Adaptation to a Linear Vection Stimulus in a Virtual Reality Environment

by

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Abstract

In the zero-gravity environment of space, the vestibular system’s functioning is compromised and astronauts receive conflicting visual and vestibular cues concerning body orientation and motion. Experiment 136 on the Neurolab space shuttle mission explored this research question. The current experiment served as a supporting study, examining human “looming linear vection” responses produced by a virtual checkerboard hallway scene moving towards the observer. In the Earth’s gravity environment, the input of the vestibular system can be explored by setting the subject’s body orientation (and axis of the vestibular system) in line with or perpendicular to the gravity axis. Five different virtual scene speeds were used. Six vection measures were calculated for each trial: latency, decay latency, peak magnitude of perceived self motion, rise time of magnitude, rise slope, and area (integrated distance traveled). In addition, both latency and magnitude of self-motion were examined for signs of adaptation. Particularly at low scene speeds, the latency of the onset of looming vection was significantly greater in the supine than upright posture, opposite to the effect reported by Kano (1991). Most subjects interpreted the scene as a moving horizontal hallway and the conflict between the visual and gravitational verticals may have delayed the onset of vection in the supine posture. Posture did not affect the magnitude values indicating that the vestibular system plays a minimal role in the perception of speed of self-motion. Virtual scene speed influenced all measures significantly except after-latencies. Latency decreased slightly over the first few trials in the upright posture. However, for both latency and magnitude, adaptation to the stimulus seems to be minimal when considering changes over time in either measure.

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Press on:
Nothing in the world can take the place of perseverance. 
Talent will not;
Nothing is more common than unsuccessful men with talent. 
Genius will not;
Unrewarded genius is almost a proverb. 
Education will not; 
The world is full of educated derelicts. 
Persistence and determination alone are omnipotent. 
Press on!

-Calvin Coolidge
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Table of Contents

ABSTRACT 3

ACKNOWLEDGEMENTS 7

TABLE OF CONTENTS 9

TABLE OF FIGURES 11

LIST OF TABLES 14

INTRODUCTION 15
  MOTIVATION 15
  SYNOPSIS 16

BACKGROUND 17
  VECTION 17
  KANO EXPERIMENT 19
  MAGNITUDE ESTIMATION 20
  ADAPTATION 22

EXPERIMENTAL PROCEDURE 24
  SUBJECTS 24
  STIMULUS 27
  JOYSTICK CALIBRATION PROCEDURE 29
  TEST PROCEDURE 30
  MEASUREMENTS 31

RESULTS 33
  CALIBRATION 33
  PROFILES 37
  SUBJECT VARIABILITY 38
  LATENCY 41
  MAXIMUM MAGNITUDE 44
  AREA UNDER THE CURVE 48
  RISE TIME 48
  RISE SLOPE 49
  ADAPTATION 50
    Aftereffects 50
    Repetition 53

DISCUSSION 57
  MAGNITUDE ESTIMATION 57
  USEFULNESS OF CALIBRATION 60
  SPEED 62
  POSTURE 62
  ADAPTATION 64
    Vection Aftereffects 64
    Repetition 65

FUTURE WORK 65
Table of Figures

FIGURE 1- VIRTUAL ENVIRONMENT EQUIPMENT- UPRIGHT POSTURE ........................................... 26
FIGURE 2- SUBJECT IN SUPINE POSTURE .................................................................................. 27
FIGURE 3-VECTION STIMULUS-VIRTUAL TUNNEL WITH FRAME ........................................... 29
FIGURE 4-VECTION MEASURES, SIMULATED DATA FOR A SINGLE TRIAL ............................... 32
FIGURE 5-TYPICAL CALIBRATION DATA (SUBJECT 14).......................................................... 33
FIGURE 6- T-TEST VALUES FOR PRE/POST REGRESSION VARIABLE ....................................... 35
FIGURE 7-INDIVIDUAL CALIBRATION CURVES, INTERCEPT VALUES- THE ideal CALIBRATION CURVE HAS AN INTERCEPT EQUAL TO 128. ................................................................. 36
FIGURE 8- INDIVIDUAL CALIBRATION CURVES- SLOPE VALUES THE SLOPE OF THE ideal CALIBRATION CURVE EQUALS -1.28 ........................................................................ 36
FIGURE 9- TYPICAL MAGNITUDE PROFILES FOR THE FIRST TWO TRIALS AT SPEED 3 FOR EACH EXPERIMENTAL BLOCK. (RECALL THAT SPEED 3 WAS DESIGNATED THE MODULUS AND THE SUBJECT WAS INSTRUCTED TO DEFLECT THE JOYSTICK 50% TO INDICATE THE MAXIMUM MAGNITUDE OF THAT TRIAL). .................................................... 38
FIGURE 10- PERCENT OF TRIALS ACHIEVING VECTION........................................................ 39
FIGURE 11- NUMBER OF TRIALS WITH VECTION AS A FUNCTION OF POSTURE .................. 40
FIGURE 12- NUMBER OF VECTION TRIALS AS A FUNCTION OF PRESENTATION ORDER ....... 41
FIGURE 13- LATENCIES VS. SPEED, UPRIGHT POSTURE ....................................................... 42
FIGURE 14- LATENCIES VS. SPEED, SUPINE CONDITION ..................................................... 43
FIGURE 15- MEAN LATENCIES UPRIGHT AND SUPINE COMPARED ..................................... 43
FIGURE 16- BOX PLOT OF MAXIMUM MAGNITUDE DISTRIBUTION VS. SPEED, SUPINE POSTURE ....................................................................................................................... 44
FIGURE 17- BOX PLOT OF MAXIMUM MAGNITUDE DISTRIBUTION VS. SPEED, UPRIGHT POSTURE ....................................................................................................................... 45
FIGURE 18- BOX PLOT OF TRANSFORMED MAXIMUM MAGNITUDE DISTRIBUTION VS. SPEED, UPRIGHT POSTURE ....................................................................................... 45
FIGURE 19- BOX PLOT OF MAXIMUM TRANSFORMED MAGNITUDE DISTRIBUTION VS. SUPINE POSTURE .............................................................................................................. 46
FIGURE 20- MAXIMUM MAGNITUDE VS. SPEED, UPRIGHT POSTURE ................................... 46
FIGURE 21- MAXIMUM MAGNITUDE VS. SPEED, SUPINE POSTURE ................................... 47
FIGURE 22- MAXIMUM MAGNITUDE, SUPINE AND UPRIGHT COMPARED .......................... 47
FIGURE 23- MEAN AREA, UPRIGHT AND SUPINE POSTURES COMPARED .............................. 48
FIGURE 24- MEAN RISE TIME, UPRIGHT AND SUPINE POSTURES COMPARED ..................... 49
FIGURE 25- MEAN TRANSFORMED SLOPE, UPRIGHT AND SUPINE COMPARED ................... 50
FIGURE 26- MEAN DECAY LATENCIES, SUBJECTS REPORTING AFTEFEFFS (YES GROUP) ARE COMPARED TO SUBJECTS WHO DID NOT (NO GROUP). MEANS FOR BOTH UPRIGHT AND SUPINE POSTURES ARE PLOTTED. ................................................................. 51
FIGURE 27- INDIVIDUAL AFTER-LATENCY MEANS FOR SUBJECTS REPORTING AFTEFEFFS (YES GROUP) AND FOR THOSE NOT REPORTING THEM (NO GROUP)- UPRIGHT POSTURE. 52
FIGURE 28 - INDIVIDUAL AFTER-LATENCY MEANS FOR SUBJECTS REPORTING AFTEFEFFS (YES GROUP) AND FOR THOSE NOT REPORTING THEM (NO GROUP)- SUPINE POSTURE. 52
FIGURE 29- MEAN LATENCY VS. REPEITION, SUPINE POSTURE ........................................... 54
FIGURE 30- MEAN LATENCY VS. REPETITION, UPRIGHT POSTURE ........................................ 55
FIGURE 31- MEAN MAX. MAGNITUDE VS. REPETITION, SUPINE POSTURE .................. 55
FIGURE 32- MEAN MAX. MAGNITUDE VS. REPETITION, UPRIGHT POSTURE .......... 56
FIGURE 33- HYPOTHETICAL MAXIMUM MAGNITUDE CURVES- CHANGE IN POSTURE
  CAUSED A SHIFT IN THE INTERCEPT (CASE 1) ................................................................. 58
FIGURE 34- HYPOTHETICAL MAXIMUM MAGNITUDE CURVES- POSTURE PRODUCED
  A CHANGE IN SLOPE BUT THE PERCEPTION AT THE MODULUS SPEED IS EQUAL IN BOTH
  CONDITIONS (CASE 2) ..................................................................................................... 58
FIGURE 35- HYPOTHETICAL MAXIMUM MAGNITUDE CURVES- POSTURE PRODUCED BOTH A
  SHIFT AT THE MODULUS SPEED AND A CHANGE IN SLOPE (CASE 3) ....................... 59
FIGURE 36- MAXIMUM MAGNITUDE- MEANS FOR ALL SUBJECTS CALCULATED FROM
  INDIVIDUAL CALIBRATION CURVES COMPARED WITH VALUES FROM GENERAL IDEAL
  CALIBRATION CURVE ...................................................................................................... 61
FIGURE 37- STANDARD ERROR OF THE MEAN FOR MAXIMUM MAGNITUDE, COMPARISON
  BETWEEN VALUES CALCULATED WITH INDIVIDUAL CALIBRATION CURVES AND VALUES
  USING IDEAL CALIBRATION CURVE ............................................................................. 61
FIGURE 38- LATENCY, UPRIGHT POSTURE .................................................................. 93
FIGURE 39- LATENCY, SUPINE POSTURE .................................................................. 93
FIGURE 40- MEAN DECAY, UPRIGHT POSTURE ...................................................... 94
FIGURE 41- AFTER DECAY- SUPINE POSTURE .......................................................... 94
FIGURE 42- MAX. MAGNITUDE, UPRIGHT POSTURE .............................................. 95
FIGURE 43- MAX. MAGNITUDE, SUPINE POSTURE .................................................. 95
FIGURE 44- RISE TIME- UPRIGHT POSTURE ............................................................. 96
FIGURE 45- MEAN RISE TIME, SUPINE POSTURE ..................................................... 96
FIGURE 46- MEAN AREA, UPRIGHT POSTURE ............................................................ 97
FIGURE 47- AREA- SUPINE POSTURE ......................................................................... 97
FIGURE 48- SLOPE, UPRIGHT POSTURE ..................................................................... 98
FIGURE 49- SLOPE, SUPINE POSTURE ....................................................................... 98
FIGURE 50- SUBJECT 1 PROFILES, UPRIGHT POSTURE ......................................... 99
FIGURE 51- SUBJECT 1 PROFILES, SUPINE POSTURE ............................................. 99
FIGURE 52- SUBJECT 2 PROFILES, UPRIGHT POSTURE ......................................... 100
FIGURE 53- SUBJECT 2 PROFILES, SUPINE POSTURE ........................................... 100
FIGURE 54- SUBJECT 3 PROFILES, UPRIGHT POSTURE ......................................... 101
FIGURE 55- SUBJECT 3 PROFILES, SUPINE POSTURE .......................................... 101
FIGURE 56- SUBJECT 4 PROFILES, UPRIGHT POSTURE ........................................ 102
FIGURE 57- SUBJECT 4 PROFILES, SUPINE POSTURE ........................................... 102
FIGURE 58- SUBJECT 5 PROFILES, UPRIGHT POSTURE ........................................ 103
FIGURE 59- SUBJECT 5 PROFILES, SUPINE POSTURE ........................................... 103
FIGURE 60- SUBJECT 6 PROFILES, UPRIGHT POSTURE ........................................ 104
FIGURE 61- SUBJECT 6 PROFILES, SUPINE POSTURE ............................................ 104
FIGURE 62- SUBJECT 7 PROFILES, UPRIGHT POSTURE ........................................ 105
FIGURE 63- SUBJECT 7 PROFILES- SUPINE POSTURE ........................................... 105
FIGURE 64- SUBJECT 8 PROFILES, UPRIGHT POSTURE ......................................... 106
FIGURE 65- SUBJECT 8 PROFILES, SUPINE POSTURE ............................................ 106
FIGURE 66- SUBJECT 9 PROFILES, UPRIGHT POSTURE .......................................... 107
List of Tables

TABLE 1 - EXPERIMENT TIMELINE ............................................................................. 31
TABLE 2 PRE- AND POST- EXPERIMENT CALIBRATION REGRESSION RESULTS, * =
    SIGNIFICANT PRE/POST COEFFICIENT AT P = 0.05 ........................................... 34
TABLE 3 - REGRESSION PARAMETER T-TEST VALUES ............................................. 35
Introduction

Motivation

The visual perception of motion consists of more than the detection of image movement on the retina. Gibson separated the perception of motion into three related problems: object motion, surround stabilization, and observer movement (Gibson, 1954). In the case of observer movement, or self-motion, the visual, vestibular and somatosensory systems interact to detect self-motion. When motion cues from the various senses conflict, the central nervous system (CNS) typically combines them to arrive at a single interpretation by weighing one cue more than another. The sensory conflict created between the visual and modified vestibular systems is thought to contribute to space sickness experienced by astronauts.

Astronauts must detect motion accurately to perform tasks involved in navigation and the manipulation of objects. In space, the Earth’s gravitational force no longer provides a reference direction in relation to which body orientation and motion can be defined. Without this reference frame, astronauts sometimes become disoriented and susceptible to space sickness. The visual-vestibular sensory conflict is also a consequence of the use of immersive virtual environments. For many years, astronauts have been using flight simulators with wide field visual displays, and more recently they have trained for extravehicular activities using immersive virtual reality based systems. In the future, virtual reality technology may be used to train for certain other types of activities inside the spacecraft, and to remotely control spacecraft and manipulation systems. In most of these applications, the user interprets scene motion as self motion rather than surround motion, thus experiencing an illusion known as vection.

The term vection was first defined in the 1930’s by Fischer and Kornmuller (Fischer, 1930). When viewing a moving scene, a stationary observer may, after a delay, spontaneously report a sensation of self-motion or vection. Vection may become saturated when all motion is attributed to the observer and the scene appears stationary.
Many individuals experience vection in ordinary situations. For instance, a passenger on a train, who, in her peripheral vision, sees another train on the adjacent tracks begin to move, may experience linear vection, a sensation of self-motion in the opposite direction to the movement of the adjacent train. Vection experiments provide an opportunity to investigate the visual and vestibular contributions to the detection of self-motion. It is hypothesized that the latency of the vection onset depends on the relative weighting given to visual versus gravireceptor cues.

**Synopsis**

This investigation intended to confirm and expand on an earlier investigation by Kano regarding the influence of the gravitational and visual frames on the latency of linear vection’s onset (Kano, 1991). The Kano stimulus was produced by moving patterns displayed in the subject’s peripheral vision on large monitors on either side of the subject. The present experiment used a “looming” vection stimulus. Subjects wearing a stereoscopic helmet mounted display (HMD) viewed a virtual checkerboard hallway moving towards them. As in Kano’s study, experiments were conducted in both upright and supine postures with several different scene speeds. Six different measures, including latency and maximum magnitude of perceived speed of self-motion, were analyzed for the influence of scene speed and posture. A speed trend was found for all measures except rise time and after-latency, but only latency and rise time exhibited a change with posture.

In this investigation, the data was examined for signs of two types of adaptation over short time periods. There was no opportunity to explore long-term adaptation. Aftereffects have long been studied as an indication of habituation of motion-sensing processes. This experiment searched for the existence for an analogous aftereffect for self-motion experienced after the moving stimulus was removed. After each trial, the visual scene was blacked out and the length of time over which vection persisted was recorded. The data offered no conclusive evidence that a vection aftereffect existed.
Secondly, latency and peak magnitude values were examined for changes with repeated exposure to the stimulus. It was hypothesized that subjects would become more susceptible to vection with repeated trials as mental pathways learned to accept the moving scene as evidence of self-motion. Magnitude results did not exhibit any adaptation effects over repetition. Upright latencies decreased marginally over the first few repetitions.

This experiment served as a preliminary ground study for a looming vection experiment being conducted during the STS-90 Neurolab Space Shuttle Mission (Experiment 136). It was hypothesized that astronauts would pay less attention to gravireceptor cues and more attention to visual cues after adapting to zero-gravity, and therefore the latency of looming linear vection would decrease in space. Based on Kano's study, it was decided to test astronaut responses to looming linear vection stimuli in both erect and supine postures, preflight and postflight, expecting that spaceflight might affect the difference between erect and supine responses. The present experiments thus served as a control study to verify the effects of posture and scene velocity on a more general population. Therefore, many of the experiment parameters were tailored to apply to the operating constraints of a time intensive mission in space. For example, since a joystick was used to collect all data, calibration protocols were developed to interpret the subject's responses. Many of the analysis tools developed for this study will be applied to the data from the Neurolab mission.

This paper will discuss the research background in section 2, the experimental design in section 3. The results will be presented in section 4 and then their implications will be discussed in section 5. Future work will be considered in section 6.

1 For a fuller discussion of Kano's experiment, please refer to the Background section.
Background

Vection

The visual, vestibular and somatosensory systems all provide information about a person's movement. This experiment explores the visual-vestibular interactions in detecting self-motion during vection. The otoliths in a stationary observer will correctly signal a lack of movement (acceleration) but the addition of full scene motion will provide visual cues indicating observer movement. Eventually one interpretation prevails over the other. Vection occurs when the visual cues dominate. Most research has examined circular vection where the subject views a scene rotating around a body aligned axis. For the purposes of this research, scene is defined as the visual perspective encompassing the observer's entire field of view. Linear vection is "elicited by exposing stationary observers to a visual display that expands, contracts, or moves unidirectionally in the frontal or lateral field of view" (Carpenter-Smith, 1995). Looming vection, in response to an expanding optical flow in the frontal plane, was studied because no confounding illusions of pitch or roll are induced. Also, on Neurolab, the vection stimuli was projected using a helmet mounted display (HMD). Because it was not possible to deliver a very wide field of view vection stimuli in the HMD, a looming linear vection stimulus best suited the experimental equipment constraints. The central visual field has been shown to be sensitive to expanding or contracting optical flows and can detect forward/aft self-motion. Experiments have indicated that a small aperture in the central visual field can detect changes of heading (Warren, 1992) and produce compelling looming linear vection.

The strength of vection can also be enhanced by shifting the scene motion into the visual background. Other experiments have achieved this by placing an occluding fixation surface in front of the display (Kano, 1991). The subject is instructed to focus on the near surface. Howard and Howard used a frame to achieve the same goal in circular
vection experiments (Howard, 1994). They reported a significant increase in vection intensity and a decrease in onset latency due to the presence of the bars in the foreground compared to the no bar condition.

The strength of the observer’s vection has also been measured by their perceived speed of self-motion. Some studies examining circularvection have found a correlation between scene velocity and perceived speed of self-motion. However, this finding has been contradicted in other experiments and may only hold for low speeds of rotation. For linear vection induced by a peripheral-vision stimulus, Berthoz, Parvard and Young found that vection magnitude increased with graphic velocity up to approximately 1 m/s and then saturated at this level for all higher speeds (Berthoz, 1975). Kano also reports a link between the perceived speed of self-motion and scene speed (Kano, 1991).

**Kano Experiment**

The experimental protocol closely imitated Kano’s vection experiment (Kano, 1991). The Kano investigation compared the effect of aligning the body/head axis with gravity (upright posture) to that of setting the axes perpendicular to each other (supine posture). The experimental design also varied stimulus speed and direction of motion within the upright and supine postures. The stimulus consisted of a random dot pattern displayed on two flat screen monitors set opposite each other, on either side of the subject’s head, at 90° in the peripheral visual field of the subject. The dots moved across the screen in one of four directions (front, back, up, or, down). The two monitors subtended a total visual angle of approximately 5000 deg² (2x60°x 41.81°). This angle is more than two times the size of the HMD’s display. Subjects opened their eyes once the moving display reached a constant speed. Three stimulus speeds, 10.5, 25.4, and 41.2 degrees/sec, were presented. At the point of vection onset, the subject pushed a pedal. Each trial lasted twenty seconds. The results demonstrated that latencies for the onset of vection were shorter in the supine posture than in the upright one. The results also depended on the direction of motion within each posture. For forward vection along the body’s z-axis, latencies ranged between 2.5 and 4.3 seconds in the former posture and 8 to 10 seconds
in the latter. A speed effect was also detected with latencies decreasing with increasing speed for both postures. Subjects also reported a shift in the perceived speed of self-motion. The effect was categorized (low, medium, or high) but not quantified. Three trials per speed, per direction were presented to each subject. The small number of trials limited the experiment's ability to estimate between subject variability. No training is mentioned as part of the procedure.

The reduction in vection latencies due to posture supports the hypothesis that the vestibular system plays a role in vection. It appears that the delay in the onset of vection is necessary to overcome the antagonistic input of the vestibular system which signals that the subject is not moving. The vestibular system consists of the three semicircular canals and the two otoliths named the utricular and saccule maculae. The semicircular canals detect angular acceleration and their functioning is not relevant to this discussion. The otoliths are designed to detect linear accelerations and the direction of gravity. When motion is initiated, the maculae’s ciliae are deflected by the body’s acceleration and the otoliths send a signal to the brainstem. Once the body’s motion reaches a constant velocity, the otolith signal decays according to a physiologically determined time constant and only visual cues indicate that the subject is actually in motion. It is hypothesized that the initial lack of vestibular cues to corroborate the interpretation of scene motion as observer movement causes the latency of the onset of vection. The subject eventually experiences vection because after a time the brainstem no longer expects any vestibular cues because of constant velocity motion and the visual cues dominate the brain’s interpretation of body motion. In the supine posture, the otoliths are deflected by gravity in a direction analogous to an acceleration along the body’s z-axis and therefore the vection latency should be reduced because the visual and vestibular cues both correspond to body motion along the x-axis.

**Magnitude Estimation**

Psychophysics attempts to relate the size of human responses to the size of the stimulus. In essence, the goal is to “measure the strength of an experience”. S. S. Stevens
developed the technique of magnitude estimation for this purpose. Many perceptions such as loudness, temperature and brightness follow a power law of the form,

$$\psi = \kappa \phi^\beta,$$

(1)

between a physical stimulus (\(\phi\)), such as amplitude of a sound wave and its related perception, (\(\psi\)), such as loudness where \(\kappa\) is the constant of proportionality and \(\beta\) is the exponent (Stevens, 1974). The power law can be restated in the form “equal stimulus ratios produce equal sensation ratios”. This ratio invariance applies to all the sensory systems investigated up to this time.

Magnitude estimation assigns numbers to perceptions proportional to their apparent strength. Alternatively, cross modal sensation matching can be used to estimate the sensation ratios and has also been shown to be reliable. The loudness scale has been used to characterize the scale of a variety of perceptions such as taste and angular velocity and thermal discomfort. For example, a subject could measure the sweetness of a selection of foods by assigning an equivalent loudness of a sound source or the intensity of the sensation can be graded by the length of a bar on a computer screen. If the physical stimuli, \(\phi_1\) and \(\phi_2\), produce corresponding subjective perceptions, \(\psi_1\) and \(\psi_2\), respectively according to Eq. (1), then sensation matching requires choosing \(\psi_1 = \psi_2\) and so

$$\phi_1 = \kappa_1 \phi_2^{\beta_1/\beta_2}, \text{ where } \beta_{12} = \beta_2/\beta_1.$$

(2)

Therefore, for sensation matching, the ratio scale has an exponent, \(\beta\), equal to the ratio of the exponents of the individual ratio scale. In this experiment, the subject deflects a joystick to match their perceived speed of self-motion. A ratio scale for vection magnitude was constructed by comparing the perceived speed of self-motion to that generated by the modulus scene speed which was defined as the mid-range speed. The joystick deflection was measured as a percentage of full forward deflection. The ratio scale was anchored at the midpoint rather than the endpoints. Subjects were instructed to treat the vection magnitude ratio of the modulus as equal to 50% of the joystick deflection range.
Other methods to measure the strength of vection have been developed. Some experiments have measured postural sway in response to a sinusoidal linear motion. This paradigm tests responses to acceleration cues rather than to a constant velocity condition. Another method involves the use of a nulling paradigm where the subject must try to control the motion of the cart they are riding while viewing a moving visual scene (Carpenter-Smith, 1995). The shift in the point of subjective equality (PSE) indicates the strength of the vection. Both these alternatives require large set-ups that would not be possible on the space shuttle. Secondly, neither method allows for the examination of the development of vection in a single trial. Magnitude estimation with the joystick deflection allows the subject to continuously report the speed of perceived vection during a trial.

**Adaptation**

Passengers in motor vehicles have difficulty accurately estimating their speed especially after long periods of travel at high velocities (Denton, 1966). In their extensive study of linear vection, Berthoz, Parvard, and Young found that over prolonged exposure to the moving visual scene, subjects needed to increase the speed of the scene in order to maintain a constant vection intensity (Berthoz, 1975). This type of adaptation is known as habituation and is related to a reduction in firing rate of neurons sensitive to the stimulus due an extended exposure. Berthoz et. al. estimated the time constant for adaptation to be approximately 30-50s for their experimental setup.

Each trial in the current experiment only lasts 10 seconds and thus the active procedure described above can not be used to study adaptation of the subjects’ responses. Alternatively, motion aftereffects (MAE) have long been studied as a manifestation of the adaptation of the output of neurons involved in vision processing. Also known as the “waterfall illusion”, a subject who has been observing a moving scene for an extended time will frequently report observing paradoxical motion of a subsequent stationary scene in a direction opposite the original motion. The sensation is paradoxical in the sense that while the subjects report motion there is no impression of a change of
position. When the stimulus is removed, the firing rate of the stimulated neurons
decreases to below the resting rate and when summed with another neuron sensitive to
motion in the opposite direction, the output indicates motion in opposite direction
(Mather, 1998). In the history of scientific inquiry of MAE, its duration has been the
most popular measure of its intensity. It has been shown that duration increases with the
speed of the adapting stimulus. However, the phenomenon is complicated and many of
its characteristics depend on the properties of both the adapting and test stimuli.

The current experiment investigates whether an analogous phenomenon exists for
vection. If the neurons specifying vection also habituate as suggested in Berthoz, 1975,
then a sense of vection may remain once the moving scene is removed. A blacked out
scene rather than a stationary pattern was chosen as the test stimuli in order to reduce the
possibility of the subjects confusing a MAE for a vection aftereffect. A MAE is best
elicited by a visual pattern but a weaker response can result from viewing a black test
scene. Secondly, pilot studies indicated that a stationary test scene eliminated any
lingering vection at the end of the trial. Subjects were asked to press the trigger button
once their vection had dissipated during the blackout and provide an estimate of the
duration of the vection aftereffect.

Another type of adaptation was also examined in this experiment. Many vection
experiments include a training period where the subject practices his responses to the
stimulus before data collection. This procedure has two purposes: to familiarize the
subject with his tasks, and, to allow any adaptation processes to be completed before data
recording. This type of adaptation can be considered a form of learning where the brain
changes its responses to a stimulus over repeated exposure. The interpretation of
ambiguous visual cues relies partially on the observer’s prior experience. Nakayama
showed that subjects consistently interpreted ambiguous stereograms as the most
common real world situation even if this meant that it was necessary to fill in contours or
areas of colour to complete the image (Nakayama, 1992). He modeled the visual
processing of such images as finding the appropriate situation in a lookup matrix between
an actual object and a variety of two-dimensional images it could project. Each cell in
the matrix is assigned an associate probability and possible views are designated as
generic or accidental. Nakayama hypothesizes that probabilities are based on the
observer's past experience as she moves around and views objects from different angles.
Adaptation or learning necessitates a change in these probabilities through the
presentation of additional visual information. If the interpretation of observer motion
from visual and vestibular cues can be thought of as governed by a similar set of
probabilities. If the repeated experience of vection may cause adaptation, then it is
expected that the next presentation of the vection stimulus will elicit a greater vection
response.

Experimental Procedure

Subjects
In total, thirteen subjects from the MIT community, four women and nine men,
completed the experiment. Another subject began but did not finish the experiment
because of discomfort caused by wearing the experimental equipment. Their ages ranged
between 21 and 34 years. All subjects volunteered and none had previously viewed the
experimental stimulus. One possessed prior knowledge of the goals of the experiment.
Before starting the experiment, each subject completed a questionnaire to screen for
vestibular problems, peripheral or stereo vision deficiencies, and unusual susceptibilities
to motion sickness. Subjects wore contact lenses or glasses as necessary to correct their
vision to normal. Furthermore, the questionnaire asked for an account of previous
experience with virtual environments or video games. This experience was considered
potentially influential on their performance during the experiment. Each subject
completed the experiment in approximately an hour and a half.

All experiments were run using the prototype equipment for Neurolab Experiment 136
supplied by NASA at Johnson Space Center (Figure 1 and Figure 2). Kaiser Electro-
Optics manufactured the ProView 80 High Resolution Head Mounted Display (HMD).
The field of view of each ocular screen spanned 62 degrees horizontal x 46 degrees vertical, and they were set for stereoscopic viewing with 100% overlap. The resolution of each display screen was (640 horizontal x 3 colours) x 480 vertical with an resolution of 6 arcmin/colour group. For the experiments, a Thrustmaster joystick was modified. The springs that resist joystick deflections were replaced with a more compliant set. Also, two canvas belts were threaded through slots in the base to secure the joystick to the thigh and waist of the subject. The strap system minimized the tilting of the base and improved the feedback to the subject about the joystick position. The graphics were rendered by World Tool Kit (WTK), an OpenGL-based library of C subroutines designed for interactive real time graphic simulations. A Pentium Pro 200 MHz computer controlled the sequence of graphics and the data collection during a simulation. Two Intergraph GLZ-13 graphics accelerator boards with 16 MB of texture memory provided a dual-piped rendering of left/right stereo images. The maximum update rate was measured at 30 frames/sec. However, due to the polygon count in the visual scene, the frame rate dropped to approximately 16 frames/sec during the experiment. The scene for each eye was piped to a colour active matrix LCD in the HMD. Each subject customized the inter-pupillary distance (IPD) of the helmet until the stereo images were easily fused. The subject indicated his or her sensations by means of the joystick which returned an 8-bit joystick deflection value, and a 6-bit packet to indicate joystick button presses. The main computer sampled the output of the joystick at a rate of approximately 15 Hz. For
supine trials, the subjects rested on a medical observation table (Figure 2). A visor (not shown in Figure 1 and Figure 2) was slipped over the front of the HMD and blocked out stray light. Furthermore, the experiment was conducted in darkness. The small fans on the HMD supplied white noise to mask any directional audio cues.
Figure 2- Subject in Supine Posture

Stimulus

During each experimental trial, the subject observed a virtual-reality simulation of a three dimensional moving tunnel displayed in the HMD as shown in Figure 3. A similar corridor was used in postural sway experiments and was a reliable generator of vection (Gielen and van Asten, 1990). The black and white checkerboard texture provided a high contrast pattern lacking easily recognizable features. The cross-section measured 2 meters in height and 1 meter in width. The cross-sectional width of each wall was divided into four squares. A semi-transparent black cloud pane, which was inserted forty meters down the tunnel from the viewpoint, occluded the far end to create the illusion of an infinite hallway. The viewpoint was placed in the center of the cross-section corresponding to a normal height for a sitting subject. In the absence of other cues, eyeheight is set at the level of the horizon defined by the limit of the ground texture convergence (Warren and Whang, 1987). A three-dimensional structural cage surrounded the viewpoint. It consisted of two square window frames, one smaller than the other separated in depth by four struts. The subject was instructed to focus on the far
opening of the frame during translation of the tunnel. Thus, the motion of the tunnel was
displaced to the visual background in order to elicit a stronger vection response (Howard,
1994). The tunnel speed was varied in a pseudo-random order from a set of five speeds
spaced logarithmically: 0.4, 0.6, 0.8, 1.1, and 1.6 m/s along the body's forward z-axis.
In pilot tests, the chosen speed range produced vection on a reliable basis. This scale was
chosen in order to collect more data at the lower speeds where the changes in vection
measures as a function of speed and posture were expected to be larger and perhaps
capture possible non-linear trends in the data. Since we were using a ratio scale, the
speeds were chosen such that the ratios of successive speeds were close to being constant
and also that their geometric mean equalled the third speed in the series which had been
chosen as the modulus for magnitude estimation. It has often been observed in many
different types of magnitude estimation experiments that a subject's recollection of the
modulus drifted towards the average of the speeds presented over time. Thus, it was
hoped the modulus would remain constant over the course of the experiment. These z-
axis speeds correspond to angular velocities of 38.7, 50.2, 58.0, 65.6, and 72.6
degrees/sec respectively. These angular velocities were calculated for a point on the side
wall of the tunnel at eyepoint level 90° from the line of sight.
Joystick Calibration Procedure

Before starting the experiment, each subject completed the joystick calibration procedure. This procedure familiarized the subject with the functioning of the joystick. It was hoped that after training, the subjects would be able to use the joystick to continuously report their vection sensations, and that after applying the calibration curve established for each subject, a joystick deflection could be converted to a numeric value of perceived self-motion on a magnitude estimation scale anchored at 50%. A small pilot study showed that after only a small number of trials, joystick accuracy asymptoted. The experimental protocol duplicated some of the logistics of the STS-90 Neurolab space shuttle experiment, where there were time constraints that did not allow for many calibration trials.
Each subject was presented with a randomized sequence of numbers from 10 to 90 flashed on the screen. For each number displayed, they were asked to deflect the joystick forward by the percentage of the full deflection that matched the number presented. On the first 18 trials, the simulation provided feedback on their performance in the form of the actual joystick deflection. Then, the subject was tested for another 18 trials with no feedback. These responses were used to create individual calibration curves used in transforming the joystick deflections into measures of the subject's perception of the speed of self-motion. The no feedback calibration routine was repeated at the end of the experiment in order to detect any significant shifts in their internal calibration curve over the course of the experiment.

**Test Procedure**

Before performing the experiment, each subject was introduced to the sensation of vection. They briefly observed the rotation of the spotted inner surface of a drum designed to induce circular vection. The experimenter emphasized that vection would occur spontaneously and that the subject did not need to force the perception. The subject strapped the joystick to his or her thigh and donned the HMD. At this point, all instructions were displayed in the HMD and were supplemented by verbal coaching. There was no need to take the helmet off except for breaks. First, the subject viewed a stationary hallway exactly the same in texture and dimensions as the one used in the experimental trials. The experimenter verbally rehearsed the event sequence of a single trial in order familiarize the subject with the joystick use to indicate perceptions. After practicing with the joystick, the subject completed the joystick calibration procedure as previously detailed.

The experimental trials were split into four blocks (Table 1); each block consisted of 30 trials allocated equally among the five scene speeds presented in a pseudo-randomized order. Each block was completed in a single posture and successive blocks alternated between the supine and upright postures. Half the subjects began the first block upright while the other half began supine in order to balance any order of
presentation effects. The experiment's division into four blocks also counteracted fatigue by providing scheduled breaks during which the experimenter had the opportunity to question the subject about his or her sensations. The subjects were encouraged to volunteer any observations about their perceptions and any differences between blocks. In addition, for each block, the subject was asked to state his or her perceived orientation during vection and whether they experienced aftereffects.

<table>
<thead>
<tr>
<th>Group</th>
<th>Trial Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td></td>
<td>1-30</td>
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</tr>
<tr>
<td>2</td>
<td>Supine</td>
</tr>
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</table>

Table 1-Experiment Timeline

Each trial began in darkness. Then, the tunnel was displayed translating at a steady velocity. While maintaining gaze straight ahead, the subject pressed the trigger button when she first experienced vection, and indicated the perceived speed of self-motion by deflecting the joystick forward proportionally. Each trial lasted 10 seconds. The scene was then blacked out and the simulation waited for the subject to indicate that vection had dissipated by depressing the trigger button a second time.

Measurements

During each trial the computer automatically collected the X- and Y-deflections of the joystick and the status of the buttons. From this data, two latency measurements and a subjective estimate of the speed of self-motion, were automatically calculated immediately after each trial. The latency of the onset of vection was calculated as the time elapsed between the start of the trial and the first trigger-press. Similarly, the latency of vection decay (referred to as the "after-latency") was defined as the time between the scene blackout and the second trigger-press. Thirdly, the subjective estimate of the speed of self-motion was continuously tracked by the forward deflection of the joystick. The joystick deflection was ignored once the scene was blacked out. The onset
of vection was indicated by a button press rather than the time of the initial joystick deflection. This choice provided an unambiguous indication of vection and did not require the choice of an arbitrary threshold deflection to denote vection. Finally, individuals completing the pilot studies using the joystick did not feel that using both button presses and the deflection of the joystick required an excessive mental burden.

In addition, the post-experiment data analysis calculated four other measures for each trial from the raw data files (Figure 4). The maximum magnitude was defined as the peak joystick deflection after the trigger button was pushed. The time to reach 90% of the peak deflection minus the latency defined the rise time. The rise slope equalled 90% of the maximum magnitude divided by the rise time. The area under the deflection curve, which can be considered as the perceptual distance travelled, was calculated (by the trapezoidal rule). Statistical analyses (regression and ANOVA) were performed using SYSTAT V. 7.0 (Systat, Inc.).

Figure 4-Vection Measures, Simulated Data for a Single Trial
Results

Calibration
The calibration curves of joystick deflections were calculated and used to convert the joystick deflection to a vection magnitude percentage scale. As a first step in the analysis, a two-parameter linear regression was performed on the joystick deflection training data (Figure 5). A linear fit was used for simplicity of calculation. To detect any change in an individual’s joystick response over the course of the experiment, a multiple regression compared each subject’s pre- and post-experiment data. The independent variables consisted of the desired percent deflection and a category variable that differentiated pre- and post-experiment data. The actual deflection was the dependent variable. A non-significant pre/post coefficient would be consistent with the null hypothesis that the pre- and post-data sets were drawn from the same underlying population.

![Joystick Deflection Calibration Curves](image)

**Figure 5-Typical Calibration Data (Subject 14)**
Table 2 Pre- and Post- Experiment Calibration Regression Results, * = significant pre/post coefficient at p = 0.05.

Seven of thirteen subjects had a significant pre/post coefficient according to a two-tailed t-test (Table 2). The distribution of t-values for the pre/post coefficient was shown in the following graph (Figure 6). Notice that Subject 4’s t-value was an outlier and suggested that the errors in the joystick calibration procedure were large. Since the t-values did not appear to be biased (either positively or negatively) but to be randomly distributed, an alternative test compared the slopes of the pre- and post-experiment regressions separately from the intercepts. A significant difference in the slopes might suggest that the subject’s sensitivity to joystick deflection changed during the experiment or that a skewed error existed in the data. This would have precipitated the rejection of that subject’s magnitude data as unreliable. A significant shift in the intercept would have affected all ratios equally and masked any failures of the basic hypothesis. As shown in Table 3, none of the t-test values for the slopes and intercepts were significant at the 5% level for a two-tailed test. For each individual, the pre- and post-experiment data points were pooled to calculate a single regression line. With this linear equation, all raw joystick deflections were converted to a percentage scale for each subject’s perceived speed of self-motion. The intercept and slope of these individual calibration curves
T-value for Pre/Post Coefficient of Calibration Curve
Multiple Regression

Figure 6- T-test Values for Pre/Post Regression Variable

<table>
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<th>Subject</th>
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<th>Intercept</th>
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</thead>
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<td>p-value</td>
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</table>

Table 3-Regression Parameter t-Test Values

For a two-tailed t-test, \( t > t_{0.025} \) for a result to be significant at the 5% level
Intercept for Individual Calibration Curves

Figure 7-Individual Calibration Curves, Intercept Values- The ideal calibration curve has an intercept equal to 128.

Slope of Individual Calibration Curves

Figure 8- Individual Calibration Curves- Slope Values  The slope of the ideal calibration curve equals -1.28
were plotted in Figure 7 and Figure 8 respectively. In general, individual calibration curves underestimated the percentage joystick deflection compared to the ideal calibration curve.

Profiles

The magnitude of self-motion was plotted with time for each trial (Figure 9). Typically, after a latency period, the magnitude of self-motion increased at a constant rate and then maintained a constant level near the peak magnitude for the rest of the trial. An occasional dropout occurred but the perceived speed of self-motion did not necessarily decline to zero. Some subjects seemed to overshoot their indication of the magnitude of self-motion and reduce the joystick deflection to a lower level. Alternatively, vection diminished after a few seconds to a stable plateau. This decay occurred more frequently at higher scene speeds. All profiles may be reviewed in Appendix E- Vection Magnitude Profiles. The subject’s certainty of their motion may have influenced the slope of perceived speed increase more than the scene velocity. The first two trials of each block were examined to determine if the subject complied with the instructions to consider the maximum self-motion on the first trial to equate 50% of the joystick scale. The profiles indicated that many subjects underestimated their speed of self-motion when viewing the modulus. Consequently, comparing the perceived speed of self-motion between subjects was uncertain; however the analysis of within subject changes in magnitude due to scene or posture is still possible by comparing the ratios of perceived speeds for different subjects.

3 The first two trials were examined because some subjects did not attain vection on the first trial. In these cases, the second repetition of the middle speed was designated the modulus.
Subject Variability

The number of trials during which an individual experienced vection varied with scene speed and from subject to subject (Figure 10). The development of vection was less robust at the lower speeds. In particular, Subject 3 experienced vection infrequently at all speeds. Furthermore, during post-experiment interview, the subject described her vection as very weak and only occurring at the end of the trial. Often, she did not have enough time to indicate the magnitude of vection. This study was concerned with the
effects for subjects experiencing vection and thus it seemed reasonable to explore the results with this subject excluded.

**Figure 10 - Percent of Trials Achieving Vection**

Each vection measure was analyzed with repeated measures statistics. This analysis did not permit missing values in the data set. Therefore, empty cells due to trials with no vection were replaced by the average value of the measure for that particular subject, block, and speed. In total, 14.7% of the cells were empty. In theory, injecting average values into empty cells would reduce the degrees of freedom in the statistical analysis. This loss of degrees was not compensated for in the analysis. The substitution should not have greatly affected the results since the number of degrees of freedom was large. Furthermore, many of the calculations were redone with Subject 3 omitted and the percentage of empty cells in the data set was reduced. Although the variability in the data was artificially reduced, so were the likely effects of speed and posture and therefore the results would be erring on the conservative side of the hypothesis. It was possible that vection would have occurred in some of the missing trials had the trial continued beyond the 10 second trial length. Consequently, the substitution for missing data
reduced the mean values of the measures of subjects with a substantial number of missed trials. The substitution also distorted adaptation trends linked to repetition of the stimulus.

Posture also influenced the average number of trials achieving vection. Subjects experienced vection at all speeds more frequently when upright (Figure 11). The overall difference between upright and supine posture was significant (F(1,12) = 5.225, p = 0.041). The greatest difference occurred at the lowest speed. No significant difference between blocks was observed (F(1,12) = 0.898, p = 0.362).

![Graph](image-url)  
**Figure 11** - Number of Trials with Vection as a Function of Posture
For each vection measure, the data set was structured as a three factor repeated measures analysis across Repetition (4 levels), Posture and Block (4 levels), and Speed (5 levels). Each subject observed 6 repetitions of each stimulus level but Systat allowed a maximum of 99 data points per case for a repeated measures analysis. The last four repetitions were chosen because fewer trials, and therefore, fewer degrees of freedom were missing from that data subset (Figure 12). Finally, for each measure, the means of the first four repetitions and that of the last four repetitions were plotted to ensure that the choice of data sets did not influence the results (Appendix D- Early and Late Repetitions Compared) The General Linear Model method (Systat V. 7) was used to model the mean latencies of the repeated measures.

**Latency**
Latencies (Figure 13 and Figure 14) decreased with speed ($F(4, 44) = 13.654; p = 0.0$). The subject means were slightly positively skewed but their distribution was close to
normal. Individually, nine of thirteen subjects showed an inversely proportional trend between latency and speed. Posture exerted a significant influence on latency ($F(1, 11) = 5.609, p = 0.037$). The difference between postures diminished at the higher speeds (Figure 15). The order of presentation of postures did not produce a significant effect on the results ($F(1, 11) = 0.594, p = 0.457$). (Note that the subject means were coarsely distributed about the mean for each speed).

Average Vection Latency- Upright Posture

![Graph showing average vection latency vs. speed with upright posture.](image)

Figure 13-Latencies vs. Speed, Upright Posture

4 Unless specified, all error bars indicate the standard error of the mean.
Average Vection Latency - Supine Posture

Figure 14-Latencies vs. Speed, Supine Condition

Average Vection Latency - Upright and Supine Compared (Subject 3 Omitted)

Figure 15- Mean Latencies Upright and Supine Compared
**Maximum Magnitude**

As shown in Figure 16 and Figure 17, the variance of the magnitude values increased with scene speed in violation of one of the underlying assumptions of ANOVA. The values were transformed by a power relationship in order to stabilize the variance with scene speed (Figure 18 and Figure 19). All peak magnitude values were raised to the power of 0.325. Then, the transformed magnitude data set was analyzed by repeated measures statistics to uncover any significant posture or speed effects. The overall and subjects means for the peak magnitudes were displayed in logarithmic plots for each posture separately (Figure 20 and Figure 21). These two plots confirmed the skewness of the range of subjects means and the dependence of the variance on scene speed. For both postures, the maximum magnitude (Figure 22) increased with speed (F(4,44) = 50.584, p = 0.0). Neither order of presentation (F(1,11) = 0.343, p = 0.570) nor posture (F(1, 11) = 0.028, p = 0.871) had an impact.
Figure 16- Box Plot of Maximum Magnitude Distribution vs. Speed, Supine Posture\textsuperscript{5}

\textsuperscript{5} The length of each box indicates the range within which the central 50% of the values fall. The mean is represented by the line partitioning the box. The hinges mark the limits of the first and third quantiles. The asterisks denote outliers.
Figure 17- Box Plot of Maximum Magnitude Distribution vs. Speed, Upright Posture

Figure 18- Box Plot of Transformed Maximum Magnitude Distribution vs. Speed, Upright Posture
Figure 19-Box plot of Maximum Transformed Magnitude Distribution v. Speed - Supine Posture

Subject Means for Maximum Magnitude Upright Posture

Figure 20-Maximum Magnitude vs. Speed, Upright Posture
Subject Means for Maximum Magnitude Supine Posture

Figure 21- Maximum Magnitude vs. Speed, Supine Posture

Means of Transformed Maximum Magnitude- Postures Compared

Figure 22-Maximum Magnitude, Supine and Upright Compared
Area Under the Curve
Area increased with the scene speed ($F(4, 44) = 47.206, p = 0.0$). This result was expected since maximum magnitude also increased with speed, and latency decreased. Figure 23 indicated that area was slightly greater upright than the supine; however, this difference was not statistically significant ($F(1, 11) = 1.890, p = 0.197$). The order of presentation did not influence the results ($F(1, 11) = 0.004, p = 0.954$).

![Mean Area, Upright and Supine Postures Compared](image)

**Figure 23- Mean Area, Upright and Supine Postures Compared**

Rise Time
The rise time was defined as the time from the onset of vection to 90% of the peak vection magnitude. The order of presentation showed no significant main effect ($F(1, 11) = 0.159, p = 0.698$). Speed had a significant effect ($F(4, 44) = 5.492, p = 0.003$). The difference in rise time between the lowest and the highest speed in the upright
Rise Time Means—Upright and Supine Postures

Figure 24- Mean Rise Time, Upright and Supine Postures Compared
posture is approximately 1.0 s while for supine the increase is about 0.7 s. Upright mean rise times are longer than for the supine posture (F(1,11) = 4.969, p = 0.048).

Rise Slope
The slope increased with speed (F(4,44) = 16.587, p = 0.0) with indications of a plateau at higher speeds (Figure 25). Neither posture (F(1,12) = 0.037, p = 0.850) nor order of presentation (F(1, 11) = 0.341, p = 0.571) were statistically significant factors. Similar to the maximum magnitude results, the slope values were transformed by raising the values to the power of 0.1 in order to stabilize the variance with scene speed.
Adaptation

Aftereffects
During post-experiment questioning, seven subjects reported a persistence of vection after the scene was blacked out. Many described the aftereffect as intermittent and subtle. Some noticed that aftereffects occurred more regularly at the higher scene speeds. The subjects were separated into two groups: those that did and those that did not report aftereffects during the post-experiment interview (Figure 26). Statistical analysis of the data did not detect a significant difference in decay latency between the two aftereffects groups ($F(1, 11) = 2.056, p = 0.179$). An examination of the subject means (Figure 27 and Figure 28) confirmed that the members of each group overlapped significantly. Consequently, the difference between the means of the two groups resulted from a couple of subjects in the yes group with very large after-latencies. In addition, posture did not influence the decay latency values significantly either ($F(2, 11) = 1.650, p = 0.236$).
Figure 26- Mean Decay Latencies, subjects reporting aftereffects (Yes group) are compared to subjects who did not (No group). Means for both upright and supine postures are plotted.
Figure 27 - Individual after-latency means for subjects reporting aftereffects (Yes group) and for those not reporting them (No group)- Upright posture.

Figure 28 - Individual after-latency means for subjects reporting aftereffects (Yes group) and for those not reporting them (No group)- Supine posture.
Repetition
Both latency and maximum magnitude results were examined for trends over the time span of the experiment. Any adaptation appeared to be minimal or non-existent. Both measures were plotted versus repetition for each scene speed and posture separately. Latency decreased slightly over time for the upright posture (Figure 30). However, latencies exhibited no adaptation across the supine trials (Figure 29). The magnitude of vection was constant across repetitions during both upright (Figure 32) and supine trials (Figure 31). Note that there is a significant spike in magnitude at Repetition 7. This marked the start of Block 2 and the subjects were told to consider their vection on the first trial at speed 3 as equal to 50% of the joystick scale. The large change between repetitions 7 and 8 suggested that either the magnitude scale was subsequently modified (or forgotten) during each experimental block or our instructions did not correspond in some way to the subject's internal scale and consequently were discarded by the next repetition. The magnitude scale will be discussed further in the following section.

The latencies were examined for each posture separately as a three-factor (Repetition, Block, and Speed) repeated measures analysis. Unlike previous analyses, data from all 6 repetitions were included. Considering upright latencies, repetition was not significant (F(5,60) = 1.495, p= 0.218), but the interaction factor between repetition and block was significant (F(5,60) = 3.168, p= 0.013). This result suggested that adaptation may have been restricted to the first few trials and the analysis was performed on each block of trials separately. In Block 1, repetition produced a significant result (F(5,60) = 3.399, p= 0.009) with Repetition 2 differing significantly from Repetition 3 (F(1,12)= 4.702, p = 0.051). Furthermore, the plot in Figure 30 suggests that latencies decreased over the first few repetitions but then remained constant over the rest of the trials. There still was a large amount of noise in the data. Latencies in Block 2 did not show a significant influence of repetition (F(5,60) = 1.083, p= 0.377). For the supine results, repetition was not significant either when the two blocks of trials were merged (F(5,60)= 1.008,

6Also, the multivariate test was not significant (F(5,8) = 1.212, p= 0.385).
p = 0.417) or when they were analyzed separately: Block 1 (F(5,60) = 0.253, p = 0.929), Block 2 (F(5,60) = 1.812, p = 0.124).

Figure 29- Mean Latency vs. Repetition, Supine Posture
Average Latency vs Repetition, Upright Blocks 1&2

Figure 30- Mean Latency vs. Repetition, Upright Posture

Average Max. Magnitude vs Repetition, Supine Block 1 & 2

Figure 31- Mean Max. Magnitude vs. Repetition, Supine Posture
The analysis of the magnitude data followed the same procedure as latency. Results from each posture were analyzed as a three factor repeated measure with all 6 repetition included in the data set. Upright maximum magnitude values did not vary significantly with repetition (F(5,60) = 0.755, p=0.567). Then the blocks were re-analyzed separately to search for a possible influence of repetition in one block but not the other. Neither Block 1 nor Block 2 produced an effect with repetition (F(5,60) = 0.237, p = 0.935 and F(5,60) = 0.065 respectively). For supine posture, repetition indicated a nearly significant effect (F(5,60) = 2.214, p = 0.068) when considering both blocks together. Repetition showed no significant effect on either block analyzed separately: Block 1 (F(5,60) = 1.572, p = 0.199). and Block 2 (F(5,60) = 1.802, p = 0.147).

Figure 32- Mean Max. Magnitude vs. Repetition, Upright Posture
Discussion

Magnitude Estimation
Instructions to subjects regarding magnitude estimation introduced a bias into the data that may have affected the comparison of results between postures. At the start of each block of trials, the subject was instructed to assign a value of 50% to the magnitude of perceived speed of self-motion experienced during the first presentation of the modulus. The magnitude of vection on all consequent trials in that block was reported as a ratio to the response to the remembered modulus. The modulus was redefined at the start of each block and thus changed with posture. Consequently, the magnitude of perceived speed was not compared to a consistent reference perception. While the scene speed of the modulus remained constant over blocks, the methodology also wrongly assumed that the perceived speed of self-motion at the modulus speed remains constant under changes in posture. Unless posture does not influence perceived speed of self-motion, the modulus will not remain constant over the course of the experiment. The implied assumption, therefore makes comparisons between postures difficult. The trend between scene speed and magnitude will still hold but the slope of the curve would most likely change under a revised protocol.

Three hypothetical scenarios for the relationship between posture, scene speed and magnitude were examined to determine the effect of the changing modulus:
1. a change in posture caused a shift in the intercept of the scene speed-magnitude curve but no change in slope (Figure 33);
2. posture changes the slope of the curve but the value at the modulus for both posture was equal (Figure 34);
3. both the slope and the value of perceived speed of self-motion varied with posture (Figure 35).
Figure 33- Hypothetical Maximum Magnitude Curves- Change in Posture caused a shift in the intercept (Case 1).

Figure 34- Hypothetical Maximum Magnitude Curves- Posture produced a change in slope but the perception at the modulus speed is equal in both conditions (Case 2).
Figure 35- Hypothetical Maximum Magnitude Curves- Posture produced both a shift at the modulus speed and a change in slope (Case 3)  
The results did not indicate an effect of posture on the perceived speed of motion. The three hypothetical situations were explored to determine whether it was possible that posture did influence the maximum magnitude values, but that this effect was masked by the error in defining the modulus. In the first case, under the experiment’s instructions, the two parallel magnitude curves would have been transformed such that the lines would have crossed at the modulus speed and their slopes would not longer be equal. The second situation would not be altered since the perceived speed of self-motion was the same for both postures as was assumed. The general situation, illustrated in Figure 35, involved both a change in slope and a difference between the perceived speeds at the modulus scene speed. In this case, only one set of circumstances could have transformed an influence of posture on the maximum magnitude into a null result. The ratios of the slopes and of the intercepts of the two lines must each equal the ratio of the perceived speeds of self-motion at the modulus scene speed. Since the choice of the modulus speed was somewhat arbitrary, it was unlikely that this relationship held. Therefore, the results support the conclusion that posture did not influence the perceived speed of self-motion.
However, without knowing the ratio of the magnitudes of perceived self-motion in the upright and supine postures, it would have been impossible to quantify any difference between the two magnitude curves under the current procedure. Under the transformation caused by the two values for the modulus, the three hypothetical situations can not be distinguished.

**Usefulness of Calibration**

In order to evaluate the usefulness of the calibration curves, each subject's perceived speed of self-motion was recalculated using an ideal linear calibration curve as shown in Figure 5. The mean maximum magnitude for all subjects was compared with and without the calibration and plotted in Figure 36. The curves were similar but the ideal calibration maximum magnitude values were shifted higher. The speed and posture relationships remained the same. Notice that in neither situation, does the mean maximum magnitude for the modulus speed (middle speed) reach the 50% mark stipulated in instructions to the subjects. However, this comparison did not provide a method to evaluate whether the calibration procedure improves the quality of data since the ratio scale was somewhat arbitrary. The calibration curves were intended to remove any extra variation in responses between subjects due to a difference in the subject's internal joystick deflection scale. The use of the calibration curves was presumed to reduce the variance in magnitude responses among subjects. Figure 37 shows that the standard error of the mean maximum magnitude is less for all speeds and both postures without the individual calibration curves. It was expected that the calibration curves would either decrease the standard error if it improved the data or that the standard error would not change significantly if no improvement was provided by the calibration curves. The calibration curves appeared to increase the variance among subjects. However, the calibration procedure still provided the subjects with an opportunity to practice using the joystick and improved the accuracy of their responses. In future experiments, the ideal calibration curve should be used for all trained subjects.
Figure 36- Maximum Magnitude- Means for all subjects calculated from individual calibration curves compared with values from general ideal calibration curve.

Figure 37- Standard error of the mean for maximum magnitude, comparison between values calculated with individual calibration curves and values using ideal calibration curve.
Speed

Latencies decreased and maximum magnitude increased with scene speed. These results agreed with Kano’s observations and supported the conclusion that vection was strengthened with the increased surround velocity. This relationship confirmed the input of the visual system to the process of determining body motion.

For maximum magnitude, the data did not saturate at higher scene velocities as observed in earlier studies on linear vection (Berthoz, 1975). Rather a nearly linear relationship holds between maximum magnitude and the scene velocity. The peak magnitude would possibly have saturated at a higher velocity than 1.6m/s, outside the range tested in this experiment. Some aspect of the looming vection stimulus such as the depth cues or the involvement of the central visual region, may have extended the subject’s range of motion detection before saturation. However, differences in anchoring the ratio scale may have also contributed to the lack of saturation in the data.

As shown in Figure 15, at low speeds, the rate of decrease in latencies was shallower. Then latency decreased rapidly with higher scene velocities. This relationship is similar to the output of a low pass filter and may indicate that the input of the otoliths was weighted more at low temporal frequencies. However, the current experiment can not state this result with certainty. As mentioned in the previous section, at the low scene velocities, vection occurred less frequently. Therefore, if the trials were extended in duration, vection may have developed with a latency of greater than 10s. Then, the average latency would have increased and a more linear relationship between latency and scene velocity may have resulted.

Posture

The effect of posture on latency may have been greater than indicated by the results. No-vection trials (those in which subjects did not report vection) occurred more frequently in the supine than in the upright posture. If the trial duration had been extended, then, vection may have developed with a latency in excess of 10 seconds during some of the
observed novection trials. Then, the average latency in the supine posture would have increased and the difference between postures would have been emphasized. Also, the difference between the supine and upright latencies diminished at higher scene speeds. A strong visual cue appears to be able to overcome vestibular inputs.

The difference between postures was reversed from the results observed by Kano. The different content of the visual stimulus may have provided additional cues that influenced vection. Previous studies have explored the paradoxical response of the otoliths to either an acceleration along the z-axis or a forward pitch. Fighter pilots, during take-off from an aircraft carrier at night, have been known to misinterpret the sudden acceleration of the plane as an unexpected increase in pitch and they have overcompensated by pushing the nose of the plane down. In fact, this experiment partially depended on the assumption that a change in pitch (when the subject was lying supine) being interpreted as a motion cue by the otoliths. However, what happens if the visual and vestibular conflict over the interpretation of the observer's orientation in addition to motion? Observers have been shown to use visual cues to set the "down" vector in the egocentric frame in studies such as the rod and frame experiments. Nemire investigated the characteristics of a virtual environment that influenced a subject's perception of pitch (Nemire, 1994). Using a box similar to the hallway, he found that adding longitudinal lines along the interior side walls would modify the subject's perception of the tilt of the horizon. Many of our subjects indicated during post-experiment questioning that regardless of body posture, they felt they were travelling in horizontal direction perpendicular to gravity. The linear motion of the tunnel most likely provided dynamic cues to determining the level of the horizon in addition to the static cues studied by Nemire. Therefore, supine subjects received conflicting cues regarding their orientation. The virtual hallway suggested that the horizon is always perpendicular to the subject's z-axis. This second conflict may have delayed vection in the supine posture because while it was determined whether the otoliths were signalling a change in orientation or motion. This additional cue conflict would not be as strong in other types of scenes such as random dot stimulus. Also, the occlusion of the central visual would have omitted some
of the visual information regarding the vanishing point and limited the visual perception of the artificial horizon. This experiment should be run again using scenes with different levels of structure to observe whether the results agree with this hypothesis.

Furthermore, the frame could be replaced with an opaque card that will permit viewing of motion in the peripheral visual field.

On the other hand, the maximum magnitude values did not exhibit a posture influence. Unlike latencies, extended trials would not have changed these results. The magnitude profiles indicated that the magnitude of perceived motion achieved its peak level rapidly after the onset of vection and remained near a constant level for the rest of the trial. Therefore, it was unlikely that the short duration of the vection trials diminished any posture effect. These results suggest that both vision and the vestibular system contribute to the detection of observer motion but that the speed of motion was estimated solely on the basis of visual inputs. The otoliths have been modeled as integrators of accelerations and therefore, it was thought that they would have provided an estimate of the velocity. Perhaps two separate neural pathways for the detection of motion and the measurement of speed were activated.

**Adaptation**

**Vection Aftereffects**

The experiment failed to detect the presence of vection aftereffects. While some subjects asserted that they experienced the aftereffects, their after-latencies were not significantly different from those of the other subjects. Furthermore, unlike MAE, the after-latency did depend on the speed of the test stimulus. The lack of a speed dependence contributed additional evidence that subjects did not experience vection aftereffects. Secondly, no subjects mentioned a reversal of the direction of motion. The instructions to subjects did not refer to the direction of the aftereffect and the omission may explain the lack of comments. However, subjects did report lingering unsteadiness after completing the experiment especially after the removal of the HMD. So perhaps some residual effects
existed. In comparison with MAE experiments, the test stimulus was very short and may have been inadequate to elicit an aftereffect. Therefore, this experiment did not rule out the possibility of a vection aftereffect.

Repetition

Latency did exhibit a small reduction in duration over the first few trials in the upright posture. The same effect was not observed in the supine posture. This discrepancy between postures was more likely due to the greater number of no vection trials in the supine posture (and the insertion of the average latency into the empty cells) rather than some underlying difference in motion processing. Consequently, the neural processes involved with detection of observer movement reached an equilibrium quickly with little learning. Observer motion plays such a large role in everyday life that its processing by the brain has well established parameters that were not influenced by a relative few presentations of a new combination of inputs.

Peak magnitude did not exhibit any change with repetition. The fact that latency and magnitude do not share the same pattern of adaptation may support the theory that the detection and measurement of self-motion are processed by different neural pathways. Also the absence of any decrease in peak magnitude indicates that the reduction in vection intensity noted by Berthoz et. al. over the course of one long presentation of the stimulus is not replicated by the summation of a series of short trials and thus confirms that the underlying process is habituation of the activated neurons.

Future Work

The joystick training did not exactly duplicate the magnitude deflection task. The task of assessing vection placed a greater mental load on the subjects and increased the difficulty of using the joystick as an accurate indicator of their perceptions. Secondly, during training trials, the subjects were asked to complete a set of static deflections whereas during experimental trials, they attempted to report continuously on their vection
magnitude without resetting the joystick to center position between data samples. The joystick training data provided no estimate of the drift error as a function of time. During the pilot studies, the subjects were asked to complete both tasks (static individual deflections and sequential deflections without resetting) and there was no significant difference in the accuracy of the tasks. If the joystick is to be retained as device for reporting continuously changing perception, then a dynamic tracking drill must be developed. For example, a subject could attempt to report with the joystick the variable length of a displayed bar for a period of time. Furthermore, the joystick training procedure should be repeated in the supine posture. A few subjects commented that deflecting the joystick “felt” different during supine trials. Finally, an algorithm should be implemented such that the subject continues with the joystick calibration training protocol until a certain criterion has been met. It is suggested the subject complete sets of twenty random trials until a multiple regression of the pooled data points indicates that there is no significant effect of data set.

A number of follow-up experiments need to be performed to confirm the hypotheses presented in the discussion. The influence of the scene content should be analyzed by repeating the experiment while varying the scenes and measuring the latencies in each posture. Emulating Nemire’s design, four different scenes should be tested: a random dot cloud, a hallway with longitudinal lines, a hallway with cross-sectional lines and the checkerboard hallway of the current experiment. If Nemire’s result can be extended to vection, then the longitudinal lines should be sufficient to create an artificial horizon and latencies will be less in the upright than the supine posture. In another experiment, the green frame could be replaced with an occluding plane in the central visual area. The subjects may be extrapolating orientation information including a vanishing point from the central visual field.

In order to gather conclusive data on the vection aftereffects, the trial duration should be lengthened. It is possible that the trials in this experiment were too short to habituate the activated motion processing neurons. Instead of a blackout at the end of each trial, a
stationary scene could be inserted at the end of randomly chosen trials and the latencies could be compared. Also the longer trials provide the opportunity to ascertain whether vection would have developed eventually in the no effect trials or if there is a certain probability, as a function of scene speed, of vection occurring.

Conclusion

This experiment investigated the influence of scene speed and subject posture on the development of looming vection. In the upright posture, the gravitational axis and motion axes were perpendicular to each other while they were aligned in the supine posture. The visual stimulus was displayed in a stereoscopic head mounted display. Six measures were calculated for each vection trial. All except rise time and after-latency were influenced by scene speed. The latency of vection onset decreased and peak magnitude of perceived speed of self-motion increased with higher speeds. This result confirmed the influence of the visual cues on the determination of observer movement and was consistent with previous experimental results. Also, latencies were lower in the upright posture than in the supine while peak magnitude was not affected by changes in posture. The difference in posture influence may indicate the existence of different neural processes for the detection and estimation of observer movement where only detection was influenced by vestibular inputs. Previous experiments have found that latencies were reduced in the supine posture contradicting the present result. It was hypothesized that the virtual checkerboard hallway provided visual cues that subjects used to define an artificial horizon used in determining their body orientation. When supine, this visually defined orientation conflicted with vestibular cues and the resolution of this conflict delayed the onset of vection. Finally, vection was analyzed for the signs of adaptation. The experiment asked subjects to indicate when their vection dissipated after the removal of the visual stimulus. The results found no conclusive evidence for the existence of a vection aftereffect. The 0.5 to 1.5 sec latency in reporting loss of vection after the scene went dark might simply be due to joystick indication delay. However, in post-experiment questioning, seven subjects affirmed that their sense of
vection extended beyond the end of the translation of the tunnel. The experimental trials may have been too short in duration to habituate the active motion processing neurons. Furthermore, latencies and peak magnitude were examined for changes over repeated presentation of the stimulus. Latencies exhibited a small reduction over the first few trials before reaching a constant value. No adaptation was detected in the sequence of peak magnitude values. Repeated exposure to the vection stimulus did not affect subsequent responses.
Bibliography


Appendix A - Subject Questionnaire and Instruction Set

Virtual Environment Questionnaire

Subject No. : _________

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do you have medical conditions that would be aggravated if you became motion sick? (yes, no)</td>
<td></td>
</tr>
<tr>
<td><em>If you said “yes,” you should not be a subject for this experiment and you should stop right now. Otherwise, please continue...</em></td>
<td></td>
</tr>
<tr>
<td>Have you ever experienced dizzy spells? (yes, no)</td>
<td></td>
</tr>
<tr>
<td>If yes, can you please describe these experiences?</td>
<td></td>
</tr>
<tr>
<td>or ... motion sickness? (yes, no)</td>
<td></td>
</tr>
<tr>
<td>If yes, can you please explain some of your experiences?</td>
<td></td>
</tr>
<tr>
<td>Do you have normal peripheral vision? (yes, no)</td>
<td></td>
</tr>
<tr>
<td>Do you have normal depth perception? (yes, no)</td>
<td></td>
</tr>
<tr>
<td>Do you need corrective lenses? (yes, no)</td>
<td></td>
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</tbody>
</table>
Check all that apply. I have...

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</table>

- □ astigmatism
- □ dyslexia
- □ near-sightedness
- □ blind spots
- □ far-sightedness
- □ color-blindness

Do you have any hearing loss? (yes, no)
If yes, please explain how you have/are lost/losing your hearing.

Do you have any balance problems? (yes, no)
If yes, please describe the nature of your balance problem(s)?

Do you have a history of chronic ear infections? (yes, no)
If yes, can you please elaborate?

What is your gender? M or F
<table>
<thead>
<tr>
<th>Previous Experience</th>
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<tr>
<td>Please describe any experience you have had with Virtual Reality systems.</td>
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</table>

<table>
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<tr>
<th>How often do you play video games? What kind?</th>
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</table>
Instructions for subjects

This experiment investigates the influence of vision on a person's sense of motion and orientation. Typically, the sensory information from the visual and vestibular (inner ear) systems combine to provide us with information about our body's position and orientation. However, in a zero gravity environment, the signal from the vestibular organs is distorted and astronauts tend to rely more heavily on vision for this information. The data collected from this experiment will aid in the design of another experiment scheduled to fly on the Neurolab Shuttle mission in 1998.

After completing the attached questionnaire and receiving further instructions from the experimenter, the head mounted display (HMD) will be securely placed on your head. The interpupillary distance will be adjusted such that the left and right images fuse into a three-dimensional visual scene. Once the HMD is worn, all instructions will be displayed on the screen. The HMD will be removed during rest breaks. You will view a series of moving visual scenes created by the computer and projected onto two colour TV screens inside the HMD. The computer draws a slightly different scene for each of your eyes, producing an illusion of depth. Once you have donned the HMD, help us check the following things (the experimenter will talk you through this list):
1. Is the display reasonably comfortable?
2. Does the scene seem to be focused in each eye?
3. When you look with both eyes, does the image fuse? (We can adjust the offset between the two eyes).
4. Are both screens about the same brightness? (If not, adjust the display up or down, or left and right a bit).
5. If you look around the scene, can you still see all of it? (If not, try adjusting the display left or right a bit).

The entire experiment session should last approximately an hour. The experiment is arranged in four blocks of trials with breaks in between. Two blocks will be completed while sitting upright and the other two while lying supine. All personal and experimental data will remain confidential and anonymous in publications.

In each trial, a visual scene will be presented and set in motion in a horizontal direction towards you. You should direct your gaze directly ahead and fixate the center window of the green structure in the foreground. During each trial, you might feel a sense of self motion. This perception is known as vection. Many individuals have experienced vection previously when sitting in a stationary car or train compartment. Another vehicle in an adjacent lane or track moves slowly at the edge of the visual field. This occasionally triggers a perception that you are moving in the opposite direction. Certain scenes in an IMAX film can also induce vection. During the experiment trials, the vection may be intermittent. An interruption in the perception of vection defines a
"dropout". Furthermore, the speed of self-motion may vary during a trial while the visual scene may appear to slow down but not necessarily stationary.

You will use a joystick to report your perceptions of vection. At the beginning and end of the experiment, you will complete a set of quick trials to gauge your accuracy when deflecting the joystick. If the vection sensation emerges, it may take some time to develop. At the moment when you perceive vection during a trial, press the trigger button on the joystick. Then, push the joystick forward in proportion to your perceived speed of vection. Try to judge your vection speed on a percentage scale from 0 to 100%. On the first trial of every block, consider your maximum vection speed to be equal to 50% of the scale. Then, judge your speed relative to this modulus in subsequent trials. Report your vection speed dynamically throughout the trial. At the end of each trial, the visual scene will black out. Your perception of vection may persist in darkness. Press the joystick trigger again when vection speed has been reduced by 90%. Then, release all the joystick buttons and wait for further instructions to appear on the screen.

Our subjects sometimes ask if we want them to deliberately imagine that they are moving. No, rather, we would like you to assume that self-motion is possible, and that vection might happen, but to wait for it to spontaneously to occur. Feel free to ask the experimenter any questions. She will be happy to discuss the purpose of the experiment after the session.
Appendix B- Committee on the Use of Humans as Experimental Subjects (COUHES) Experiment Description

The proposed ground experiments investigate the adaptive nature of the responses of linear vection. The experimental setup is identical to the Neurolab configuration with the subject viewing a set of moving scenes in a stereo head mounted display (HMD). These moving scenes intend to illicit a sense of linear self-motion in the forward/backward axis. The subject will report his or her sensations of self-motion by deflecting a joystick. We intend to measure the latency of vection onset and the intensity of self-motion and track the changes as the subject is repeatedly exposed to the stimulus. Trial length, scene speed and scene content are variables examined in a series of three experiments. The experiments will be run with the subject in both upright and supine conditions. Each session will last no more than one hour and breaks will be scheduled at approximately fifteen minute intervals. Some subjects may be asked to return for multiple sessions but on no more than 4 separate days. Minimal risks are associated with this experiment. Some subjects may experience slight nausea. Subjects will be advised that they can terminate the experiment at any moment when they begin to feel uncomfortable.

Informed Consent Form for Neurolab Experiments conducted at MIT (1/16/97)

ROLE OF VISUAL CUES IN SPATIAL ORIENTATION (LINEAR VECTION PROTOCOL)

I have been asked to participate in a study investigating the role of visual cues in spatial orientation. This particular experiment, the linear vection test, examines whether gravity influences the onset of visually induced illusory self-motion.

Ground tests will be conducted in both erect or supine positions. The study will take approximately one and a half hours to complete during a single testing day. Up to 7 repeat test sessions may be requested. Sessions may be videotaped. However, I understand my name will be kept strictly confidential and not be associated with my data in any publications. I realize that there is a slight risk of motion sickness. I may decline to answer questions, and I may ask questions about the study at any time, and that my participation is strictly voluntary. I am free to withdraw at anytime without penalty. I am at least 18 years of age.

In the linear vection test, I will view several different moving visual scenes (up to four) projected by a head mounted display. I will be asked to indicate the onset and magnitude of my illusory self-motion either verbally or via a joystick/button box. Breaks have been incorporated in the experimental procedure. However, should I require additional rests due to fatigue or queasiness, I should not hesitate to inform the experimenter.
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 MIT's Insurance and Legal Affairs Office at 617 253-2822.) I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT, telephone 253-6787, if I feel I have been treated unfairly as a subject.

I have been informed as to the procedures and purpose of this experiment and agree to participate.

Participant _______________________ Date ___________

Witness _________________________ Date ___________
for i = 1:nspeeds
    subplot(2,3,i)
    hold on
    title(sptitle(i,:))
    xlabel('Time (s)')
    ylabel('Raw joystick output')
    axis([0 10 0 130]);
end

upright = figure;
%set up subplots figure
for i = 1:nspeeds
    subplot(2,3,i)
    hold on
    title(sptitle(i,:))
    xlabel('Time (s)')
    ylabel('Raw joystick output')
    axis([0 10 0 130]);
end

%read in first line of data- start of trial indicator
[frame, fcount]= fscanf(FDATA, '%f %f %f %f %f
', 5);

while (~isempty(frame)& EFLAG) %at the start of a trial

    %read in a line of argument file
    [arglist, count] = fscanf(FTRIALS, '%s \n',1)
    if isempty(arglist) %end of .arg file
        trialID = ";
        trialtype = ";
        frame = ";
    else
        %parse argument lists
        delimit= find(arglist==',');
        %all lines should have 4 comma delimiters
        trialID = arglist(2:delimit(1)-2);
        trialtype = arglist(delimit(4)+1:length(arglist));

        %read in line of .raw data file
        [frame, fcountl]= fscanf(FDATA, '%f %f %f %f %f
', 5);
        if ~isempty(frame)
            trialno= frame(5);
            trialstart = frame(1);
            trial = [0 0 0]; %initialize array every trial
        else %end of .raw file
            81
fprintf(1,'%s
', 'reached empty string');
frame= [0];
trialtype = 'nonsense'
end

% determine trial type
if strcmp(trialtype,'JSTICK')
    % calibration trial
    while (frame(1))
        prevjstick = frame(4);
        [frame, fcount2]= fscanf(FDATA, '%f %f %f %f %f /n', 5);
        if isempty(frame)
            frame = [0];
        end
    end
    % end of trial found
    % consider last joystick measurement as the intended deflection
    % print to result jstick file
    fprintf( FJSTICK, '%s	%3.0f	%3.0f
', trialID, prevjstick, trialno);
    % print on a line the desired deflection, intended deflection, trial number
else
    while frame(1)
        % add that line to matrix for that trial [time, buttons, deflection]
        % joystick center position equals 128; full throttle forward is 0- these values are transformed such that joystick deflection is an monotonic increasing function
        trial = [trial; (frame(1)-trialstart)/100, frame(2), max([128-frame(4);0])];
        [frame, fcount]= fscanf(FDATA, '%f %f %f %f %f
', 5);
        if isempty(frame)
            frame(1)=0;
            % set an end of file flag
            EFLAG=0;
        end
    end
    trialsize = size(trial);
    trial = trial(2:trialsize,:);
    if strcmp(trialID,'SUPSP1')
        % select right plot
        figure(supine)
        stats= maganalyze(trial);
        latency = stats(1);
subplot(2,3,1)
%plot magnitude curve in raw
if latency > 0
    plot(trial(:,1),trial(:,3)) %only plot trials where subject experienced vection
end
fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f\n', 'SUP_SP1', stats, trialno);
elseif strcmp(trialID,'SUP_SP2')
    figure(supine)
    subplot(2,3,2)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f\n', 'SUP_SP2', stats, trialno);
elseif strcmp(trialID,'SUP_SP3')
    figure(supine)
    subplot(2,3,3)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f\n', 'SUP_SP3', stats, trialno);
elseif strcmp(trialID,'SUP_SP4')
    figure(supine)
    subplot(2,3,4)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f\n', 'SUP_SP4', stats, trialno);
elseif strcmp(trialID,'SUP_SP5')
    figure(supine)
subplot(2,3,5)
stats = maganalyze(trial);
latency = stats(1);
% plot magnitude curve in raw
if latency > 0
    plot(trial(:,1),trial(:,3))
end
fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f\n',
    'SUP_SP5',stats,trialno);

elseif strcmp(trialID,'UPR_SP1')
    figure(upright)
    subplot(2,3,1)
    stats = maganalyze(trial);
    latency = stats(1);
    % plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f\n',
        'UPR_SP1',stats,trialno);

elseif strcmp(trialID,'UPR_SP2')
    figure(upright)
    subplot(2,3,2)
    stats = maganalyze(trial);
    latency = stats(1);
    % plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f\n',
        'UPR_SP2',stats,trialno);

elseif strcmp(trialID,'UPR_SP3')
    figure(upright)
    subplot(2,3,3)
    stats = maganalyze(trial);
    latency = stats(1);
    % plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f\n',
        'UPR_SP3',stats,trialno);
elseif strcmp(tialID,'UPR_Sp4')
figure(upright)
subplot(2,3,4)
stats = maganalyze(trial);
latency = stats(1);
%plot magnitude curve in raw
if latency >0
    plot(trial(:,1),trial(:,3))
end
fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f
',
'UPR_Sp4',stats,trialno);

elseif strcmp(tialID,'UPR_Sp5')
figure(upright)
subplot(2,3,5)
stats = maganalyze(trial);
latency = stats(1);
%plot magnitude curve in raw
if latency >0
    plot(trial(:,1),trial(:,3))
end
fprintf(FMAG, '%s\t%3.2f\t%3.2f\t%3.2f\t%3.2f\t%3.0f
',
'UPR_Sp5',stats,trialno);

else
    %if this is a break trial or an aftereffects trial.. do nothing-skip trial data
end
end
end

%print plots to file- couldn’t figure out to give them more flexible pertinent filenames-
%encapsulated postscript format
figure(supine)
print -deps 'sup_grph'
figure(upright)

print -deps 'upr_grph'
fclose('all');
%end after_raw.m
after_raw_trans.m

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%98/02/02
%Christine Tovee
%After-Effect experiment Raw Data Manipulation with Joystick Calibration
Transformation
%creates of file containing latency, max. magnitude, rise time, area and aftervection latency
%for each trial .. all joystick deflections are transformed into perceptual units
%plots the real time continuous joystick plots
%change path to include 'c:\My Documents\Thesis\Vection\AfterEffects\Data\Subjectx'
%where data files are stored
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% constants
nspeeds = 5;
sptitle = ['Speed 1'; 'Speed 2'; 'Speed 3'; 'Speed 4'; 'Speed 5'];
zerodefln = 128;
EFLAG = 1;

%input file names
subject= input('What subject do you want to analyze?\n','s');
datafile = [subject,'.raw'];
name=subject(1 :find(subject == '_'));
trial = input('Which trial sequence (1 or 2)?', 's');
trialfile=['AFTER_EFFECT',trial,'.arg'];

%open files
FTRIALS= fopen(trialfile, 'rt')
FDATA = fopen(datafile, 'rt')
FJSTICK = fopen([name,'jstk.res'], 'wt')
FMAG = fopen([name,'magtrans.res'], 'wt')

%ask for calibration curve parameters
calibcoeff = input('Input the calibration coefficient for the subject\n');
calibconst = input('and the calibration constant?');

%create two figures one each for upright and supine
supine = figure;
for i = 1:nspeeds
subplot(2,3,i)
hold on
title (sptitle(i,:))
xlabel('Time (s)')
ylabel('Raw joystick output')
axis([0 10 0 135]);
end

upright = figure;
%set up subplots in figure for each tunnel speed
for i = 1:nspeeds
    subplot(2,3,i)
    hold on
    title (sptitle(i,:))
    xlabel('Time (s)')
    ylabel('Raw joystick output')
    axis([0 10 0 135]);
end

%read in first line of data- start of trial indicator
[frame, fcount]= fscanf(FDATA, '%f%f%f%f%f
', 5);

while (~isempty(frame)& EFLAG) %at the start of a trial

delimit= find(arglist==',');
%all lines should have 4 comma delimiters
trialID = arglist(2:delimit(1)-2);
trialtype = arglist(delimit(4)+1:length(arglist));
[frame, fcount1]= fscanf(FDATA, '%f%f%f%f%f
', 5);
if ~isempty(frame)
    trialno= frame(5);
    trialstart = frame(1);
    trial = [0 0 0]; %initialize array every trial
end
else
    fprintf(1,'\%s \n', 'reached empty string');
    frame= [0];
    trialtype = 'nonsense'
    trialID = 'nonsense2'
end
if strcmp(trialtype,'JSTICK')
    %calibration trial
    while (frame(1))

        prevjstick = frame(4);
        [frame, fcount2]= fscanf(FDATA, '\%f \%f \%f \%f \n', 5);
        if isempty(frame)
            frame = [0];
        end
    end
    %end of trial found
    %consider last jstick measurement as the intended deflection
    %not printing results to file since we have calculated calibration coefficients already
else
    while frame(1)

        %add that line to matrix for that trial [ time, buttons, xdeflection]
        %deflection data transformed to perceptual units
        trial = [trial; (frame(1)-trialstart)/100, frame(2), max(((frame(4)-
calibconst)/calibcoeff;0))];
        [frame, fcount]= fscanf(FDATA, '\%f \%f \%f \%f \n', 5);
        if isempty(frame)
            frame(1)=0;
            %set an end of file flag
            EFLAG=0;
        end
    end
trialsz = size(trial);
trial = trial(2:trialsz,:);
if strcmp(trialID,'SUPSPl')
    %select right plot
    figure(supine)
    stats= maganalyze(trial);
    latency = stats(1);
    subplot(2,3,1)
%plot magnitude curve in raw
if latency >0
    plot(trial(:,1),trial(:,3))
end
fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'SUP_SP1',stats,trialno);
elseif strcmp(trialID,'SUP_SP2')
    figure(supine)
    subplot(2,3,2)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency >0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'SUP_SP2',stats,trialno);
elseif strcmp(trialID,'SUP_SP3')
    figure(supine)
    subplot(2,3,3)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency >0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'SUP_SP3',stats,trialno);
elseif strcmp(trialID,'SUP_SP4')
    figure(supine)
    subplot(2,3,4)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency >0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'SUP_SP4',stats,trialno);
elseif strcmp(trialID,'SUP_SP5')
    figure(supine)
    subplot(2,3,5)
stats = maganalyze(trial);
latency = stats(1);

%plot magnitude curve in raw
if latency > 0
    plot(trial(:,1),trial(:,3))
end
fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'SUP_SP5', stats, trialno);

elseif strcmp(trialID,'UPR SP1')
    figure(upright)
    subplot(2,3,1)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3)) %add options later
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'UPR_SP1', stats, trialno);

elseif strcmp(trialID,'UPRSP2')
    figure(upright)
    subplot(2,3,2)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'UPR_SP2', stats, trialno);

elseif strcmp(trialID,'UPRSP3')
    figure(upright)
    subplot(2,3,3)
    stats = maganalyze(trial);
    latency = stats(1);
    %plot magnitude curve in raw
    if latency > 0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f', 'UPR_SP3', stats, trialno);
elseif strcmp(trialID,'UPR_SP4')
    figure(upright)
    subplot(2,3,4)
    stats = maganalyze(trial);
    latency = stats(1);
    % plot magnitude curve in raw
    if latency >0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f',
            'UPR_SP4',stats,trialno);

elseif strcmp(trialID,'UPR_SP5')
    figure(upright)
    subplot(2,3,5)
    stats= maganalyze(trial);
    latency = stats(1);
    % plot magnitude curve in raw
    if latency >0
        plot(trial(:,1),trial(:,3))
    end
    fprintf(FMAG, '%s	%3.2f	%3.2f	%3.2f	%3.2f	%3.0f',
            'UPR_SP5',stats,trialno);

elseif strcmp(trialID(1:5),'AFTER')
    % Calculate aftereffect latency
    % find first button press after a zero button value
    j = min(find(trial(:, 2) == 0));
    iprime = find(trial(:,2) ==1);
    % requires that joystick button be reset before finding latency
    i = min(find(iprime>j));
    if isempty(i)
        afterlat=-99999;
    else
        afterlat = trial(iprime(i), 1);
    end

    % aftereffect latency = time of button push - trial startime
    % print aftereffect latency on same line as other measures for trial
    fprintf(FMAG, '
', afterlat);

end
end
%print plots to files
figure(supine)
print -deps 'sup_grph_trans'
figure(upright)

print -deps 'upr_grph_trans'
fclose('all');

%end after_raw_trans.m

maganalyze.m

%%%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\\%\n
function y = maganalyze( data)
%calculate latency
%find first button push - indicates vection
%just in case subject holds down joystick button too long to advance trial
%make sure button is reset to zero before the next button press to indicate
%vection
j = min(find(data(:, 2) == 0)); %find button reset
iprime = find(data(:,2) ==1); %find all trigger button pushes
%requires that joystick button be reset before finding latency
i = min(find(iprime>j)); find first trigger push after button reset
if isempty(i) %no trigger push, no vection
    latency = -99999;
    rise = -99999;
    maxmag = -99999;
    area = -99999;
else %subject experienced vection
    latency = data(iprime(i),1); %this is in seconds; time stamps is 1/100th sec
    %calculate max magnitude, consider only data after trigger push

92
truncdata = data(iprime(i):size(data,1),:);

[maxmag, imaxmag] = max(truncdata(:,3));
%calculate rise time
% rise time definition: time to 90% max value- latency
k= find(data(:, 3) >=0.9*maxmag);
if isempty(k) %betcha sometimes k is empty if subject forgot to estimate magnitude
    rise = -99999
else
    irise = k(min(find(k>iprime(i))));
    rise= data(irise,1)-latency; %see latency calculation
end
%calculate integration of curve, estimate by the trapezoidal rule
area = trapz(truncdata(:,1), truncdata(:,3));
end

%return results
y= [latency, maxmag, rise, area];
%end maganalyze.m
Appendix D - Early and Late Repetitions Compared

Mean Latency, Early vs Late Repetitions, Upright

Figure 38 - Latency, Upright Posture

Mean Latency, Early vs Late Repetitions, Upright

Figure 39 - Latency, Supine Posture
Figure 40- Mean Decay, Upright Posture

Mean Decay, Early vs Late Repetitions, Supine

Figure 41- After Decay- Supine Posture
Mean Max. Magnitude, Early vs Late Repetitions, Upright

Figure 42- Max. Magnitude, Upright Posture

Mean Max. Magnitude, Early vs Late Repetitions, Supine

Figure 43- Max. Magnitude, Supine Posture
Mean Rise Time, Early vs Late Repetitions, Upright

Figure 44- Rise Time- Upright Posture

Mean Rise Time, Early vs Late Repetitions, Supine

Figure 45- Mean Rise Time, Supine Posture

97
Figure 46 - Mean Area, Upright Posture

Mean Area, Early vs Late Repetitions, Upright

Figure 47 - Area - Supine Posture
Mean Slope, Early vs Late Repetitions, Upright

![Graph showing the mean slope for early vs late repetitions in an upright posture.](image_url)

Figure 48- Slope, Upright Posture

Mean Slope, Early vs Late Repetitions, Supine

![Graph showing the mean slope for early vs late repetitions in a supine posture.](image_url)

Figure 49- Slope, Supine Posture
Appendix E- Vection Magnitude Profiles

Figure 50- Subject 1 Profiles, Upright Posture

Figure 51- Subject 1 Profiles, Supine Posture
Figure 52- Subject 2 Profiles, Upright Posture

Figure 53-Subject 2 Profiles, Supine Posture
Figure 54-Subject 3 Profiles, Upright Posture

Figure 55- Subject 3 Profiles, Supine Posture
Figure 56—Subject 4 Profiles, Upright Posture

Figure 57—Subject 4 Profiles, Supine Posture
**Figure 58-Subject 5 Profiles, Upright Posture**

**Figure 59- Subject 5 Profiles, Supine Posture**
Figure 60- Subject 6 Profiles, Upright Posture

Figure 61- Subject 6 Profiles, Supine Posture
Figure 62- Subject 7 Profiles, Upright Posture

Figure 63- Subject 7 Profiles - Supine Posture
Figure 64- Subject 8 Profiles, Upright Posture

Figure 65-Subject 8 Profiles, Supine Posture
Figure 66- Subject 9 Profiles, Upright Posture

Figure 67- Subject 9 Profiles, Supine Posture
Figure 68- Subject 10 Profiles, Upright Posture

Figure 69- Subject 10 Profiles, Supine Posture
Figure 70-Subject 12 Profiles, Upright Posture

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Figure 71- Subject 12 Profiles, Supine Posture
Figure 72- Subject 13 Profiles, Upright Posture

Figure 73-Subject 13 Profiles, Supine Posture
Figure 74- Subject 14 Profiles, Upright Posture

Figure 75-Subject 14 Profiles, Supine Posture