup computer animation software and space-ball, when making yaw head turns from RED to NU and NU to RED on the rotating centrifuge in the dark.

9. General questions part 2

a. On a scale of 0-10, how accurately does the Worldup animation recreate the sensation you experienced (0 = not very accurately, 10 very accurately)?

b. On a scale of 0-10, how difficult is it to use Worldup to recreate your sensations? (0 = not very difficult, 10 very difficult)

c. Which technique enables you to best describe the sensations felt when describing yaw head turns on the rotating centrifuge, verbal or Worldup computer animation?

d. Did you feel like you were rotating while on the centrifuge, after the initial acceleration to constant velocity?

10. Comparison with previous days

a. How does your motion sickness compare with previous days?

b. How do your sensations experienced when making yaw head turns in the dark compare with previous days?

c. Do you feel like you are retaining adaptation to the stimulus?

11. Post Motion Sickness Survey

Complete the following form every 30 minutes starting from now until you go to bed, rating your overall feeling of discomfort from 0-20. Use the same scale as used on the centrifuge. Also, assign one value to describe your feeling when you awake in the morning.

Time	***Scale (0-20)***

Appendix F – 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 G – Pensacola Motion-Sickness Scores

Pensacola	Sub 2 Day 1	Sub 2 Day 2	Sub 2 Day 8	Sub 4 Day 1	Sub 4 Day 2	Sub 4 Day 8	Sub 6 Day 1	Sub 6 Day 2	Sub 6 Day 8	Sub 7 Day 1	Sub 7 Day 2	Sub 7 Day 8
Nausea	4	2	1	0	0	0	16	4	4	0	0	0
Temp	1	1	1	0	0	0	1	1	1	0	0	0
Pallor	2	0	2	0	0	0	2	2	2	2	2	0
Sweat	0	0	0	0	0	0	0	4	0	0	0	0
Salivation	0	0	0	0	0	0	2	2	2	0	0	0
Drowsiness	2	2	0	0	0	0	0	0	0	0	2	0
Headache	0	0	0	1	1	0	1	0	1	0	0	0
Dizziness	0	0	0	0	0	0	1	1	0	0	0	0
Total Score	**9**	**5**	**4**	**1**	**1**	**0**	**23**	**14**	**10**	**2**	**4**	**0**
Severity	Severe Malaise	Mod Malaise	Mod Malaise	Slight Malaise	Slight Malaise	No effects	Frank sickness	Severe malaise	Severe malaise	Slight malaise	Mod Malaise	No effects

	Sub 9 Day 1	Sub 9 Day 2	Sub 9 Day 8	Sub 10 Day 1	Sub 10 Day 2	Sub 10 Day 8	Sub 11 Day 1	Sub 11 Day 2	Sub 11 Day 8	Sub 12 Day 1	Sub 12 Day 2	Sub 12 Day 8
Nausea	1	1	1	8	2	2	4	0	0	0	0	0
Temp	0	1	0	0	0	0	1	0	0	0	0	0
Pallor	2	2	2	2	2	2	2	2	0	2	0	0
Sweat	4	0	2	0	0	0	2	0	0	0	0	0
Salivation	0	0	0	0	0	0	0	0	0	0	0	0
Drowsiness	4	0	2	2	4	2	4	0	0	0	0	2
Headache	0	0	0	0	0	0	0	0	1	0	0	0
Dizziness	0	0	0	1	0	0	0	0	0	0	0	0
Total Score	**11**	**4**	**7**	**13**	**8**	**6**	**13**	**2**	**1**	**2**	**0**	**2**
Severity	Severe Malaise	Mod Malaise	Mod Malaise	Severe Malaise	Severe Malaise	Moderate Malaise A	Severe Malaise	Slight Malaise	Slight Malaise	Slight Malaise	No effects	Slight malaise

Note: Each of the subjects were assigned a number (2,4,6,7,9,10,11 &12). Missing numbers are due to subjects who were unable to complete the experiment or apparatus failure.

Appendix H – Post experiment motion-sickness scores

The table below shows the post-experiment motion-sickness scores recorded every 30 minutes after the experiment (using the 0-20 scale).

Time	S2 D1	S2 D2	S2 D8	S4 D1	S4 D2	S4 D8	S6 D1	S6 D2	S6 D8	S7 D1	S7 D2	S7 D8	S9 D1	S9 D2	S9 D8	S10 D1	S10 D2	S10 D8	S11 D1	S11 D2	S11 D8	S12 D1	S12 D2	S12 D8
Min																								
30	10	3		0	0	0	3	16	4	0	0	0	3	1	2	10	2	5	8	1	1	0	0	0
60	4	2		0	0	0				0	0	0	4	1	1	5	0	5	8	1	1	0	0	0
90	3	2		0	0	0		12	2	0	0	0	4	1	0	2		5	5	0	1	0	0	0
120	3	1		0	0	0				0	0	0	3	1	0	5		5	4		1	0	2	0
150	3	0		0	0	0	3			0	0	0	3	1	0	5		2	4		1	4	2	0
180	2	0		0	0	0			0	0	0	0	3	0	0	5		0	2		1	4	2	0
210	2	0		0	0	0		5		0	0	0	3	0	0	5			1		0	4	2	0
240	2	0		0	0	0				0	0	0	3	0	0	5			0			4	2	0
270	1	0		0	0	0				0	0	0	3	0	0	5						2	2	0
300	0	0		0	0	0				0	0	0			0	5						2	2	0
330	0	0		0	0	0				0	0	0			0	5						2	2	0
360	0	0		0	0	0			2	0	0	0			0	5						2		0
390	0	0		0	0	0		3	0	0	0	0			0	0								0
420	0	0		0	0	0				0	0	0			0									0
450	0	0		0	0	0				0	0	0			0									
480	0	0		0	0	0	2			0	0	0			0									
510	0	0		0	0	0				0	0	0			0									
540	0	0		0	0	0		0		0	0	0			0									
570	0	0		0	0	0					0	0			0									
600	0				0	0					0	0												
630	0				0																			
660	0				0																			
690	0																							
720	0																							
750	0																							
780	0																							
810	0																							
840	0																							
870	0																					0 (m)	0 (m)	
900	0																							
930	0																							
960							0 (m)																	
990																								
1020																								
morning				0	0	0		0	0	0				0			0		0	0	0	0	0	0
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Appendix I – Verbal Reports

The table below shows the verbal reports obtained during centrifugation. The numbers represent the no. of degrees in pitch (+ refers to pitch forwards and – refers to pitch backwards).

S2	Pre adap				Adap				Post adap			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	-50	spinning, pitch nose up (translated to pitch back)	40	nose down (translated as pitch forward)	-30/-40	nose up (translated as pitch back)	35	nose down (translated as pitch forwards)	-40	nose up (translated as pitch back)	30	nose down (translated as pitch forwards)
D2	-30	pitch back	25/30	pitch forward	-25	pitch back, head down, feet up	20	pitch forwards, nose down	-15	pitch back	10	pitch forward
D8	-15	pitch back, nose up	5	pitch forward, very little	-10	pitch back	2	pitch forward, nose down	-5	pitch back, very small	1/2	pitch forward, barely noticeable

S4	Pre adap				Adap				Post adap			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	80	nose down (translated as pitch forwards), swinging around to left	-30	nose up (translated as pitch back) feet up, turning to right	40	Feet down, pitch forward, move to left	-10	pitch back	60	pitch up (confusion about direction intended, according to post account motion was pitch forwards)	-40	pitch down (confusion about direction intended, according to post account motion was pitch forwards backwards)
D2		whole body forwards, head up, pitch down (confusion about intended direction, according to post account motion was pitch forwards)	-50	pitch back, turn to left, feet up head back	70	head up, feet down (translated as pitch forwards)	-40	pitch backwards	50	pitch forwards, feet down, head up	-25/-30	pitch back
D8	40	pitch forwards	-20	pitch back	30	pitch forwards	-10	pitch back	30	pitch forwards	-10	pitch back

S6	Pre adap				Adap				Post adap			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	no value	disc rotating to left and pitch forward	no value	pitch back, moving back on big disc, no discrete angle	no value	spinning down, environment is spinning down	no value	pitched back from my body	no value	pitching forward not as much as before, 25% of last head movement	no value	no comments

D2	20	sensation less, head rotation same speed as previous trial, pitch forward	-30/-35	pitch back, rotation to the side, weird disorientation, pitch back greater than pitch forward	30	pitch forward	-35	pitch back, towards right ear	45	pitching forward, constantly pitching forward, angular velocity 8sec/rev	-30	pitching back, value given is a magnitude of sensation rather than actual degrees
D8	20	pitching forward, spinning with bed	-50	pitch back	10/20	pitch forward	no value	small pitch back and roll to the right	20	pitch forward	-40	pitch back

S7	Pre adap				Adap				Post adapt			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	-35	pitch back and to the right, rotation about an angle 20 degrees about axis of body	20	pitch forward, confirmed during post subjective data collection	10	slight forward pitch (different direction compared to post and dark subjective data)	-15/-20	backward pitch (different direction compared to post and dark subjective data)	-30	2 second feeling of pitch back	20	1 to 2 sec pitch forward
D2	-10	slight pitch back, larger on first couple of turns	15	pitch forward	-10	slight pitch back, canopy moves down	15	pitch forward	-10	pitch back, small magnitude, continued for 2 secs	less than 10 degrees	0.5 second pitch forward
D8	-50	pitch back for 1.5 secs	40	pitch forward, just less than 1 second	-10	canopy translating down, I am pitching back	no value	pitch forward, more environmental pitch back, nothing meaningful	no value	very little experienced	15	pitch forward and slightly to the left

S9	Pre adapt				Adapt				Post adapt			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	360	pitch forward full rotation	-720	pitch backwards 2 revolutions	180	pitch forward, to the right and down	-360	pitch backwards	720	pitch forwards	-720	pitch backwards
D2	>360	pitch forwards	-360	pitch backwards	180	pitch forwards	no value	yaw top the right	360	pitch forwards	-360	pitch back and yaw to the right
D8	720	pitch forwards	-720	pitch back	720	pitch forwards	no value	roll to the right (no pitch)	720	pitch forwards	-720	pitch backwards

S10	Pre adapt				Adapt				Post adapt			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	+/- 30	Pitching oscillations both up and down, died out within a few seconds.	+/-30	Roll to the right	No value	Circular motion in clockwise direction, pitch and yaw.	+/- 10/15	Circular motion in counterclockwise direction, pitch and yaw.	+/-15	Rotation clockwise, pitch and roll.	+/-15	Counterclockwise rotation.

D2	+/-10	Rotating clockwise	+/- 10/15	Rotation counterclockwise of eyes and head.	+/-15	Rotation clockwise	+/- 10/15	Rotation counterclockwise, damped oscillations.	+/-10	clockwise rotation	+/-10/15	Counterclockwise rotation.
D8	+/-15	clockwise rotation of field of view, pitch oscillations, damped.	+/- 15	counterclockwise rotation of field of view, damped oscillations.	+/- 15	Clockwise rotation of field of view, oscillations	+/- 15	counterclockwise rotation, pitch component, oscillations.	+/-15	pitch and clockwise turn, oscillations.	+/-15	counterclockwise rotation, pitch component.

S11	Pre adapt				Adapt				Post adapt			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	30	Pitch forwards, right side tilted down (15 degrees)	- 30/40	Pitch back at an angle along my body	40	Pitch forwards	-40	Pitch back	30	Pitch forwards at an angle	-30	Pitch back at an angle
D2	20	pitch forwards, body at an angle	-35/40	Pitch back, body at a smaller angle.	45	Pitch forwards, off to the side	-10	Pitch back	10	Pitch forwards, body at a smaller angle	-5	Pitch back
D8	20	pitch forwards	-40	pitch back, body tilted right side down	5	pitch forwards, body right side down	-10	pitch back	5	pitch forwards, body tilted right side down	-5	pitch back, body tilted

S12	Pre adapt				Adapt				Post adapt			
	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments	RED-HU	comments	HU-RED	comments
D1	20	pitch forwards	10	pitch forwards	no value	spin clockwise, vision swirling, no head sensation	10	pitch forwards, swirling vision	10	head swirls, pitch forwards	10	pitch forwards
D2	10	pitch forwards	0	nothing	5	pitch forwards	5	pitch forwards	5	pitch forwards	3	pitch forwards
D8	5	pitch forwards	5	pitch forwards	5	pitch forwards	5	pitch forwards	3	pitch forwards	2	pitch forwards

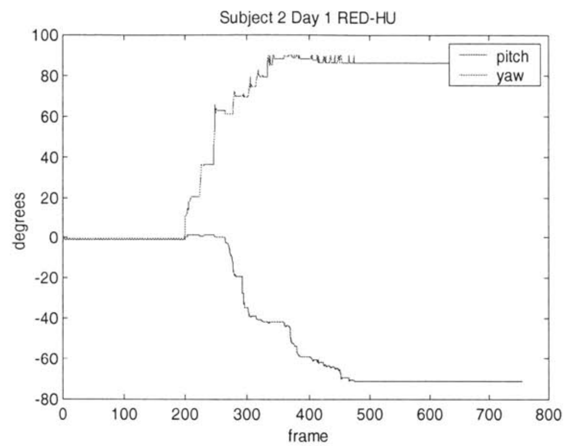
Appendix J – Matlab code for Worldup analysis

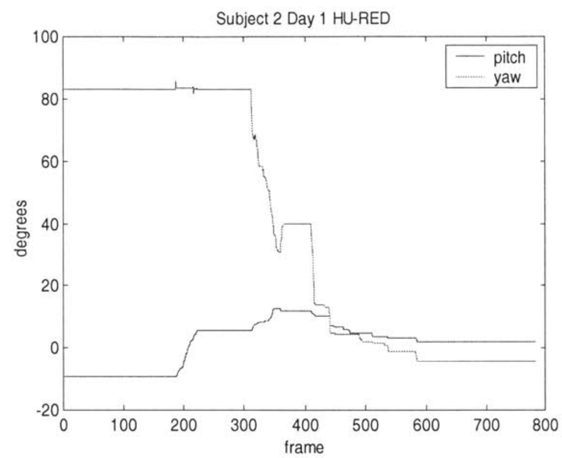
```
load ps12wubt3t.txt;
filename=ps12wubt3t;
[r,c]=size(filename);
data1=filename(:,1), data2=filename(:,2), data3=filename(:,3);
for i=1:(r/2-1);
   data1a(i)=data1(2*i+1);
   data2a(i)=data2(2*i+1);
   data3a(i)=data3(2*i+1);
   end
data1b=transpose(data1a);
data2b=transpose(data2a);
data3b=transpose(data3a);

load ps12wubt3f.txt;

E1=data1b;
E2=data2b;
E0=data3b;
E3=ps12wubt3f;

r=asin(2.*E0.*E2-2.*E1.*E3);
p=asin((2.*E1.*E2+2.*E0.*E3)./cos(r));
y=asin(2.*E2.*E3+2.*E0.*E1)./cos(r);

rdeg=r.*360/(2*pi);
pdeg=p.*360/(2*pi);
ydeg=y.*360/(2*pi);

i=1:size(rdeg);
k=transpose(i);

plot(k,pdeg,'b')
hold
plot(k,ydeg,'r')
xlabel('frame')
ylabel('degrees')
title('Subject 12 Day 7 HU-RED')
legend('pitch', 'yaw')
```

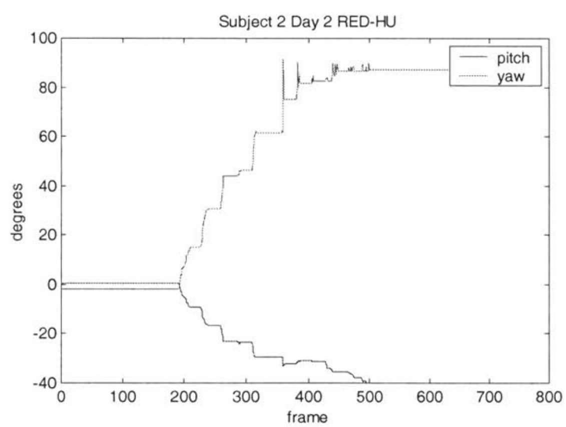
Appendix K – Worldup pitch and yaw plots

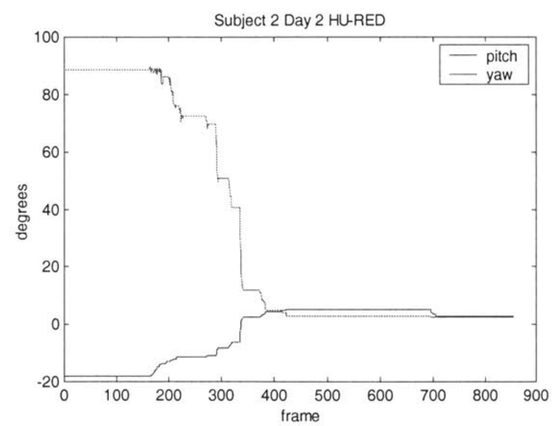
The graphs below show the pitch and yaw profiles recorded with the Worldup software and tracker.

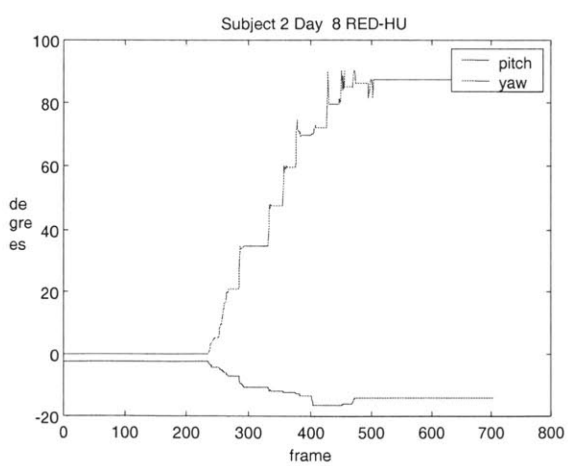
Subject 2

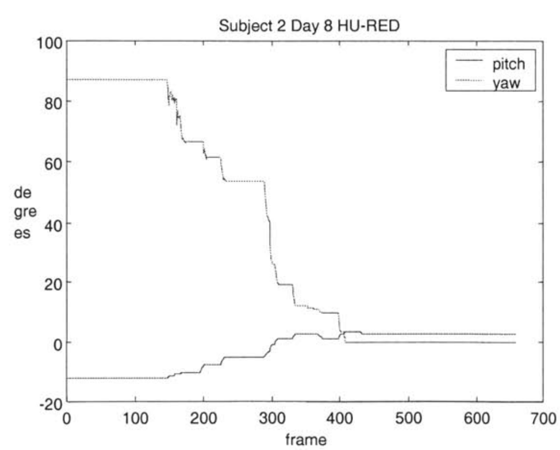




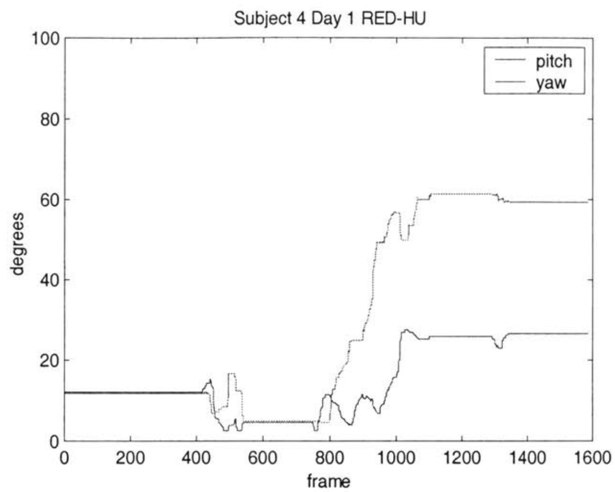




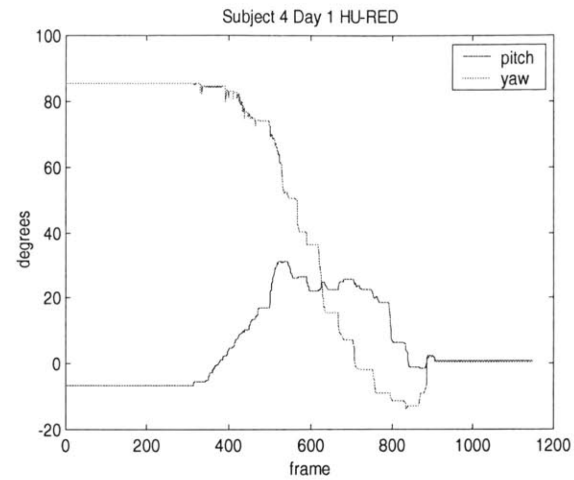




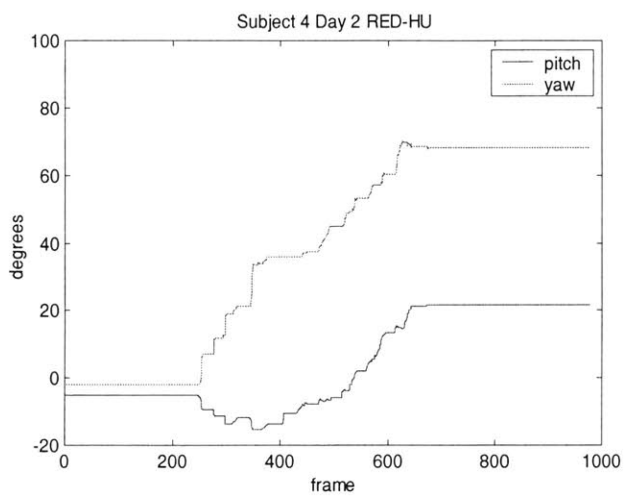
Subject 4



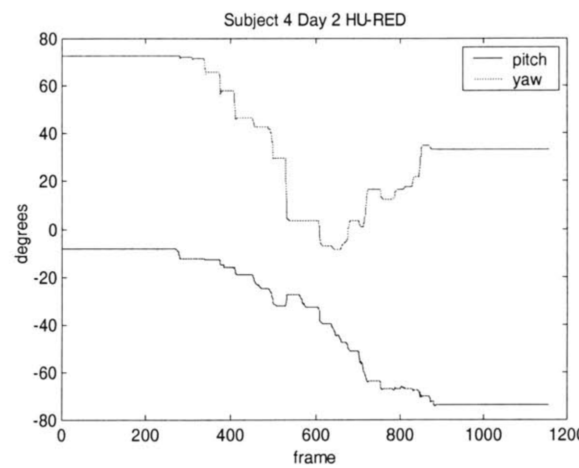
Subject 4 Day 1 RED-HU
pitch
yaw
degrees
frame



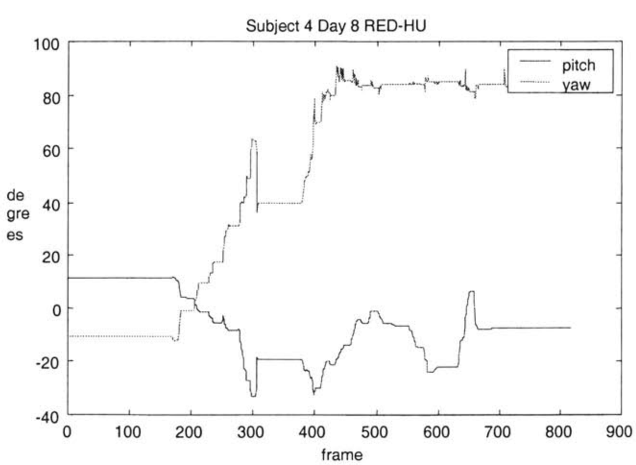
Subject 4 Day 1 HU-RED
pitch
yaw
degrees
frame



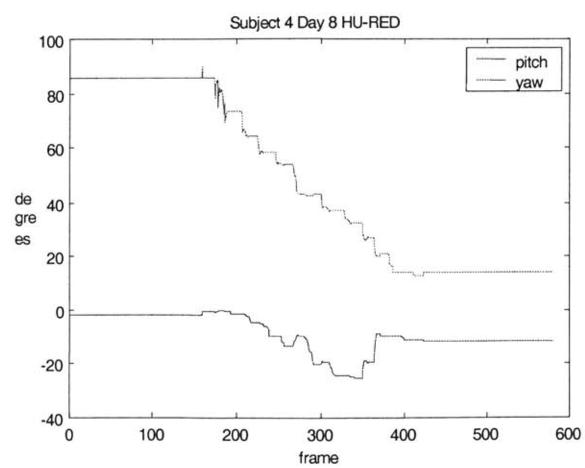
Subject 4 Day 2 RED-HU
pitch
yaw
degrees
frame



Subject 4 Day 2 HU-RED
pitch
yaw
degrees
frame

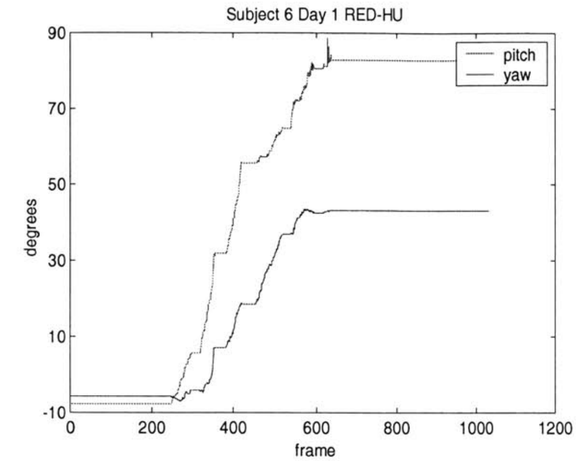


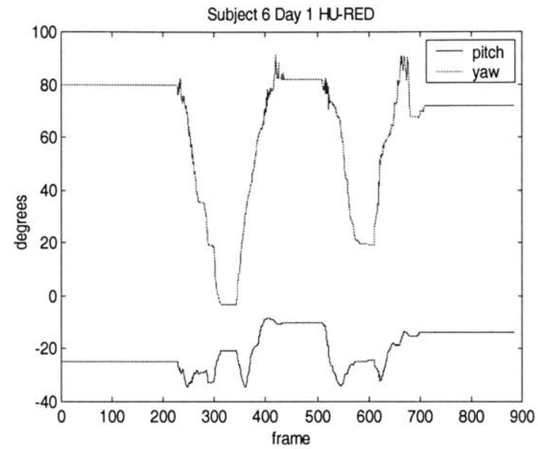
Subject 4 Day 8 RED-HU
pitch
yaw
de gre es
frame

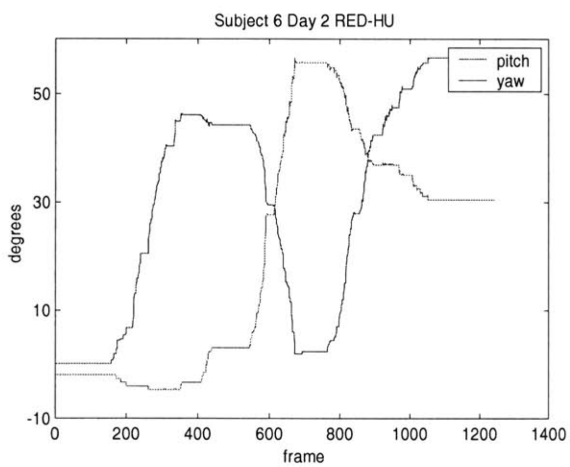


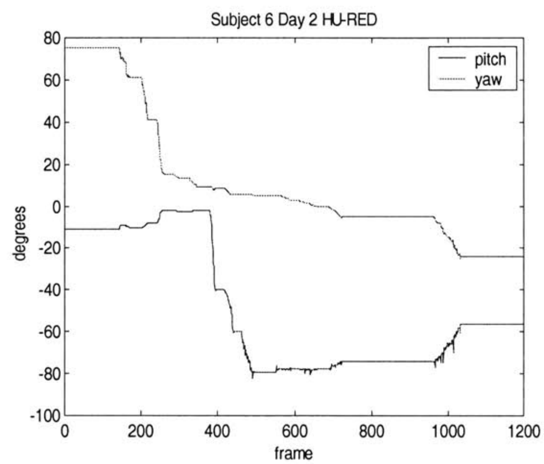
Subject 4 Day 8 HU-RED
pitch
yaw
de gre es
frame

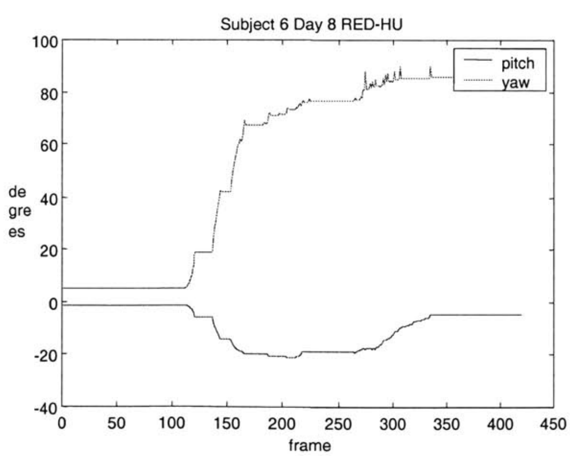
Subject 6

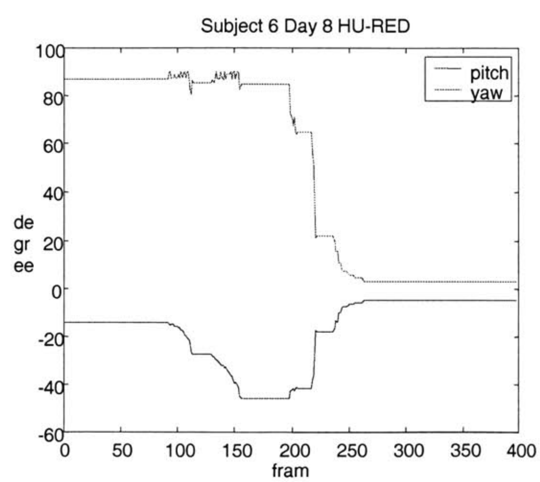

Subject 6 Day 1 RED-HU
pitch
yaw
degrees
frame


Subject 6 Day 1 HU-RED
pitch
yaw
degrees
frame

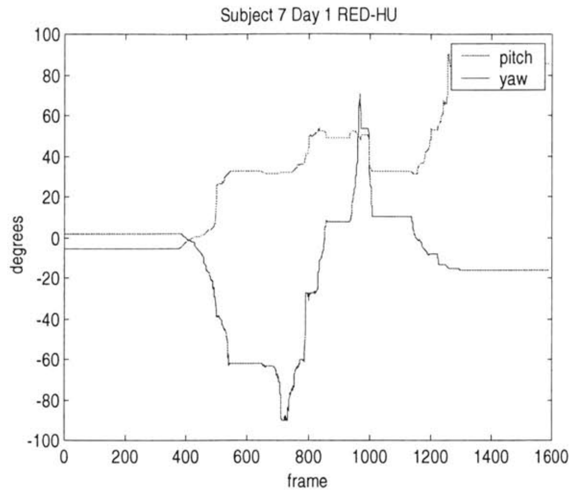

Subject 6 Day 2 RED-HU
pitch
yaw
degrees
frame

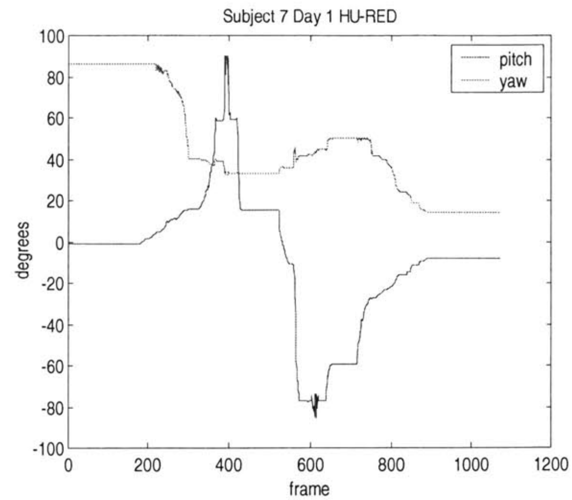

Subject 6 Day 2 HU-RED
pitch
yaw
degrees
frame

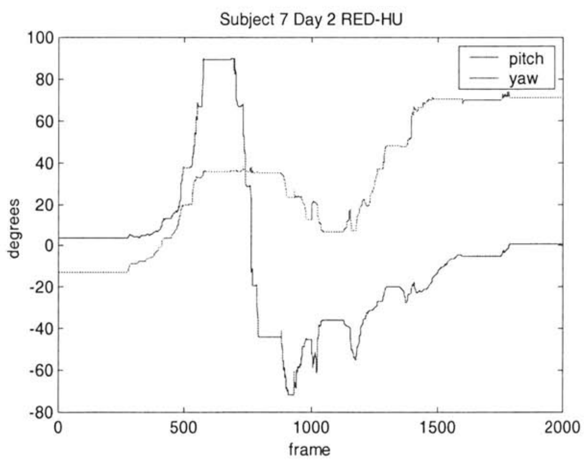

Subject 6 Day 8 RED-HU
pitch
yaw
de
gre
es
frame

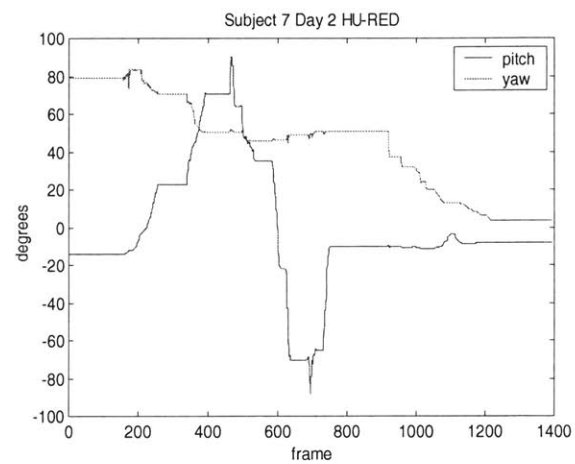

Subject 6 Day 8 HU-RED
pitch
yaw
de
gr
ee
fram

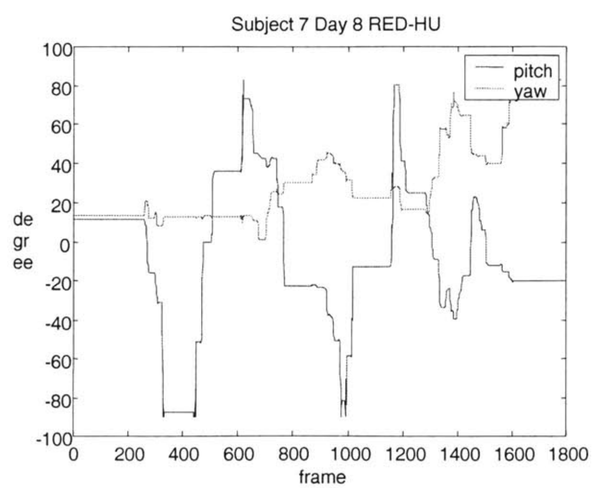
Subject 7

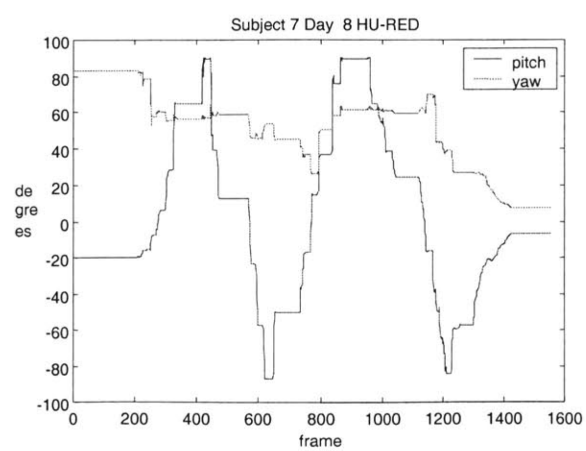

Subject 7 Day 1 RED-HU
pitch
yaw
degrees
frame


Subject 7 Day 1 HU-RED
pitch
yaw
degrees
frame

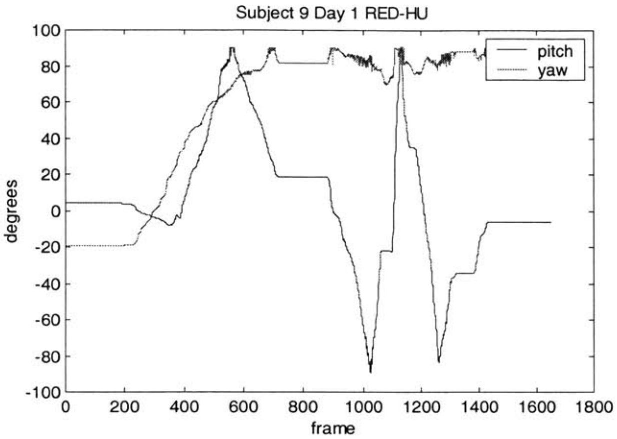

Subject 7 Day 2 RED-HU
pitch
yaw
degrees
frame


Subject 7 Day 2 HU-RED
pitch
yaw
degrees
frame

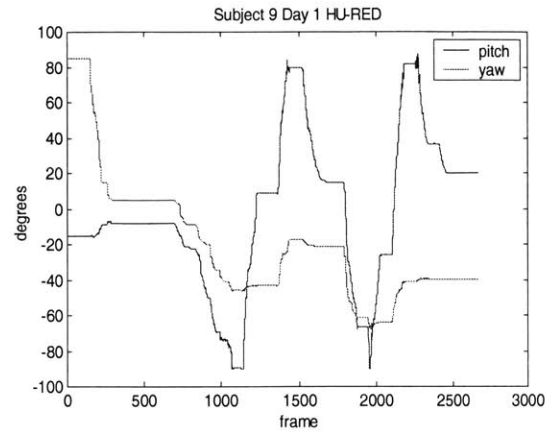

Subject 7 Day 8 RED-HU
pitch
yaw
de
gr
ee
frame


Subject 7 Day 8 HU-RED
pitch
yaw
de
gre
es
frame

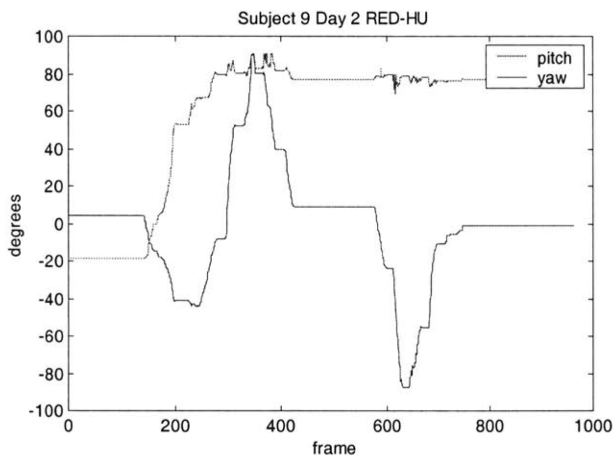
Subject 9



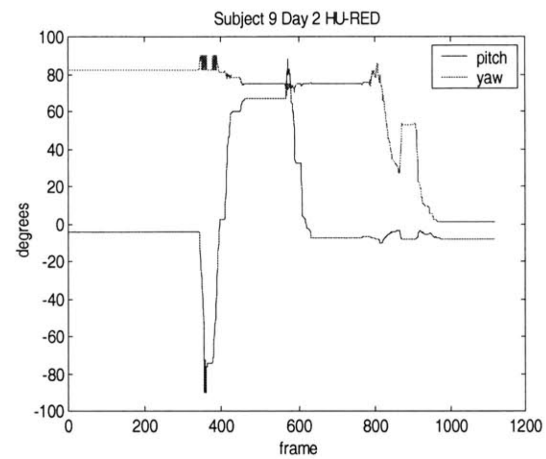
Subject 9 Day 1 RED-HU
pitch
yaw
degrees
frame



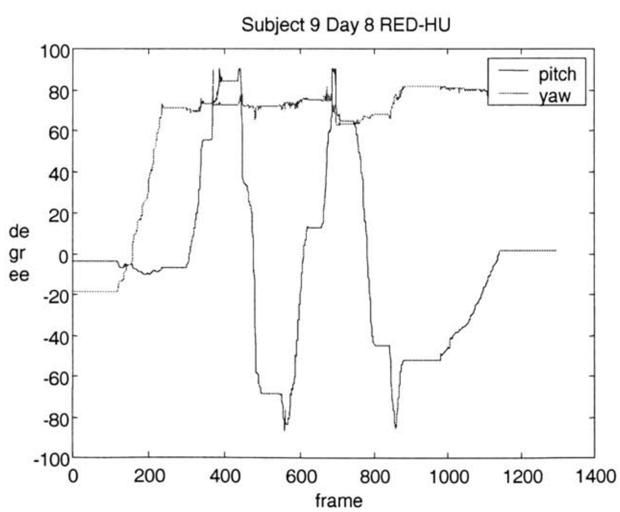
Subject 9 Day 1 HU-RED
pitch
yaw
degrees
frame



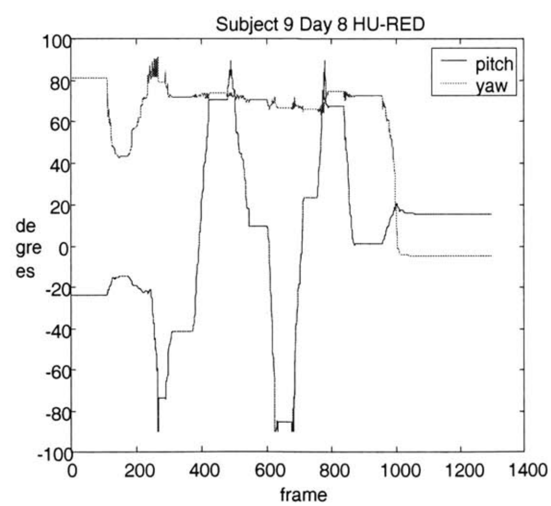
Subject 9 Day 2 RED-HU
pitch
yaw
degrees
frame



Subject 9 Day 2 HU-RED
pitch
yaw
degrees
frame

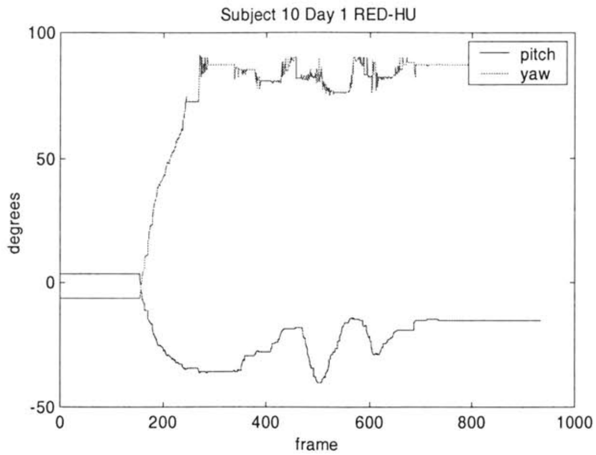


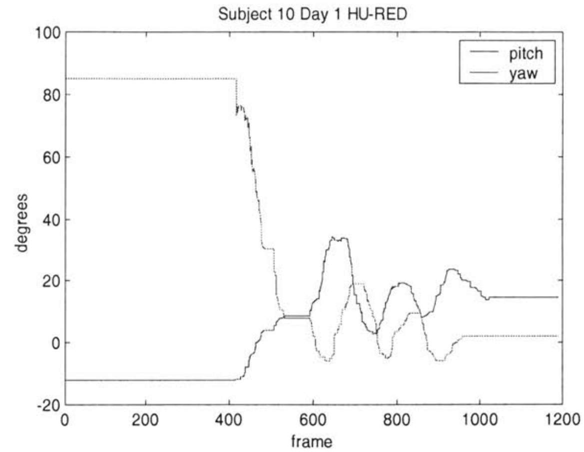
Subject 9 Day 8 RED-HU
pitch
yaw
de
gr
ee
frame

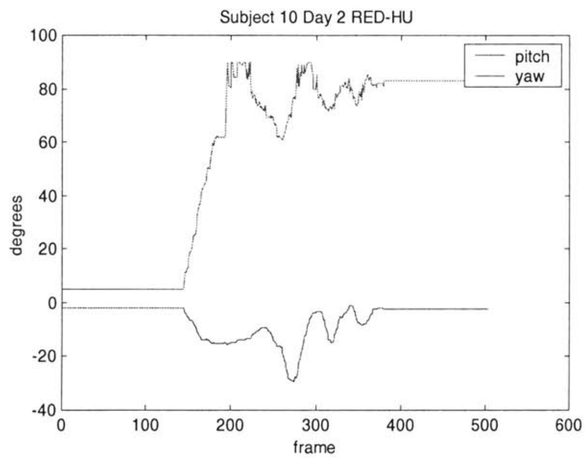


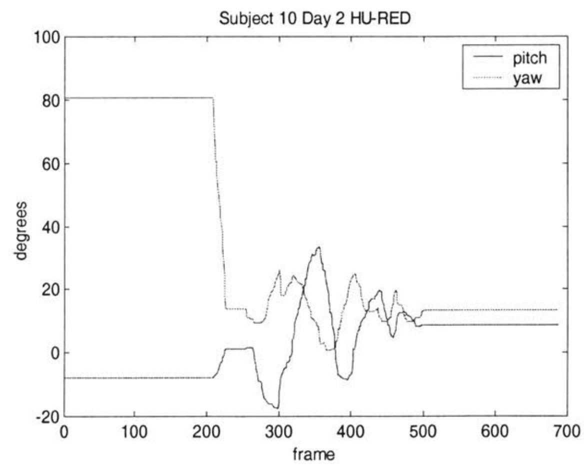
Subject 9 Day 8 HU-RED
pitch
yaw
de
gre
es
frame

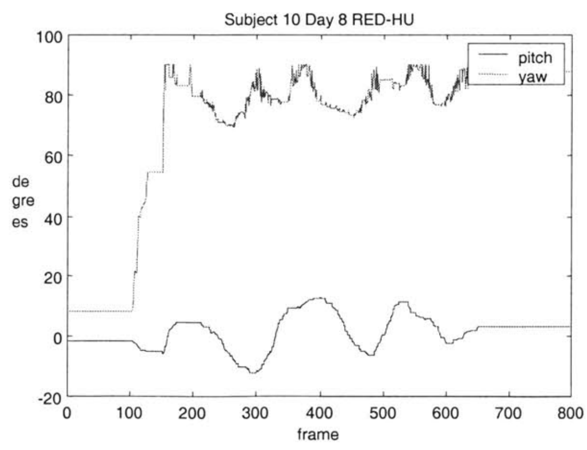
Subject 10

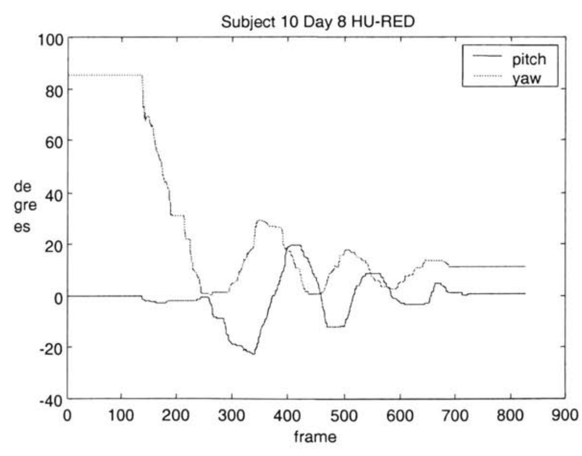

Subject 10 Day 1 RED-HU
pitch
yaw
degrees
frame


Subject 10 Day 1 HU-RED
pitch
yaw
degrees
frame

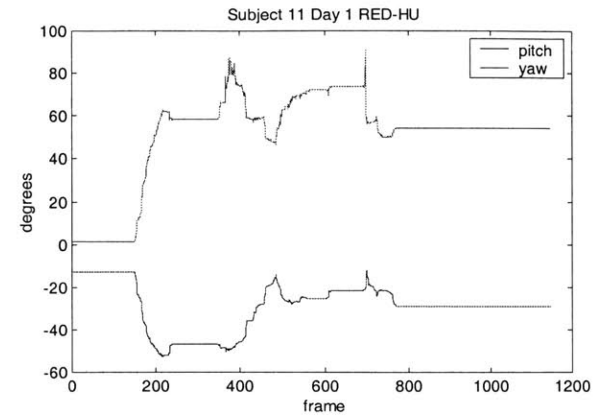

Subject 10 Day 2 RED-HU
pitch
yaw
degrees
frame

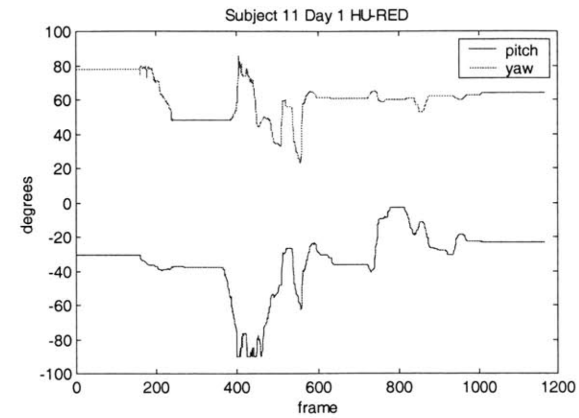

Subject 10 Day 2 HU-RED
pitch
yaw
degrees
frame

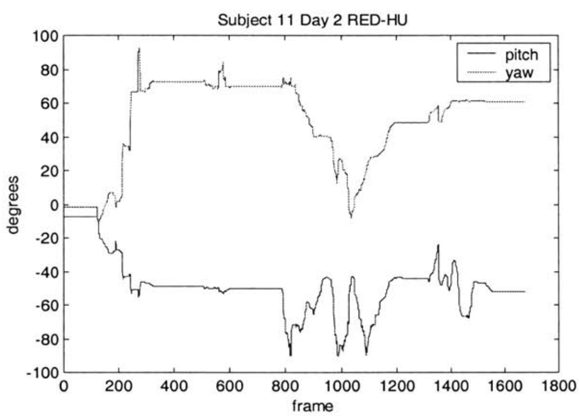

Subject 10 Day 8 RED-HU
pitch
yaw
de gre es
frame

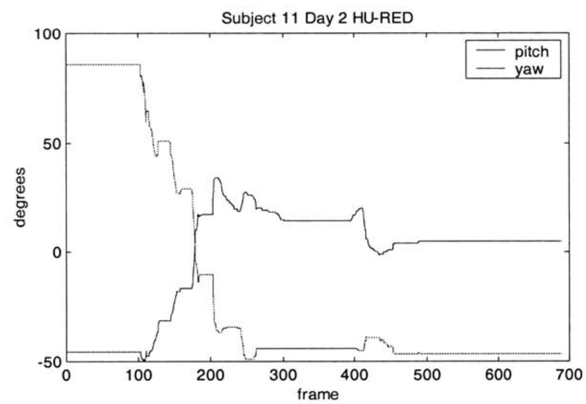

Subject 10 Day 8 HU-RED
pitch
yaw
de gre es
frame

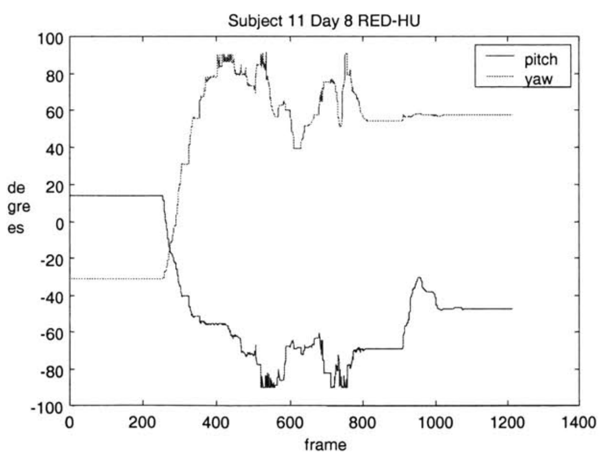
Subject 11

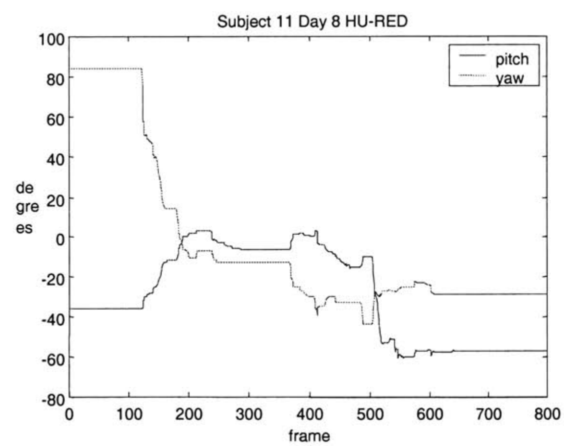

Subject 11 Day 1 RED-HU
pitch
yaw
degrees
frame


Subject 11 Day 1 HU-RED
pitch
yaw
degrees
frame

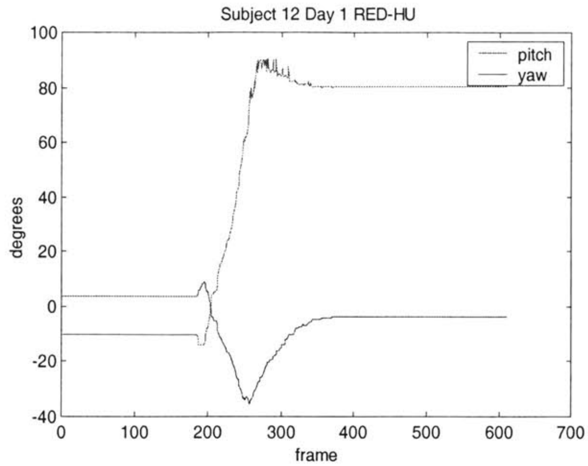

Subject 11 Day 2 RED-HU
pitch
yaw
degrees
frame

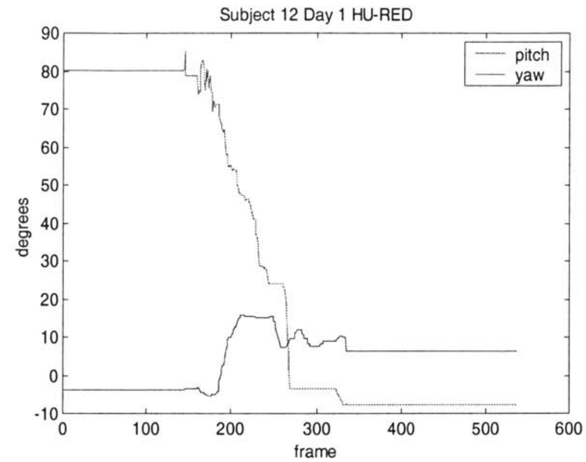

Subject 11 Day 2 HU-RED
pitch
yaw
degrees
frame

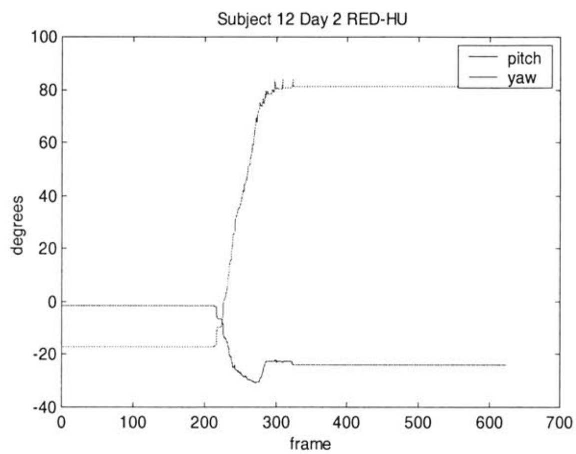

Subject 11 Day 8 RED-HU
pitch
yaw
de
gre
es
frame

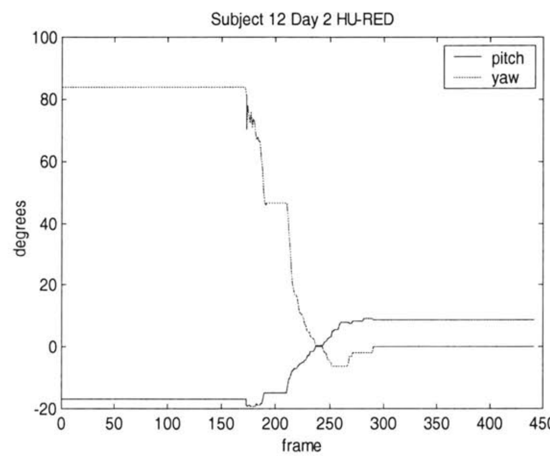

Subject 11 Day 8 HU-RED
pitch
yaw
de
gre
es
frame

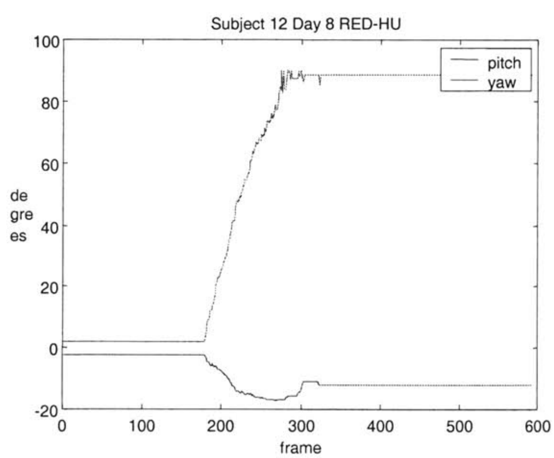
Subject 12

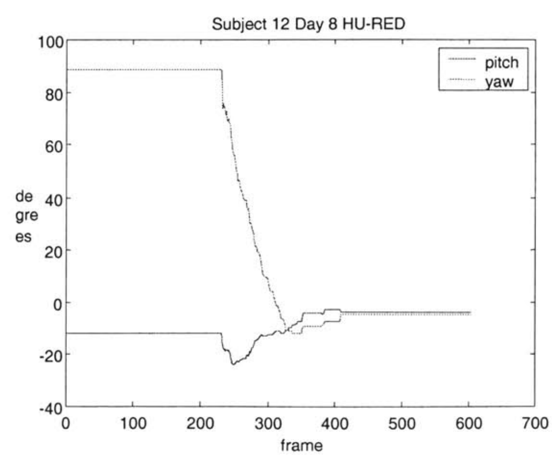

Subject 12 Day 1 RED-HU
pitch
yaw
degrees
frame


Subject 12 Day 1 HU-RED
pitch
yaw
degrees
frame


Subject 12 Day 2 RED-HU
pitch
yaw
degrees
frame


Subject 12 Day 2 HU-RED
pitch
yaw
degrees
frame


Subject 12 Day 8 RED-HU
pitch
yaw
de
gre
es
frame


Subject 12 Day 8 HU-RED
pitch
yaw
de
gre
es
frame

Appendix L – Worldup Results

The table below shows the peak pitch magnitudes obtained using the Worldup software and tracker.

Worldup pitch				
	RED - HU magnitude	**Direction**	**HU-RED Magnitude**	**Direction**
sub2 D1	70	Backwards	22.5	Forwards
sub2 D2	40	Backwards	23.5	Forwards
sub2 D8	15	Backwards	15	Forwards
sub4 D1	24	Forwards	30	Backwards
sub4 D2	38	Forwards	66	Backwards
sub4 D8	38	Forwards	23	Backwards
sub6 D1	50	Forwards	23	Backwards
sub6 D2	56	Forwards	95	Backwards
sub6 D8	15	Forwards	33	Backwards
sub7 D1	360	Backwards	360	Forwards
sub7 D2	360	Forwards	360	Forwards
sub7 D8	720	Backwards	720	Forwards
sub9 D1	720	Forwards	720	Backwards
sub9 D2	360	Forwards	360	Backwards
sub9 D8	720	Forwards	720	Backwards
sub10 D1	22	Backwards and Forwards	24	Backwards and Forwards
sub10 D2	14	Backwards and Forwards	26	Backwards and Forwards
sub10 D8	13	Backwards and Forwards	22	Backwards and Forwards
sub11 D1	36	Forwards	60	Backwards
sub11 D2	90	Backwards	81	Forwards
sub11 D8	71	Backwards	41	Forwards
sub12 D1	33	Forwards	21	Forwards
sub12 D2	8	Forwards	30	Forwards
sub12 D8	6	Forwards	21	Forwards

Appendix M – Motion-sickness scores reported during the experiment

The table below shows the motion-sickness scores obtained during centrifugation, the number of head turns, motion-sickness scores/No. of head turns, No. of head turn till peak motion-sickness score, time till peak motion-sickness score and peak motion-sickness score.

Subject 2

S2 D1						S2 D2					S2 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns
Before experiment starts	0:05:00	300	0	0	#DIV/0!	0:07:50	470	0	0	#DIV/0!	0:06:20	380	0	0	#DIV/0!
After 3 yaw head movements	0:07:50	470	0	6	0.00	0:10:10	610	0	6	0.00	0:09:55	595	0	6	0.00
After acc to 23rpm	0:09:50	590.00	0	6	0.00	0:12:15	735.00	0	6	0.00	0:11:35	695.00	0	6	0.00
After 3 yaw head movements	0:13:05	785.00	6	12	0.50	0:14:40	880.00	0	12	0.00	0:14:35	875.00	1	12	0.08
Adaptation 1	0:17:50	1070.00	13	47	0.28	0:17:50	1070.00	3	21	0.14	0:17:20	1040.00	3	29	0.10
Adaptation 2	0:18:45	1125.00	15	49	0.31	0:18:45	1125.00	5	30	0.17	0:18:20	1100.00	3	38	0.08
Adaptation 3	0:19:10	1150.00	15	50	0.30	0:19:45	1185.00	8	38	0.21	0:19:20	1160.00	5	47	0.11
Adaptation 4	0:21:35	1295.00	14	53	0.26	0:20:40	1240.00	10	47	0.21	0:20:30	1230.00	5	54	0.09
Adaptation 5	0:23:15	1395.00	13	57	0.23	0:21:35	1295.00	10	52	0.19	0:21:20	1280.00	5	63	0.08
Adaptation 6	0:24:10	1450.00	13	60	0.22	0:22:45	1365.00	8	53	0.15	0:23:30	1410.00	3	71	0.04
Adaptation 7	0:26:15	1575.00	12	67	0.18	0:23:45	1425.00	7	55	0.13	0:24:20	1460.00	5	85	0.06
Adaptation 8	0:27:25	1645.00	10	69	0.14	0:24:40	1480.00	8	63	0.13	0:25:20	1520.00	4	95	0.04
Adaptation 9						0:25:45	1545.00	8	70	0.11	0:26:10	1570.00	5	106	0.05
Adaptation 10											0:26:55	1615.00	4	108	0.04
After 3 yaw head movements	0:29:30	1770.00	13	75	0.17	0:31:25	1885.00	8	76	0.11	0:31:10	1870.00	3	114	0.03
After dec to 0	0:33:05	1985.00	8	77	0.10	0:33:55	2035.00	6	78	0.08	0:34:25	2065.00	2	116	0.02
After 3 yaw head movements	0:35:50	2150.00	6	83	0.07	0:36:00	2160.00	5	84	0.06	0:36:40	2200.00	1	122	0.01
No. head turns until peak MSS	43					41					41				
Time till peak MSS (sec)	535.00					505.00					465.00				
Peak MSS	15.00					10.00					5.00				

Subject 4

S4 D1						S4 D2					S4 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/ turns
Before experiment starts	0:01:40	100	0	0		0:02:15	135	0	0		0:07:15	435	0	0	#DIV/0!
After 3 yaw head movements	0:03:55	235	0	6	0.00	0:04:25	265	0	6	0.00	0:10:05	605	0	6	0.00
After acc to 23rpm	0:05:40	340.00	0	6	0.00	0:07:20	440.00	0	6	0.00	0:11:30	690.00	0	6	0.00
After 3 yaw head movements	0:09:10	550.00	0	12	0.00	0:10:05	605.00	0	12	0.00	0:14:05	845.00	0	12	0.00
Adaptation 1	0:12:50	770.00	0	18	0.00	0:14:10	850.00	0	52	0.00	0:16:40	1000.00	0	38	0.00
Adaptation 2	0:13:30	810.00	0	24	0.00	0:16:10	970.00	0	96	0.00	0:17:40	1060.00	0	56	0.00
Adaptation 3	0:14:20	860.00	0	32	0.00	0:17:00	1020.00	0	105	0.00	0:18:35	1115.00	0	82	0.00
Adaptation 4	0:15:20	920.00	0	43	0.00	0:18:00	1080.00	0	106	0.00	0:19:30	1170.00	0	101	0.00
Adaptation 5	0:16:20	980.00	0	51	0.00	0:19:00	1140.00	1	122	0.01	0:20:35	1235.00	1	123	0.01
Adaptation 6	0:18:10	1090.00	0	63	0.00	0:19:45	1185.00	1	144	0.01	0:21:50	1310.00	0	132	0.00
Adaptation 7	0:19:15	1155.00	0	68	0.00	0:20:55	1255.00	1	180	0.01	0:22:35	1355.00	0	151	0.00
Adaptation 8	0:20:25	1225.00	0	68	0.00	0:21:55	1315.00	0	187	0.00	0:23:45	1425.00	0	181	0.00
Adaptation 9	0:21:30	1290.00	0	94	0.00						0:24:45	1485.00	1	197	0.01
Adaptation 10											0:25:25	1525.00	1	202	0.00
After 3 yaw head movements	0:26:20	1580.00	0	194	0.00	0:26:30	1590.00	1	193	0.01	0:28:15	1695.00	0	208	0.00
After dec to 0						0:29:15	1755.00	1	195	0.01	0:30:35	1835.00	1	210	0.00
After 3 yaw head movements	0:32:15	1935.00	0	202	0.00	0:31:40	1900.00	1	201	0.00	0:32:55	1975.00	1	216	0.00
No. head turns until peak MSS	N/A					116					117				
Time till peak MSS	N/A					700.00					545.00				
Peak MSS	N/A					1.00					1.00				

Subject 6

S6 D1						S6 D2					S6 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/ turns
Before experiment starts	0:07:00	420	0	0	#DIV/0!	0:07:25	445	1	0	#DIV/0!	0:08:00	480	0	0	#DIV/ 0!
After 3 yaw head movement s	0:10:15	615	0	6	0.00	0:10:30	630	0	6	0.00	0:10:15	615	0	6	0.00
After acc to 23rpm			0	6	0.00	0:12:50	770.00	0	6	0.00	0:11:50	710.00	0	6	0.00
After 3 yaw head movement s	0:14:40	880.00	0	12	0.00	0:16:10	970.00	0	12	0.00	0:14:20	860.00	0	12	0.00
Adaptation 1	0:18:05	1085.00	2	21	0.10	0:21:15	1275.00	2	14	0.14	0:22:40	1360.00	2	19	0.11
Adaptation 2	0:19:00	1140.00	4	28	0.14	0:22:25	1345.00	3	16	0.19	0:23:40	1420.00	2	22	0.09
Adaptation 3	0:20:05	1205.00	5	33	0.15	0:23:50	1430.00	5	20	0.25	0:24:30	1470.00	5	26	0.19
Adaptation 4	0:20:55	1255.00	9	38	0.24	0:25:05	1505.00	7	22	0.32	0:25:30	1530.00	7	30	0.23
Adaptation 5	0:22:00	1320.00	11	41	0.27	0:25:50	1550.00	12	24	0.50	0:26:35	1595.00	9	33	0.27
Adaptation 6	0:24:15	1455.00	13	47	0.28	0:26:50	1610.00	13	27	0.48	0:27:20	1640.00	12	35	0.34
Adaptation 7	0:25:20	1520.00	14	49	0.29	0:28:10	1690.00	15	29	0.52	0:29:15	1755.00	14	36	0.39
Adaptation 8	0:26:50	1610.00	15	54	0.28	0:28:55	1735.00	15	31	0.48	0:29:50	1790.00	15	38	0.39
Adaptation 9						0:29:45	1785.00	18	31	0.58	0:30:30	1830.00	17	38	0.45
Adaptation 10											0:31:00	1860.00	17	38	0.45
After 3 yaw head movement s	0:30:30	1830.00	16	62	0.26	0:33:25	2005.00	19	38	0.50	0:34:55	2095.00	9	44	0.20
After dec to 0	0:33:55	2035.00	5	64	0.08	0:37:05	2225.00	15	40	0.38	0:37:45	2265.00	7	46	0.15
After 3 yaw head movement s	0:36:15	2175.00	2	70	0.03	0:39:25	2365.00	9	46	0.20	0:39:50	2390.00	4	52	0.08
No. head turns until peak MSS	56					32					32				
Time till peak MSS	1215.00					1235.00					1120.00				
Peak MSS	16.00					19.00					17.00				

Subject 7

S7 D1						S7 D2					S7 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec+M143)	MSS	Turns	MSS/ turns
Before experiment starts	0:06:40	400	0	0	#DIV/0!	0:06:45	405	0	0	#DIV/0!	0:03:05	185	0	0	#DIV/ 0!
After 3 yaw head movements	0:09:05	545	0	6	0.00	0:09:25	565	0	6	0.00	0:05:30	330	0	6	0.00
After acc to 23rpm	0:10:50	650.00	0	6	0.00	0:10:55	655.00	0	6	0.00	0:07:10	430.00	0	6	0.00
After 3 yaw head movements	0:13:05	785.00	0	12	0.00	0:13:30	810.00	0	12	0.00	0:09:45	585.00	1	12	0.08
Adaptation 1	0:17:00	1020.00	0	17	0.00	0:15:55	955.00	0	23	0.00	0:13:05	785.00	1	31	0.03
Adaptation 2	0:18:40	1120.00	0	30	0.00	0:17:00	1020.00	0	35	0.00	0:14:05	845.00	1	43	0.02
Adaptation 3	0:19:40	1180.00	0	34	0.00	0:18:00	1080.00	2	45	0.04	0:15:00	900.00	1	51	0.02
Adaptation 4	0:20:30	1232.00	0	40	0.00	0:18:55	1135.00	1	52	0.02	0:15:55	955.00	1	57	0.02
Adaptation 5	0:22:05	1325.00	0	44	0.00	0:20:00	1200.00	1	62	0.02	0:18:10	1090.00	1	63	0.02
Adaptation 6	0:23:10	1390.00	0	51	0.00	0:20:10	1210.00	0	62	0.00	0:19:15	1155.00	1	70	0.01
Adaptation 7	0:24:00	1440.00	0	59	0.00	0:21:35	1295.00	0	64	0.00	0:20:05	1205.00	1	81	0.01
Adaptation 8	0:25:10	1510.00	2	67	0.03	0:23:35	1415.00	0	86	0.00					#DIV/ 0!
Adaptation 9	0:26:00	1565.00	1	74	0.01	0:24:30	1470.00	0	102	0.00					#DIV/ 0!
Adaptation 10						0:25:25	1525.00	0	109	0.00					#DIV/ 0!
After 3 yaw head movements	0:29:25	1765.00	0	80	0.00	0:28:15	1695.00	0	115	0.00	0:24:25	1465.00	1	96	0.01
After dec to 0	0:32:40	1960.00	0	82	0.00	0:31:20	1880.00	0	117	0.00	0:26:15	1575.00	1	98	0.01
After 3 yaw head movements	0:35:00	2100.00	0	88	0.00	0:33:35	2015.00	0	123	0.00	0:28:25	1705.00	0	104	0.00
No. head turns until peak MSS	61					39					6				
Time till peak MSS	860.00					425.00					155.00				
Peak MSS	2.00					2.00					1.00				

Subject 9

S9 D1						S9 D2					S9 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/ turns
Before experiment starts	0:06:10	370	0	0	#DIV/0!			1	0	#DIV/0!			0	0	#DIV/ 0!
After 3 yaw head movement s	0:11:30	690	0	6	0.00	0:10:25	625	1	6	0.17	0:07:15	435	0	6	0.00
After acc to 23rpm	0:13:15	795.00	0	6	0.00	0:12:35	755.00	1	6	0.17	0:08:15	495.00	0	6	0.00
After 3 yaw head movement s	0:15:40	940.00	2	12	0.17	0:15:30	930.00	1	12	0.08	0:11:30	690.00	0	12	0.00
Adaptation 1	0:18:00	1080.00	2	16	0.13	0:17:25	1045.00	1	14	0.07	0:13:45	825.00	0	21	0.00
Adaptation 2	0:19:00	1140.00	3	20	0.15	0:18:30	1110.00	1	22	0.05	0:15:00	900.00	0	28	0.00
Adaptation 3	0:19:40	1180.00	3	22	0.14	0:19:25	1165.00	1	28	0.04	0:16:00	960.00	0	34	0.00
Adaptation 4	0:21:20	1280.00	5	24	0.21	0:20:40	1240.00	1	34	0.03	0:17:00	1020.00	0	38	0.00
Adaptation 5	0:22:00	1320.00	6	26	0.23	0:21:30	1290.00	1	38	0.03	0:17:55	1075.00	0	39	0.00
Adaptation 6	0:23:15	1395.00	6	29	0.21	0:22:40	1360.00	1	41	0.02	0:19:00	1140.00	0	46	0.00
Adaptation 7	0:24:05	1445.00	7	32	0.22	0:23:45	1425.00	2	44	0.05	0:20:00	1200.00	0	51	0.00
Adaptation 8	0:25:00	1550.00	7	35	0.20	0:24:35	1475.00	2	47	0.04	0:21:00	1260.00	0	56	0.00
Adaptation 9	0:26:05	1565.00	7	38	0.18	0:25:35	1535.00	2	51	0.04	0:22:00	1320.00	0	62	0.00
Adaptation 10	0:27:00	1620	9	40	0.23	0:26:25	1585.00	2	55	0.04					
After 3 yaw head movement s	0:31:00	1860.00	7	48	0.15	0:30:45	1845.00	1	61	0.02					
After dec to 0	0:33:05	1985.00	3	50	0.06	0:32:55	1975.00	1	63	0.02	0:27:00	1620.00	0	71	0.00
After 3 yaw head movement s	0:35:15	2115.00	1	56	0.02	0:35:25	2125.00	0	69	0.00	0:29:50	1790.00	0	77	0.00
No. head turns until peak MSS	34					38					N/A				
Time till peak MSS	825.00					670.00					N/A				
Peak MSS	9.00					1.00					0.00				

Subject 10

S10 D1						S10 D2					S10 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns
Before experiment starts	0:05:35	335	0	0	#DIV/0!	0:02:40	160	0	0	#DIV/0!	0:09:15	555	0	0	#DIV/0!
After 3 yaw head movements	0:09:10	550	0	6	0.00	0:05:30	330	0	6	0.00	0:12:05	725	0	6	0.00
After acc to 23rpm	0:11:20	680.00	0	6	0.00	0:07:50	470.00	0	6	0.00	0:15:05	905.00	0	6	0.00
After 3 yaw head movements	0:14:10	850.00	0	12	0.00	0:09:55	595.00	2	12	0.17	0:18:30	1110.00	2	12	0.17
Adaptation 1	0:19:30	1170.00	0	18	0.00	0:14:00	840.00	5	22	0.23	0:22:10	1330.00	8	14	0.57
Adaptation 2	0:20:30	1230.00	0	30	0.00	0:15:00	900.00	5	25	0.20	0:23:15	1395.00	8	18	0.44
Adaptation 3	0:21:40	1300.00	2	41	0.05	0:16:00	960.00	8	29	0.28	0:24:00	1440.00	8	20	0.40
Adaptation 4	0:22:25	1345.00	5	50	0.10	0:16:50	1010.00	10	31	0.32	0:25:15	1515.00	10	25	0.40
Adaptation 5	0:23:20	1400.00	5	55	0.09	0:18:45	1125.00	10	35	0.29	0:26:10	1570.00	10	27	0.37
Adaptation 6	0:25:55	1555.00	5	58	0.09	0:20:00	1200.00	10	36	0.28	0:27:30	1650.00	10	31	0.32
Adaptation 7	0:27:00	1620.00	5	65	0.08	0:21:00	1260.00	10	37	0.27	0:29:05	1745.00	12	34	0.35
Adaptation 8	0:28:00	1680.00	10	76	0.13	0:22:05	1325.00	12	39	0.31	0:30:00	1800.00	12	36	0.33
Adaptation 9	0:29:25	1765.00	10	78	0.13	0:23:00	1380.00	12	40	0.30	0:31:20	1880.00	12	39	0.31
Adaptation 10	0:32:40	1960	5	78	0.06										
After 3 yaw head movements	0:35:05	2105.00	8	84	0.10	0:27:15	1635.00	12	48	0.25	0:35:15	2115.00	10	45	0.22
After dec to 0	0:37:50	2270.00	10	86	0.12						0:38:20	2300.00	8	47	0.17
After 3 yaw head movements	0:40:40	2440.00	10	92	0.11	0:31:00	1860.00	5	54	0.09	0:40:35	2435.00	5	53	0.09
No. head turns until peak MSS	70					33					28				
Time till peak MSS	1000.00					855.00					840				
Peak MSS	10.00					12.00					12.00				

Subject 11

S11 D1						S11 D2					S11 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns
Before experiment starts	0:01:45	105	0	0	#DIV/0!	0:02:05	125.00	0	0	#DIV/0!	0:06:15	375	0	0	#DIV/0!
After 3 yaw head movements	0:04:50	290	0	6	0.00	0:04:55	295.00	0	6	0.00	0:08:45	525	0	6	0.00
After acc to 23rpm	0:06:40	400.00	0	6	0.00	0:06:35	395.00	0	6	0.00	0:10:15	615.00	0	6	0.00
After 3 yaw head movements	0:09:10	550.00	1	12	0.08					#DIV/0!					#DIV/0!
Adaptation 1	0:13:40	820.00	1	15	0.07	0:12:45	765.00	0	17	0.00	0:15:30	930.00	1	17	0.06
Adaptation 2	0:14:55	895.00	2	17	0.12	0:13:40	820.00	0	20	0.00	0:16:35	995.00	1	21	0.05
Adaptation 3	0:16:10	970.00	2	19	0.11	0:14:35	875.00	1	23	0.04	0:17:35	1055.00	1	24	0.04
Adaptation 4	0:17:00	1020.00	4	21	0.19	0:15:35	935.00	1	26	0.04	0:18:45	1125.00	1	26	0.04
Adaptation 5	0:17:55	1075.00	6	24	0.25	0:16:35	995.00	1	27	0.04	0:19:35	1175.00	1	29	0.03
Adaptation 6	0:19:55	1195.00	8	26	0.31	0:17:30	1050.00	2	29	0.07	0:20:50	1250.00	1	32	0.03
Adaptation 7	0:21:40	1300.00	11	28	0.39	0:19:15	1155.00	1	33	0.03	0:21:40	1300.00	1	35	0.03
Adaptation 8	0:22:40	1360.00	15	30	0.50	0:20:20	1220.00	2	36	0.06	0:22:35	1355.00	1	39	0.03
Adaptation 9	0:24:20	1460.00	19	30	0.63	0:21:35	1295.00	1	39	0.03	0:23:40	1420.00	0	44	0.00
Adaptation 10	0:26:15	1575	15	30	0.50	0:22:45	1365.00	2	44	0.05	0:24:40	1480	0	51	0.00
Adaptation 11	0:26:55	1615	12	30	0.40										
After 3 yaw head movements	0:30:40	1840.00	10	36	0.28	0:26:45	1605.00	4	52	0.08	0:28:35	1715.00	1	60	0.02
After dec to 0	0:34:00	2040.00	13	38	0.34	0:29:30	1770.00	1	54	0.02	0:30:50	1850.00	1	62	0.02
After 3 yaw head movements	0:36:15	2175.00	12	44	0.27	0:31:35	1895.00	1	60	0.02	0:33:20	2000.00	1	68	0.01
No. head turns until peak MSS	24					46					11				
Time till peak MSS	1060.00					1210.00					315				
Peak MSS	19.00					4.00					1.00				

Subject 12

S12 D1						S12 D2					S12 D8				
Position	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/turns	Time	Time (sec)	MSS	Turns	MSS/ turns
Before experiment starts	0:07:35	455	0	0	#DIV/0!	0:06:55	415.00	0	0	#DIV/0!	0:05:35	335	0	0	#DIV/ 0!
After 3 yaw head movement s	0:10:05	605	0	6	0.00	0:09:20	560.00	0	6	0.00	0:08:05	485	0	6	0.00
After acc to 23rpm	0:11:45	705.00	0	6	0.00	0:10:10	610.00	0	6	0.00	0:09:40	580.00	0	6	0.00
After 3 yaw head movement s	0:14:30	870.00	0	12	0.00	0:13:15	795.00	0	12	0.00	0:12:05	725.00	0	12	0.00
Adaptation 1	0:17:15	1035.00	0	33	0.00	0:15:20	920.00	0	33	0.00	0:14:15	855.00	0	12	0.00
Adaptation 2	0:18:10	1090.00	0	55	0.00	0:16:20	980.00	0	48	0.00	0:15:15	915.00	0	17	0.00
Adaptation 3	0:19:05	1145.00	0	81	0.00	0:17:20	1040.00	0	65	0.00	0:16:15	975.00	0	23	0.00
Adaptation 4	0:20:10	1210.00	0	109	0.00	0:18:20	1100.00	0	79	0.00	0:17:15	1035.00	0	28	0.00
Adaptation 5	0:21:10	1270.00	0	137	0.00	0:19:20	1160.00	0	94	0.00	0:18:10	1090.00	0	34	0.00
Adaptation 6	0:23:30	1410.00	0	161	0.00	0:20:25	1225.00	0	101	0.00	0:19:10	1150.00	0	38	0.00
Adaptation 7	0:25:00	1500.00	0	200	0.00	0:21:25	1285.00	0	114	0.00	0:20:15	1215.00	0	45	0.00
Adaptation 8	0:26:00	1560.00	0	230	0.00	0:22:25	1345.00	0	128	0.00	0:21:05	1265.00	0	50	0.00
Adaptation 9						0:23:20	1400.00	0	141	0.00	0:22:15	1335.00	0	58	0.00
Adaptation 10						0:24:20	1460.00	0	150	0.00	0:23:10	1390	0	62	0.00
Adaptation 11															
After 3 yaw head movement s	0:29:55	1795.00	0	257	0.00	0:27:55	1675.00	0	156	0.00	0:26:35	1595.00	0	68	0.00
After dec to 0	0:32:45	1965.00	0	259	0.00	0:30:05	1805.00	0	158	0.00	0:28:35	1715.00	0	70	0.00
After 3 yaw head movement s	0:35:10	2110.00	0	265	0.00	0:32:45	1965.00	0	164	0.00	0:30:55	1855.00	0	76	0.00
No. head turns until peak MSS	N/A														
Time till peak MSS	N/A														
Peak MSS	N/A														