The SLS-2 Mission: Effects of Spaceflight on Static Ocular Counterrolling

by

Prashant Sinha

Submitted to the Department of Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Electrical Engineering and Computer Science
at the Massachusetts Institute of Technology

May 26, 1996

Copyright 1996 Prashant Sinha. All rights reserved.

The author hereby grants to M.I.T. permission to reproduce
and distribute publicly paper and electronic copies of this thesis
and to grant others the right to do so.

Department of Electrical Engineering and Computer Science
May 26, 1996

Certified by

Laurence R. Young
Thesis Supervisor

Accepted by

F.R. Morgenthaler
Chairman, Department Committee on Graduate Theses
The SLS-2 Mission: Effects of Spaceflight on Static Ocular Counterrolling

by

Prashant Sinha

Submitted to the
Department of Electrical Engineering and Computer Science

May 28, 1996

In Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Electrical Engineering and Computer Science
at the Massachusetts Institute of Technology

ABSTRACT

The SLS-2 mission investigated various human physiological and perceptual changes in response to spaceflight and adaptation. Ocular counterrolling under conditions of static tilt was measured pre- and post-flight to investigate the nature of neurovestibular adaptation to weightlessness and readaptation to gravity. An automated video oculography system (VDAC) was tested with no useful results on the noisy and poorly collected video data, however a manual image analysis technique was developed using Photoshop® yielding measurement accuracies on the order of 0.4°.

The results of the data analysis revealed that the magnitude of ocular counterrolling was reduced post-flight for three out of the four subjects. An asymmetry between the left and right ear down tilt conditions was seen to various degrees on all of the subjects. A comparison of the these results with a rod and frame experiment, a linear motion nulling experiment, and a roll tilt motion nulling experiment demonstrated an agreement with the otolith tilt translation reinterpretation hypothesis as well as lending some support to the otolith asymmetry sensory conflict theory.

Thesis Supervisor: Laurence R. Young
Title: Apollo Program Professor of Astronautics
ACKNOWLEDGEMENTS

I would like to thank all of my friends, TA’s, professors, and research supervisors who have supported me, helped me and taught me so much in my last five years at MIT- you are the reason I came to this place in the first place.

Mom, dad, Shveta and Charita (and Bumpy too) - thank you so much for always being there, you guys are the greatest. This piece of work here is the reason, I have not seen you guys for a while but I love ya and miss you too; duh you’re my family!

To all of you MVL’ers- you guys rock! Its been so much fun working in the coolest lab at MIT, and hanging with all of you. I’ll miss Jen and her dinners, Grant and his protein powder, Dave and his famous helicopter, Keoki and Mardis Gras, Dawn and Chuck’s incredible encyclopedic depth of knowledge and random facts, Patricia and her quiet wonderful smile, Mike and Jenny and their happy goofy California aura, Mike T and his mediterranean lunches, Barbara and her funny sense of humor (is that redundant? that’s ok she deserves it.), Adam our resident hacker, Christine who was always at lab as late as I was, Anna and her Spanish papers, Matt my officemate (well, if I ever actually used my office he would be), Larry for being a great thesis supervisor even though he was always out of town, Dava and her cool EDLS stickers, Alan and his observations on variance in all aspects of life, Albert and... hey aren’t you supposed to be practicing medicine now..., Scott our flight simulator nut (or is it Dave?), Robin and her awesome tan, and Karl and his guest appearance. But wait, there’s more! We can’t forget all of our MVL groupies...

like Andy (well he’s kind of related to the MVL family through Karl), Brian who was responsible for Jen’s lovely lobby 7 portrait, Rob our regular lunch buddy, Adam my roommate of long ago, and all of you funky random people who come through and hang out with and use the lab dining facilities.

If I were to begin to thank all of my wonderful friends, I think I would have to double the length of this thesis. There are so many of you that mean so much to me, and I think you all know who you are. I love all of you, and will very much miss seeing all of you on a regular basis. When I can’t see you in person, remember that you have made more of an impact on my life than any institution possibly could and that you will be in my mind and heart forever.

Finally, I would like to thank all of the incredible people who have made space exploration possible. Keep on dreaming- I know I will, and maybe someday I will look out a little window and see all of you below me.
TABLE OF CONTENTS

1. INTRODUCTION ........................................................................................................ 8
   1.1 ADVISOR AND LAB ............................................................................................ 8
   1.2 THE SPACELAB LIFE SCIENCES 2 MISSION..................................................... 8
   1.3 THE VESTIBULAR SYSTEM .............................................................................. 8
   1.4 MICROGRAVITY ENVIRONMENT .................................................................... 9
   1.5 ORGANIZATION OF THESIS......................................................................... 9

2. MATERIALS AND METHODS .............................................................................. 12
   2.1 STATIC TILT EXPERIMENT ......................................................................... 12
   2.2 COLLECTION OF DATA USING AUTOMATED VIDEO OCULOGRAPHY .......... 13
   2.3 COLLECTION OF DATA USING PHOTOSHOP® .............................................. 14
   2.4 ANALYSIS OF DATA ...................................................................................... 15
       2.4.1 OCR gain ............................................................................................... 15
       2.4.2 OCR asymmetry ................................................................................... 16

3. RESULTS ............................................................................................................. 17
   3.1 VIDEO OCULOGRAPHY ................................................................................ 17
   3.2 PHOTOSHOP® COLLECTED DATA ............................................................... 18
       3.2.1 Comparison of OCR gains ..................................................................... 18
       3.2.2 Comparison of OCR symmetry ............................................................... 39
   3.3 CLOSED LOOP OTOLITH ASSESSMENT TESTS ........................................ 40
       3.3.1 Subject T .................................................................................................. 41
       3.3.2 Subject V ................................................................................................ 41
       3.3.3 Subject W ............................................................................................... 41
       3.3.4 Subject Y ............................................................................................... 41
   3.4 ROD AND FRAME EXPERIMENTS ............................................................... 41
       3.4.1 Subject T ................................................................................................ 42
       3.4.2 Subject W ............................................................................................... 42
       3.4.3 Subjects Y&V ......................................................................................... 42

4. DISCUSSION ..................................................................................................... 43
   4.1 OCR GAIN ...................................................................................................... 43
   4.2 OCR ASYMMETRY ...................................................................................... 44

5. CONCLUSIONS .................................................................................................. 46

6. SOURCES .......................................................................................................... 47

7. APPENDIX ......................................................................................................... 49
   7.1 VDAC AUTOMATED VIDEO OCULOGRAPHY SYSTEM ......................... 49
       7.1.1 System overview .................................................................................... 49
       7.1.2 Video data format .................................................................................. 49
       7.1.3 Setup ...................................................................................................... 50
       7.1.4 Main screen ........................................................................................... 51
       7.1.5 Capturing an initial baseline frame ....................................................... 51
       7.1.6 Automated data collection - the Track menu .................................. 56
   7.2 MATLAB® ARTEFACT REMOVAL SCRIPT FOR TORSION DATA .......... 58
       7.2.1 Screen shots .......................................................................................... 59
       7.2.2 Ocular torsion analysis script ............................................................... 61
   7.3 PHOTOSHOP® ANALYSIS METHOD ............................................................ 66
       7.3.1 Cropping ............................................................................................... 66
       7.3.2 Unsharp mask filtering ......................................................................... 67
7.3.3 Increase image resolution.............................................................................................67
7.3.4 Pupil center location...................................................................................................67
7.3.5 Landmark identification.................................................................................................68
7.3.6 Arrow vector alignment................................................................................................69
**TABLE OF FIGURES**

**FIGURE 1:** OCULAR COUNTERROLLING

**FIGURE 2:** TILT PLATFORM

**FIGURE 3:** 0° TEMPLATE PICTURE (LEFT) AND +30° TRIAL IMAGE (RIGHT)

**FIGURE 4:** SUBJECT T OCR ON L-15, R+1 & R+2

**FIGURE 5:** SUBJECT T L-15 DATA AND REGRESSION LINE

**FIGURE 6:** SUBJECT T R+1 DATA AND REGRESSION LINE

**FIGURE 7:** SUBJECT T R+2 DATA AND REGRESSION LINE

**FIGURE 8:** SUBJECT T LINEAR REGRESSION LINES

**FIGURE 9:** SUBJECT V OCR ON L-15, R+1 & R+2

**FIGURE 10:** SUBJECT V L-15 DATA AND REGRESSION LINE

**FIGURE 11:** SUBJECT V R+1 DATA AND REGRESSION LINE

**FIGURE 12:** SUBJECT V R+2 DATA AND REGRESSION LINE

**FIGURE 13:** SUBJECT V LINEAR REGRESSION LINES

**FIGURE 14:** SUBJECT W OCR ON L-15, R+1 & R+2

**FIGURE 15:** SUBJECT W L-15 DATA AND REGRESSION LINE

**FIGURE 16:** SUBJECT W R+1 DATA AND REGRESSION LINE

**FIGURE 17:** SUBJECT W R+2 DATA AND REGRESSION LINE

**FIGURE 18:** SUBJECT W LINEAR REGRESSION LINES

**FIGURE 19:** SUBJECT Y OCR ON L-15, R+1 & R+2

**FIGURE 20:** SUBJECT Y L-15 DATA AND REGRESSION LINE

**FIGURE 21:** SUBJECT Y R+1 DATA AND REGRESSION LINE

**FIGURE 22:** SUBJECT Y R+2 DATA AND REGRESSION LINE

**FIGURE 23:** SUBJECT Y LINEAR REGRESSION LINES
**Table of Tables**

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>OCR gain for Subject T, left and right ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 2</td>
<td>OCR gain for Subject T, left ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 3</td>
<td>OCR gain for Subject T, right ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 4</td>
<td>Subject T p values for gain, left and right ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 5</td>
<td>Subject T p values for gain, left ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 6</td>
<td>Subject T p values for gain, right ear down</td>
<td>20</td>
</tr>
<tr>
<td>Table 7</td>
<td>Subject T regression slopes</td>
<td>23</td>
</tr>
<tr>
<td>Table 8</td>
<td>Subject T regression intercepts</td>
<td>23</td>
</tr>
<tr>
<td>Table 9</td>
<td>OCR gains for Subject V, left and right ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 10</td>
<td>OCR gains for Subject V, left ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 11</td>
<td>OCR gains for Subject V, right ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 12</td>
<td>Subject V p values for gain, left and right ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 13</td>
<td>Subject V p values for gain, left ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 14</td>
<td>Subject V p values for gain, right ear down</td>
<td>25</td>
</tr>
<tr>
<td>Table 15</td>
<td>Subject V regression slopes</td>
<td>28</td>
</tr>
<tr>
<td>Table 16</td>
<td>Subject V regression intercepts</td>
<td>28</td>
</tr>
<tr>
<td>Table 17</td>
<td>OCR gains for Subject W, left and right ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 18</td>
<td>OCR gains for Subject W, left ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 19</td>
<td>OCR gains for Subject W, right ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 20</td>
<td>Subject W p values for gain, left and right ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 21</td>
<td>Subject W p values for gain, left ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 22</td>
<td>Subject W p values for gain, right ear down</td>
<td>30</td>
</tr>
<tr>
<td>Table 23</td>
<td>Subject W regression slopes</td>
<td>33</td>
</tr>
<tr>
<td>Table 24</td>
<td>Subject W regression intercepts</td>
<td>33</td>
</tr>
<tr>
<td>Table 25</td>
<td>OCR gains for Subject Y, left and right ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 26</td>
<td>OCR gains for Subject Y, left ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 27</td>
<td>OCR gains for Subject Y, right ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 28</td>
<td>Subject Y p values for gain, left and right ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 29</td>
<td>Subject Y p values for gain, left ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 30</td>
<td>Subject Y p values for gain, right ear down</td>
<td>35</td>
</tr>
<tr>
<td>Table 31</td>
<td>Subject Y regression slopes</td>
<td>38</td>
</tr>
<tr>
<td>Table 32</td>
<td>Subject Y regression intercepts</td>
<td>38</td>
</tr>
<tr>
<td>Table 33</td>
<td>Subject T symmetry tests (ANOVA)</td>
<td>39</td>
</tr>
<tr>
<td>Table 34</td>
<td>Subject V symmetry tests (ANOVA)</td>
<td>40</td>
</tr>
<tr>
<td>Table 35</td>
<td>Subject W symmetry tests (ANOVA)</td>
<td>40</td>
</tr>
<tr>
<td>Table 36</td>
<td>Subject Y symmetry tests (ANOVA)</td>
<td>40</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Advisor and Lab

This thesis has been conducted at the Man Vehicle Laboratory at MIT in order to partially fulfill the requirements for a Master of Engineering in the department of Electrical Engineering and Computer Science. The thesis advisor for this project is Dr. Laurence R. Young, Professor of Aeronautics and Astronautics at MIT in the Man Vehicle Laboratory. This work was supported by the NASA contract NAS9-16523.

1.2 The SpaceLab Life Sciences 2 Mission

The SpaceLab Life Sciences 2 shuttle mission (STS-58), flown in the fall of 1993, was a two week investigation of human physiology in space. Currently, an extended post-flight data analysis effort at the Man Vehicle Laboratory hopes to extract additional information to further our understanding of various physiological and perceptual processes. Among the human systems that were studied is the neurovestibular system. This system which includes inner ear, visual and musculoskeletal components enables us to remain upright and balanced, and also allows coordinated movement about our environment. The ability to orient ourselves on Earth is due in part to the information from the otolith organs which are linear gravity sensors located in the inner ear. In space however, the signals from our inner ear no longer include gravity cues. This difference may cause disorientation and symptoms of motion sickness. Fortunately, adaptation to the micro-gravity environment occurs in one or two days, and through the SLS-2 experiments the adaptive mechanisms may be better understood.

1.3 The Vestibular System

Located in the inner ear, the vestibular organs are comprised of two parts, the semicircular canals and the otolith organs. These sense angular acceleration and linear acceleration respectively. In conjunction with the visual system and imbedded muscle stretch receptors, the vestibular system acts to maintain a stably perceived environment. Although it is difficult to measure vestibular responses directly, it is possible to measure reflexive eye movements caused by vestibular stimulation, the vestibulo-ocular reflex (VOR). Stimulation of the different vestibular organs triggers different muscles of the eyes. Semicircular canals generate mostly linear eye movements while otolith organs can produce torsion of the eyeball around the optical axis. The otolith organs rely on linear accelerations such as gravity to produce a shearing motion of the otolithic membrane, containing dense calcite crystals, against receptor hair cells. A head tilt around the optical axis or a lateral acceleration will
produce rolling of the eyes in the opposite direction as if to bring the world upright again (Figure 1). The ocular counterrolling (OCR) has a typical gain, around 0.1-0.2 for a ±30° tilt and reaches a maximum of 7-8° of OCR at a tilt angle around ±60° (Graybiel 1962). VOR, although well characterized on Earth, experiences changes in microgravity environments which are not as yet fully understood.

![Figure 1: Ocular counterrolling](image)

1.4 Microgravity Environment

The absence of gravity in space may cause spatial disorientation because we usually expect signals from the otolith that correspond to gravity. It is hypothesized that trying to correlate nonsense signals from the otoliths with visual cues is a cause of space motion sickness. When gravity is absent we cannot rely on the otoliths to orient us, so we may depend only on visual and tactile cues, while selectively ignoring or suppressing the vestibular cues. The vestibular system has been observed by a variety of researchers over the years to be adaptive in many respects. In fact it has been observed in both monkeys (Dai 1993) and humans (Vogel 1986) that prolonged exposure to microgravity causes a reduction in OCR which persists for a few days post-flight.

1.5 Organization of thesis

This thesis hopes to confirm several observations and hypotheses concerning space flight and ocular counterrolling, space motion sickness, and perception. A portion of the data
that was collected from the SLS-2 mission will be used to answer a few of these questions. Ocular counterrolling in four of the crew members, under static tilt conditions, will be examined pre- and post-flight in order to observe any changes in its magnitude and symmetry. A reduction in the magnitude of the OCR would be an important indicator that there are changes in the neurovestibular system that favor the visual system over the vestibular system in self-orientation and in the perception of the vertical. The reinterpretation of otolith cues in space, hypothesized first by Young et al (1984), and later called the otolith tilt translation reinterpretation hypothesis (Parker et al 1985), will be treated with respect to these results. Furthermore, the results of this thesis will also be compared against two sets of experiments which measure the ability of the SLS-2 crew to null out linear motions (Merfeld et al 1995) and their ability to null out roll tilt motions (Merfeld 1995). A third set of experiments studying the perception of gravity will also be cross-referenced in this thesis. In these classic “Rod and Frame” experiments (Robinson et al 1994), the same four SLS-2 subjects were asked to align a rod with gravity in various visual and tilt conditions.

Secondly, we are interested in the naturally occurring asymmetries between the right ear and left ear vestibular responses. These asymmetries are normally compensated in a 1g environment (von Baumgarten 1978) but may worsen after space flight. The changes in the OCR, between the left and right ear down tilts, that would be observed after flight have been postulated to be larger because adaptation to weightlessness would include a shutdown of the processes that balance out the differences. The compensatory mechanism is thought to be responsible for the visuo-vestibular conflict causing space motion sickness (Igarashi 1988). These results will help in understanding the visual contribution to our perception of the vertical. A clearer picture of the visuo-vestibular interactions that occur during and after space flight is the goal of this thesis, however it should be noted that there are still many aspects of perception especially relating to space travel that need further exploration.

Before any of the questions above can be answered, it is necessary to accurately and unobtrusively measure ocular torsion, which is a non-trivial issue. There have been many techniques used in the past that have involved using scleral search coils, marked contact lenses, tattoo marks on the cornea, as well as natural iris landmark identification. These earlier methods typically employed photography and visual inspection of enlarged images to calculate linear and rotary motion of the eyes. However, automated systems using 2-D Fourier transforms and cross-correlations have been constructed that can quickly analyze standard 30 Hz video clips. A current system designed by Kwanjae Sung at Johnson Space Center in Houston, Texas was tested on several sets of video data collected from the SLS-2 mission. Although this high speed automated analysis of OCR is very useful for both dynamic and static OCR experiments, it has its share of problems. It is particularly sensitive to noisy data and data collected in poorly controlled conditions. A variation on the photographic techniques was developed out of frustration and need. Video images, rather than photographs,
were captured digitally and analyzed by comparing natural irial landmarks with Photoshop®, a popular image manipulation program. A discussion of the limitations and problems in the VDAC system and data collection procedure will be included as a part of this thesis.
2. Materials and Methods

2.1 Static Tilt Experiment

Four crew members from the STS-58 shuttle mission were used as subjects. The subjects were each given a letter and are referenced by these letters in all experiments in which they were subjects. They are designated T, V, W & Y. Each of the subjects were tested on two pre-flight days, one hundred fifty days before flight (L-150), and fifteen days before flight (L-15). Testing post-flight was conducted one, two, seven and nine days upon return from orbit, (R+1, R+2, R+7 & R+9). A rigid platform with an axis of rotation aligned with the optic axis was used to tilt each of the subjects. Figure 2 shows the tilt platform and a coordinate axis perpendicular to the axis of rotation. The foot rest and camera fixture are not shown. The frame includes a head rest to ensure that the head does not move freely while being tilted, a fixation target to maintain the pupil at the center of rotation, and a shroud to block any visual cues as to tilt angle. The subjects were rotated to ten different angles, 0°, 15°, 30°, 45° and 60° to each side. The angle is positive for a counter-clockwise or right ear down tilt, and negative for a clockwise or left ear down tilt. The subjects were instructed to fixate on a circular target and to keep their eyes wide open for the duration of the trial. In the video recording, a flash card with the trial day and subject letter was presented before each subject began the trials. In addition, each tilt angle is announced at the beginning of the trial and is recorded on the audio track of the video tape. The subjects were slowly rotated to each angle in 5 to 10 seconds and held there for 20 seconds to allow the semicircular canal contributions to OCR to decay away. A black and white video camera fixed to the tilt platform frame and focused on the right eye, captured eye movements onto 3/4” UMATIC format video tape. The resulting ocular torsion is assigned positive values for counter-clockwise rotation and negative values for clockwise rotations.
2.2 Collection of data using automated video oculography

An automated video-oculography system (VDAC) designed by Kwanjae Sung at the NASA Johnson Space Center, captures frames automatically from a 3/4" VCR and calculates linear and torsional eye movements. The software is designed to run on a PowerPC equipped Macintosh computer with either a nubus-based Scion LG-3 framegrabber, or a PCI-based framegrabber.

In order to accurately capture each frame and maintain temporal coherence between the software and the VCR, a timecode signal needs to be present on the video tape. Since the raw video footage did not include a timecode, a timecode generator was used to add the signal onto the video before it was processed through the VDAC eye movement software.

To calculate torsion, the VDAC software looks for the rotation of natural iris patterns. The program must locate the center of rotation, locate the iris region, and select a segment of the iris to compare all other trials against. First, an initial frame from the 0° tilt trial is captured. An optimal grayscale threshold value is then chosen either automatically or manually for pupil identification and centering. In order to identify the center of rotation, which is at the center of the pupil, the program isolates the mostly black pupil by filtering out
all of the grayscale values up to a threshold value so that only the pupil is left. The program can then calculate the center of the pupil. The user must mark up to twelve points on the iris/sclera boundary. These points are used to estimate a circular fit around the iris region so that the program knows where the iris is.

The center point is then used to position a set of search regions on the iris. There are two different methods that can be used. One method involves placing a box over a portion of the iris. A 2-D Fourier transform is then used to compare the pixels in this region with pixels in subsequent frames. The other method places concentric arcs around the pupil and samples the pixels underneath the arcs. Simple 1-D cross-correlations are performed on subsequent frames against the baseline arcs to calculate the torsion angle from the degree of correlation.

The captured data was output in Matlab® format for further processing and tallying. Artefact removal was performed interactively within Matlab® using a custom script (see section 7.2). The torsion angles were measured toward the end of each trial and sufficiently far enough away from blink artefacts so that the eyeball had enough time to settle. A number of frames (50-100) were used to calculate a mean torsion angle and its corresponding standard deviation. The data was imported into Stata®, a statistical analysis package, for further tests as described in section 2.4. A detailed system description, user guide and experimental protocol is given in section 7.1.

2.3 Collection of data using Photoshop®

Upon discovery of limitations in the automated video-oculography system, and in the data collection procedure, a visual inspection of the data was considered necessary. Previously, eye movements have been captured using film. The film would then be blown up and projected on a screen. A comparison of iral landmarks determined the torsion angle. The same process has been replicated by capturing video frames and importing them into Photoshop®. The images were cropped and unsharp mask filtered to highlight the details of the iris. The image resolution was increased from 72 dpi to 120 dpi so that finer measurements could be made. An ellipse selection tool was visually fitted around the pupil in order to locate the center of rotation. The center was marked and distinctive landmarks chosen. For each image, arrow vectors were drawn to the landmarks from the center of rotation. At least three landmarks were chosen in case one or more could not later be found. Once all of the landmarks had been marked, the arrow vectors from the 0° trial images were positioned on top of the current image with their origin centered in the pupil. The baseline vectors were then rotated until they were aligned with the vectors on the current image. The angle of rotation corresponded to the OCR angle change from the 0° tilt trial. Figure 3 below shows two filtered and marked images. A +30° trial image (on the right) can be visually...
compared to the 0° baseline image (on the left). The landmarks on the trial image appear to be rotated clockwise relative to the baseline image indicating torsion in the opposite direction of the tilt (counterrolling).

For each tilt angle per subject per day, two frames were captured and analyzed. More images would have been preferable, however time constraints only allowed a limited number of images for analysis. The video frames were captured toward the end of the trial, and as far away from blinks as possible. The calculated angles were then imported into Stata® for statistical analysis as described below. A more detailed description of the procedure is also included in section 7.3.

Figure 3: 0° template picture (left) and +30° trial image (right)

2.4 Analysis of data

Statistical analysis was performed with the Stata® statistical analysis package. The OCR for each subject was compared for magnitude reduction and changes in symmetry between the left and right ear down tilt conditions. In order to simplify the analysis, only a linear region of the OCR response was considered. It has been observed that OCR is fairly linear for tilt angles between +30° and -30°, and that it peaks around ±60° (Miller 1962), therefore the slope of the OCR, or the gain $\frac{\triangle OCR}{\triangle tilt}$, was calculated for the angles, ±15° and ±30°. OCR gains and asymmetries were both analyzed with two different statistical methods.

2.4.1 OCR gain

The gains for the ±15° and ±30° tilt angles were tested by using a one-way analysis of variance (ANOVA). A Bonferroni test (Winer et al 1991) was applied to the gains to compare each subject across the different trial days. Left and right ear down only versions were also used (see 2.4.2 below). The second method used a linear regression fit on the data points between the +30° and -30° inclusive, for each trial day and subject. The slopes and their
respective 95% confidence limits were compared against each other for any differences. One notable difference between these calculations is the exclusion of 0° data points for the ANOVA, and their inclusion in the regression calculation. Since the gain at 0° cannot be measured, the gains used in the ANOVA excluded the 0 gain points at 0°.

2.4.2 OCR asymmetry

An analysis of variance was performed on the magnitude of the OCR angle at the ±15°, ±30°, ±45° and ±60° tilt angles. Bonferroni tests were applied to determine whether there were any differences between the left and right responses at each of the angles for each trial day. An analysis of variance was performed on the right ear down tilt (+30° and +15°) and the left ear down tilt (-30° and -15°) gains, and a Bonferroni test was applied to test for differences across trial days for each subject. The linear regression fit described above also generated an intercept term which was compared against a zero intercept value. A non-zero intercept would indicate an asymmetrical response. A positive value would indicate an increased gain on left ear down and a negative intercept would indicate an increased gain on right ear down.
3. Results

3.1 Video oculography

The VDAC software did not yield useable data. The problems are discussed in this chapter in the hopes that better experimental controls are established in the future. In theory, the software should work very well. The operational assumptions for the software however are not all valid for this set of data. The first of these assumptions is that the iris patterns only change by rotating around the center of the pupil. In practice, the pupil diameter fluctuates quite a bit as a function of light intensity and subject concentration. A change in the pupil diameter significantly shifts and compresses the iris patterns radially so that the search arcs or boxes end up over a region completely different from the original baseline region. In order to prevent the pupil from changing diameter, a drug called pilocarpine hydrochloride (Curthoys et al 1992) may be administered. It causes the irl muscles to contract constricting the pupil and holding it fixed. Unfortunately, it was not administered because it would have affected the vision of the subjects who were already being subjected to a battery of tests over the period of a week. The effects of the drug, lasting several hours, are bothersome enough so that its administration would have been annoying to the subjects and would have delayed the approval of the human use proposals.

Upon visual inspection of the iris patterns on different trials, it was difficult to locate any particular set of landmarks consistently. It seems unlikely that the patterns were stable enough for software recognition across all of the trials, as well as within a particular trial considering that the search regions are located at a fixed distance from the center of the pupil. The changing pupil diameter may be attributed to several causes. The subjects would often lose the fixation target which causes a shift in the incoming light flux thus causing a change in the pupil diameter. A blink caused the pupil diameter to change, and fatigue and the change in subject alertness with each tilt could have affected pupil diameter.

The fatigue of the subjects on post flight days was a very serious problem. The frequency of their blinking and half-closed eyelids, made subjects W and Y impossible to analyze apart from any of the other errors discussed here.

A poorly focused camera will cause iris details along with torsion information to be lost. It seems that there was a systematic mechanical alignment problem that shifted the camera out of focus on the 45° and 60° trials, and to a lesser extent on the -45° and -60° trials. This was unfortunate because it introduced a large source of error at the angles where the symmetry tests were conducted.
On the trial days, L-150, R+7 and R+9, some or all of the audio track announcing the start and stop times were missing, making it difficult to correctly mark the start and stop times for data collection.

A small source of error, on the order of a couple of pixels, may also arise from the mislocation of the pupil center, however this error tends to average itself over time.

The trial days R+7 and R+9 also suffer from very low illumination resulting in poor contrast and detail in the video image. Consequently, this set of data was difficult and at most times impossible to analyze by using either the VDAC system or the Photoshop® technique.

### 3.2 Photoshop® collected data

Analysis with Photoshop® was fairly straightforward and much more flexible than the VDAC system. It was often necessary to pick several different landmarks or to use surrounding features to locate partially hidden landmarks. All of the frames for the four subjects on trial days L-15, R+1 and R+2 were successfully analyzed. The primary errors in this analysis are due to the limited resolution of the video image and in locating the center of the pupil. The approximate size of the errors was estimated to be around 0.3° to 0.5°. This is large compared to previous image analysis systems which have errors of around 0.1°, however, this technique is acceptable, especially for its ease of setup and reasonable throughput. I estimate that I spent about 4 minutes per frame. The data on days L-150, R+7 and R+9 were not analyzed. The data for each subject on days L-15, R+1 and R+2 is presented below.

### 3.2.1 Comparison of OCR gains

#### 3.2.1.1 Subject T

The torsion graph for subject T (Figure 4) appears to have a reduction in the magnitude of ocular counter-rolling on both the R+1 and R+2 post-flight days relative to the pre-flight day, L-15, and especially on left ear down tilt. Each data point represents the mean of two observations at a given tilt angle. Vertical bars indicate one standard deviation above and below each trial point. The shaded area indicates the data points used in the analysis of variance and in the linear regression. The analysis of variance indicated that both R+1 and R+2 trials have a significantly reduced gain \( p < .05 \) relative to L-15, but that there is no significant difference between R+1 and R+2. The gains and \( p \) values are listed below in Table 1 and Table 4 respectively. Bold values in the \( p \) tables indicate a significant change \( p < .05 \) in OCR gain between trial days.

Linear regression fits and the raw data are plotted in Figure 5 to Figure 8. Table 7: Subject T regression slopes lists the \( R^2 \) values and the 95% confidence intervals for the regression slopes. The \( R^2 \) values are high except for the R+2 trial (.7246), but they all indicate
a good linear fit to the data. The regression results demonstrate the same significant relationships. There is no overlap in the confidence intervals for the slopes between L-15 and either the R+1 or the R+2 trials, but there is overlap between the R+1 and R+2 trials. This suggests that OCR magnitude reduction was found post-flight on R+1 and persisted at least to R+2. Notice that the gains in the ANOVA and the linear regressions are not the same. The difference may be explained by the inclusion of the 0' data points in the regression calculation.

Separate left and right ear down comparisons were also made. The gains are listed in Table 2 and Table 3, and their significances are in Table 5 and Table 6. A reduction in gain was observed to occur primarily on the left ear down trials. The R+1 and R+2 days had a reduced gain relative to L-15, but did not have any differences with respect to each other. These results are further discussed with respect to asymmetry in section 3.2.2.
Figure 4: Subject T OCR on L-15, R+1 & R+2

Table 1: OCR gain for subject T, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.185</td>
<td>0.02748737</td>
<td>8</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.11083334</td>
<td>0.0293748</td>
<td>12</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.10291667</td>
<td>0.08751303</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2: OCR gain for subject T, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.19166667</td>
<td>0.04013865</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.10277778</td>
<td>0.04073856</td>
<td>6</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.055</td>
<td>0.03316625</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3: OCR gain for subject T, right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.17833334</td>
<td>0.0057735</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.11888889</td>
<td>0.0091084</td>
<td>6</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.15083333</td>
<td>0.10318537</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4: Subject T p values for gain, left and right ear down

<table>
<thead>
<tr>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.014</td>
<td>-</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Table 5: Subject T p values for gain, left ear down

<table>
<thead>
<tr>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.013</td>
<td>-</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Table 6: Subject T p values for gain, right ear down

<table>
<thead>
<tr>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.354</td>
<td>-</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Subject T L-15 and linear regression fit

Figure 5: Subject T L-15 data and regression line

Subject T R+1 and linear regression fit

Figure 6: Subject T R+1 data and regression line
Figure 7: Subject TR+2 data and regression line
Figure 8: Subject T linear regression lines

Table 7: Subject T regression slopes

<table>
<thead>
<tr>
<th>Day</th>
<th>Slope</th>
<th>R²</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-.179</td>
<td>.9801</td>
<td>-.1997736 -.1582264</td>
</tr>
<tr>
<td>R+1</td>
<td>-.1033333</td>
<td>.9510</td>
<td>-.1180911 -.0885756</td>
</tr>
<tr>
<td>R+2</td>
<td>-.0826667</td>
<td>.7246</td>
<td>-.1242192 -.0411141</td>
</tr>
</tbody>
</table>

Table 8: Subject T regression intercepts

<table>
<thead>
<tr>
<th>Day</th>
<th>Intercept</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>T15</td>
<td>.07</td>
<td>0.724</td>
</tr>
<tr>
<td>T1</td>
<td>-.2928571</td>
<td>0.097</td>
</tr>
<tr>
<td>T2</td>
<td>-.53</td>
<td>0.203</td>
</tr>
</tbody>
</table>
3.2.1.2 *Subject V*

The torsion graph for subject V (Figure 9) appears to have a magnitude reduction on the left ear down tilts, but not at all on the positive, right ear down tilt angles. Each data point represents the mean of two observations at a given tilt angle. Vertical bars indicate one standard deviation above and below each trial point. The shaded area indicates the data points used in the analysis of variance and in the linear regression. Table 9 lists the mean gains for subject V using the left and right ear down data points for the different trial days. Table 12 presents the results of significance testing. A significant difference in gains was not found between any of the trial days by using both left and right ear down tilt data points.

Linear regression fits, plotted in Figure 10 to Figure 13, were calculated but also revealed no significant difference between the slopes. The 95% confidence limits listed for each of the regression slopes in Table 15 overlap each other. Note that the regression gains and the ANOVA gains are not the same. This is due to the inclusion of the 0° data points in the regression calculations.

Comparisons of just the left and right ear down trials revealed that there was a significant gain reduction on left ear down (-15°, -30°), but not at all on right ear down (15°, 30°). The gain was significantly reduced on R+1 relative to L-15 but not on R+2 relative to L-15. The gain on R+2 is also significantly larger than on R+1. The gains are listed in Table 10 and Table 11, the *p* values are listed in Table 13 and Table 14. The results of these tests are also discussed in section 3.2.2. The data implies that a reduced gain on R+1 seems to have returned nearly to pre-flight levels.
Figure 9: Subject V OCR on L-15, R+1 & R+2

Table 9: OCR gains for subject V, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.2025</td>
<td>0.05299745</td>
<td>8</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.13416667</td>
<td>0.10430039</td>
<td>8</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.16416667</td>
<td>0.04417678</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 10: OCR gains for subject V, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.21083334</td>
<td>0.05833333</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.05083333</td>
<td>0.04228431</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.1475</td>
<td>0.03593976</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 11: OCR gains for subject V, right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.19416667</td>
<td>0.05445862</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.2175</td>
<td>0.07125203</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.18083335</td>
<td>0.05021251</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 12: Subject V p values for gain, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.217</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R+1</td>
<td>0.907</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>R+2</td>
<td>0.258</td>
<td>0.049</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Table 13: Subject V p values for gain, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.003</td>
<td>-</td>
</tr>
<tr>
<td>R+1</td>
<td>0.258</td>
<td>0.049</td>
</tr>
<tr>
<td>R+2</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 14: Subject V p values for gain, right ear down
Figure 10: Subject V L-15 data and regression line

Figure 11: Subject V R+1 data and regression line
Figure 12: Subject V R+2 data and regression line

Legend:
- Data
- $y = -1.46x - 0.156$
Figure 13: Subject V linear regression lines

Legend:
- - L-15: \( y = -.174x + .14 \)
- *- R+1: \( y = -.127x - 1.22 \)
- +- R+2: \( y = -.146x - .156 \)

<table>
<thead>
<tr>
<th>Day</th>
<th>Slope</th>
<th>( R^2 )</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-.174</td>
<td>.9494</td>
<td>-.2067519 - .1412481</td>
</tr>
<tr>
<td>R+1</td>
<td>-.1266667</td>
<td>.9168</td>
<td>-.1577859 - .0955475</td>
</tr>
<tr>
<td>R+2</td>
<td>-1.656667</td>
<td>.9715</td>
<td>-.2061597 - .1251737</td>
</tr>
</tbody>
</table>

Table 15: Subject V regression slopes

<table>
<thead>
<tr>
<th>Day</th>
<th>Intercept</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V15</td>
<td>.1400001</td>
<td>.655</td>
</tr>
<tr>
<td>V1</td>
<td>-1.22</td>
<td><strong>.003</strong></td>
</tr>
<tr>
<td>V2</td>
<td>.049999999</td>
<td>.897</td>
</tr>
</tbody>
</table>

Table 16: Subject V regression intercepts
3.2.1.3 Subject W

The torsion graph for subject W is shown in Figure 14. Each data point represents the mean of two observations at a given tilt angle. Vertical bars indicate one standard deviation above and below each trial point. The shaded area indicates the data points used in the analysis of variance and in the linear regression. There appears to be some magnitude reduction on R+1 for the right ear down (15° & 30°) tilts, however, there appears to be an increase in magnitude on the left ear down tilt angle for R+1. A return to baseline values on R+2 may also be seen clearly in the graph. The significance of the change in gains is given in the tables below. Table 17 and Table 20 list the gains and p values for comparisons across trial days, respectively. There were highly significant differences (p<.01) between the L-15 and R+1 trial days, and between the R+1 and R+2 trial days. There were no significant difference between L-15 and R+2. These statistics agree with the observations, at least in the -30° to +30° range. The asymmetries, also clearly visible in this graph, are explained in section 3.2.2. The gains for separate left and right ear down tilts are listed in Table 18 and Table 19, and the p values are given in Table 21 and Table 22. There was gain reduction on R+1 from L-15 but not on R+2 relative to L-15. Instead R+2 showed an increase in gain from R+1 back to L-15 levels.

The linear regression lines are plotted below as well (Figure 15 to Figure 18). The slopes, their R² values and 95% confidence intervals are given in Table 23. There appears to be a little overlap with the R+1 trial by both L-15 and R+2 showing no significance between the slopes on the different trial days. The L-15 and R+2 trials have almost identical slopes and confidence intervals indicating a complete return to the pre-flight response on R+2. Notice that the regression gains and the ANOVA gains are not the same. This difference may be explained by the inclusion of the 0° data points in the regression calculation.
Table 17: OCR gains for subject W, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.13958334</td>
<td>0.02785664</td>
<td>8</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.05708333</td>
<td>0.06318121</td>
<td>8</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.15125</td>
<td>0.04840102</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 18: OCR gains for subject W, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.12416667</td>
<td>0.02793843</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.09833334</td>
<td>0.05640462</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.17416667</td>
<td>0.05763069</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 19: OCR gains for subject W, right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.15500001</td>
<td>0.01990719</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.01583333</td>
<td>0.03994209</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.12833333</td>
<td>0.02728451</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 20: Subject W $p$ values for gain, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.008</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R+1</td>
<td>0.003</td>
<td>1.000</td>
<td>0.172</td>
</tr>
</tbody>
</table>

Table 21: Subject W $p$ values for gain, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.000</td>
<td>-</td>
</tr>
<tr>
<td>R+1</td>
<td>0.730</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 22: Subject W $p$ values for gain, right ear down
Figure 15: Subject W L-15 data and regression line

Figure 16: Subject W R+1 data and regression line
Subject W R+2 and linear regression fit

Legend:
○ Data
←− y = −.133x + .34

Torsion angle (degrees)

Figure 17: Subject W R+2 data and regression line
Figure 18: Subject W linear regression lines

Table 23: Subject W regression slopes

<table>
<thead>
<tr>
<th>Day</th>
<th>Slope</th>
<th>$R^2$</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-.1313333</td>
<td>.9555</td>
<td>-.1544286 - .1082381</td>
</tr>
<tr>
<td>R+1</td>
<td>-.0803333</td>
<td>.7352</td>
<td>-.1196417 - .041025</td>
</tr>
<tr>
<td>R+2</td>
<td>-.133</td>
<td>.9260</td>
<td>-.1636589 - .1023411</td>
</tr>
</tbody>
</table>

Table 24: Subject W regression intercepts

<table>
<thead>
<tr>
<th>Day</th>
<th>Intercept</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W15</td>
<td>-.31</td>
<td>0.183</td>
</tr>
<tr>
<td>W1</td>
<td>.78</td>
<td>0.063</td>
</tr>
<tr>
<td>W2</td>
<td>.34</td>
<td>0.262</td>
</tr>
</tbody>
</table>
3.2.1.4 Subject Y

The torsion graph for subject Y is shown in Figure 19. Each data point represents the mean of two observations at a given tilt angle. Vertical bars indicate one standard deviation above and below each trial point. The shaded area indicates the data points used in the analysis of variance and in the linear regression. The OCR appears to have decreased gain on both R+1 and R+2, notably on the left ear down tilts. The -15' trial on L-15 has a positive gain. The positive gain on this trial was not found to be statistically significant and may be explained by noise or measurement error. The data point however, does increase the variance in this data set so no significant changes in gains were observed between any of the trial days. A comparison of left ear down only and right ear down only tilts do not reveal any significant differences either although the right ear down comparison between L-15 and R+2 comes close ($p = .088$). Gain asymmetries do appear in some tests (see section 3.2.2).

The linear regression lines are plotted below in Figure 20 to Figure 23. The slopes, their $R^2$ values and 95% confidence intervals are given in Table 31. The regression data agrees with the ANOVA in that all of the confidence intervals have some overlap with each other. Qualitatively, there appears to be a reduction in OCR on R+1 and on R+2, with a slight trend toward the preflight OCR on R+2, however, the statistical tests do not reveal any significance. Also note that the regression gains and the ANOVA gains are different. This difference may be explained by the inclusion of the 0° data points in the regression calculation.
Figure 19: Subject Y OCR on L-15, R+1 & R+2

Table 25: OCR gains for subject Y, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.10875</td>
<td>0.09263236</td>
<td>8</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.07083333</td>
<td>0.05131215</td>
<td>8</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.0875</td>
<td>0.03407508</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 26: OCR gains for subject Y, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.075</td>
<td>0.1234534</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.03625</td>
<td>0.04720179</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.09</td>
<td>0.04690416</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 27: OCR gains for subject Y, right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean Gain</th>
<th>Std. Dev.</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-0.1425</td>
<td>0.04175546</td>
<td>4</td>
</tr>
<tr>
<td>R+1</td>
<td>-0.010541666</td>
<td>0.02694731</td>
<td>4</td>
</tr>
<tr>
<td>R+2</td>
<td>-0.085</td>
<td>0.02219442</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 28: Subject Y p values for gain, left and right ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.1085</td>
<td>0.753</td>
<td></td>
</tr>
<tr>
<td>R+1</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R+2</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 29: Subject Y p values for gain, left ear down

<table>
<thead>
<tr>
<th>Day</th>
<th>L-15</th>
<th>R+1</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>0.388</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R+1</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R+2</td>
<td>0.088</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 30: Subject Y p values for gain, right ear down
Subject Y L-15 and linear regression fit

Legend:
- Data

\[ y = -0.129x + 0.26 \]

Figure 20: Subject Y L-15 data and regression line

Subject Y R+1 and linear regression fit

Legend:
- Data

\[ y = -0.076x - 0.49 \]

Figure 21: Subject Y R+1 data and regression line
Figure 22: Subject Y R+2 data and regression line
Figure 23: Subject Y linear regression lines

Table 31: Subject Y regression slopes

<table>
<thead>
<tr>
<th>Day</th>
<th>Slope</th>
<th>$R^2$</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-.129</td>
<td>.8180</td>
<td>-.1786066 - .0793934</td>
</tr>
<tr>
<td>R+1</td>
<td>-.0763333</td>
<td>.8925</td>
<td>-.0979374 - .0547293</td>
</tr>
<tr>
<td>R+2</td>
<td>-.082</td>
<td>.8591</td>
<td>-.109073 - .0549269</td>
</tr>
</tbody>
</table>

Table 32: Subject Y regression intercepts

<table>
<thead>
<tr>
<th>Day</th>
<th>Intercept</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y15</td>
<td>-.26</td>
<td>0.584</td>
</tr>
<tr>
<td>Y1</td>
<td>-.49</td>
<td>0.039</td>
</tr>
<tr>
<td>Y2</td>
<td>-.1</td>
<td>0.699</td>
</tr>
</tbody>
</table>
3.2.2 Comparison of OCR symmetry

The small expected pre-flight asymmetries, observed in most people, favoring a larger right ear down torsion, was not observed or was not significant. This may be due in part to the low sample size of the data and in part to the poor recording conditions, especially for the ±45° and ±60° trials (see section 3.1). Although the OCR graphs appear to have asymmetrical shapes, and the gain comparisons show differences in left ear down tilt only and right ear down tilt only angles, an analysis of variance performed on the OCR magnitudes for all of the trial angles did not have any statistically significant differences. The OCR angles at the ±30°, ±45° and ±60° tilt angles for each subject and trial day are summarized in Table 33 to Table 36 below. The p values for left right torsion magnitude comparisons are included in the tables. A notable exception to the statistically symmetrical trials is subject W on R+1, in which there is an asymmetry favoring the left ear down tilt. The asymmetry is seen on R+1 for each of the tilt angles. This is important to note with reference to the rod and frame experiment results (see section 3.4.2). There are two other cases of asymmetry, one for subject T on day R+1 for the 45° tilt angle, and one for subject Y on day R+1 for the 60° tilt angle. Perhaps it is significant that these two observations occur on R+1, however, they occur on angles which have larger errors associated with them (see section 3.1). Their significance, by a post-hoc argument, is therefore in doubt.

The linear regression data also indicates that most of the intercepts are not significantly different from zero. A non-zero intercept would indicate a torsion bias for one ear or the other. Three exceptions need to be pointed out however. Subjects V and Y on R+1 show significant non-zero intercepts, and subject W on R+1 has an intercept that approaches significance (p=0.063). The regression results for subject W on R+1 probably reflects the results of the ANOVA which shows a left ear down tilt bias. Subjects V and Y both have asymmetries favoring the right ear down tilt, especially subject V.

Although the ANOVA performed on all of the data is a stronger test for asymmetry since it includes all of the data, we should not ignore the asymmetries that appear in the other tests. In the previous section, we saw that three out of the four subjects exhibited significant one-sided changes in gain (see section 3.2.1). Of the three (T, V & W), subject T and subject V displayed a gain reduction on the left side (Table 5 and Table 13), while subject W demonstrated a reduction on the right side (Table 22).

<table>
<thead>
<tr>
<th>Day</th>
<th>+30° OCR value</th>
<th>p value for ±30° symmetry test</th>
<th>+45° OCR value</th>
<th>p value for ±45° symmetry test</th>
<th>+60° OCR value</th>
<th>p value for ±60° symmetry test</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>5.3</td>
<td>0.999</td>
<td>2.5</td>
<td>0.999</td>
<td>-4.35</td>
<td>0.001</td>
</tr>
<tr>
<td>R+1</td>
<td>3.65</td>
<td>0.256</td>
<td>-5.8</td>
<td>0.001</td>
<td>-7</td>
<td>0.001</td>
</tr>
<tr>
<td>R+2</td>
<td>2.3</td>
<td>&gt;0.999</td>
<td>-3.95</td>
<td>&gt;0.999</td>
<td>-3.45</td>
<td>&gt;0.999</td>
</tr>
</tbody>
</table>

Table 33: Subject T symmetry tests (ANOVA)
### Table 34: Subject V symmetry tests (ANOVA)

<table>
<thead>
<tr>
<th>Day</th>
<th>+30° OCR value</th>
<th>p value for ±30° OCR value</th>
<th>+45° OCR value</th>
<th>p value for ±45° OCR value</th>
<th>+60° OCR value</th>
<th>p value for ±60° OCR value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-4.45</td>
<td>&gt;0.999</td>
<td>-4.55</td>
<td>&gt;0.999</td>
<td>-4.55</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td></td>
<td>4.85</td>
<td></td>
<td>6.0</td>
<td></td>
<td>6.15</td>
<td></td>
</tr>
<tr>
<td>R+1</td>
<td>-4.15</td>
<td>&gt;0.999</td>
<td>-5.9</td>
<td>&gt;0.999</td>
<td>-5.8</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td></td>
<td>3.55</td>
<td></td>
<td>5.95</td>
<td></td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>R+2</td>
<td>-5.35</td>
<td>&gt;0.999</td>
<td>-3.85</td>
<td>&gt;0.999</td>
<td>-6.6</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td></td>
<td>2.65</td>
<td></td>
<td>3.10</td>
<td></td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

### Table 35: Subject W symmetry tests (ANOVA)

<table>
<thead>
<tr>
<th>Day</th>
<th>+30° OCR value</th>
<th>p value for ±30° OCR value</th>
<th>+45° OCR value</th>
<th>p value for ±45° OCR value</th>
<th>+60° OCR value</th>
<th>p value for ±60° OCR value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-4.4</td>
<td>&gt;0.999</td>
<td>-5.60</td>
<td>&gt;0.999</td>
<td>-5.75</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td></td>
<td>5.15</td>
<td></td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>R+1</td>
<td>-1.45</td>
<td>0.042</td>
<td>-4.05</td>
<td>0.007</td>
<td>-5.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td></td>
<td>7.40</td>
<td></td>
<td>9.4</td>
<td></td>
</tr>
<tr>
<td>R+2</td>
<td>-4.4</td>
<td>&gt;0.999</td>
<td>-5.9</td>
<td>&gt;0.999</td>
<td>-6.5</td>
<td>&gt;0.999</td>
</tr>
<tr>
<td></td>
<td>2.85</td>
<td></td>
<td>4.6</td>
<td></td>
<td>5.7</td>
<td></td>
</tr>
</tbody>
</table>

### Table 36: Subject Y symmetry tests (ANOVA)

<table>
<thead>
<tr>
<th>Day</th>
<th>+30° OCR value</th>
<th>p value for ±30° OCR value</th>
<th>+45° OCR value</th>
<th>p value for ±45° OCR value</th>
<th>+60° OCR value</th>
<th>p value for ±60° OCR value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-15</td>
<td>-3.55</td>
<td>0.338</td>
<td>-3.25</td>
<td>&gt;0.999</td>
<td>-3.65</td>
<td>0.294</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td></td>
<td>4.5</td>
<td></td>
<td>5.25</td>
<td></td>
</tr>
<tr>
<td>R+1</td>
<td>-2.775</td>
<td>&gt;0.999</td>
<td>-2.075</td>
<td>&gt;0.999</td>
<td>-5.875</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>2.025</td>
<td></td>
<td>1.775</td>
<td></td>
<td>2.575</td>
<td></td>
</tr>
<tr>
<td>R+2</td>
<td>-3.0</td>
<td>0.989</td>
<td>-3.63</td>
<td>&gt;0.999</td>
<td>-4.9</td>
<td>0.989</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td></td>
<td>2.4</td>
<td></td>
<td>3.6</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3 Closed loop otolith assessment tests

Since changes in OCR may be related to otolith function, we will compare each subject’s OCR results with three other related pre-post flight tests; two closed loop otolith assessment tests and the rod and frame experiments. A summary of the closed loop nulling task results is presented in this section. A detailed description and analysis of these experiments can be found in Merfeld 1995 (roll tilt) and Merfeld et al 1995 (linear). Two types of closed loop tasks were performed. The subjects were asked to null out either a roll tilt motion or a linear motion by using a joystick. Sinusoidal linear motion was produced on a motorized sled. In the absence of any external cues, subjects were previously trained to learn a nulling strategy. The nulling errors were measured pre- and post-flight. The tests compared the relative abilities of the otolith organs to sense either gravitationally induced tilts, or linear accelerations after space adaptation.
3.3.1 Subject T

Subject T was found to perform the linear nulling task better post-flight. The performance increase persisted for a period over a week. Y-axis and Z-axis accelerations were both tested, but T only improved on the Y-axis accelerations. On the roll tilt nulling task, performance was worse on R+0, on R+1 and on R+2 than on pre-flight. The errors returned to pre-flight levels by R+9.

3.3.2 Subject V

Subject V did not show any differences in the linear nulling task post-flight on either the Y-axis or Z-axis accelerations. On the roll tilt nulling task, performance was better on R+1 and on R+2 than on pre-flight. On the next trial day, R+9, errors had returned to pre-flight levels.

3.3.3 Subject W

Subject W was not able to perform the linear nulling task, however, performance on the roll tilt nulling task was worse on R+0 and on R+1 than on pre-flight. There was also a return to pre-flight values by R+2 on the roll tilt task.

3.3.4 Subject Y

Subject Y was found to perform the linear nulling task better post-flight. The performance increase persisted for a period over a week. Y-axis and Z-axis accelerations both demonstrated performance gains. On the roll tilt nulling task, results were not significantly different from preflight averages.

3.4 Rod and frame experiments

The results of the rod and frame experiments indicate that our perception of the vertical is altered due to microgravity adaptation. The results are summarized here, but a detailed description may be found in Robinson et al, 1995. The experiments show that a subject was more likely to make larger errors in aligning a rod with gravity post-flight than pre-flight. The significant alignment errors accumulated when the subjects were tilted ±28° to the left or the right. The errors worsened if the visual frames were rotated 28° in the opposite direction giving the illusion of a larger degree of self-tilt. Errors also worsened when the frame was tilted 28° toward the already tilted subject, giving the illusion of a lesser degree of self-tilt. The type of errors exhibited however, varied from subject to subject, illustrating the different strategies that may be taken perceptually to orient a person. The notable results are summarized here.
3.4.1 Subject T

Subject T showed a quick readaptation back to normal gravity. In this sense, the rod and frame experiments do not match up with the static tilt experiments. Subject T made errors that were within the noise margin of the experiment under all of the conditions in the rod and frame experiments. This result indicates, as suggested in the rod and frame paper that this subject has a “hypersensitivity” to gravity. Even under tilt conditions, the reduced OCR gain that was observed did not impair the ability to properly locate the vertical.

3.4.2 Subject W

For subject W, the rod and frame experiments seemed to match up partly with the trends observed in these static tilt experiments. An asymmetry between left and right (-28° and +28°) tilted aligning responses was observed in the rod & frame tests. The subject tended to have greater errors on the left ear down tilt than on the right ear down tilt in all of the experimental conditions and trial days. In a similar fashion, W was observed to have a marked OCR asymmetry between the left and right ear down responses for the ±30°, ±45° and ±60° tilt trials on R+1. Also, a trend toward baseline values was noticed in both sets of experiments, especially in the static tilt experiment- there is a practically complete return to baseline on R+2.

3.4.3 Subjects Y&V

These subjects were field-dependent, relying on the polarization of their environment to orient themselves. Their field-dependence was verified by reports that they did not feel illusions of self inversions in space. When tested in the rod and frame experiments on return, the subject's visual reliance was seen to have increased, especially under body tilted conditions. Neither of these subjects demonstrated a return to pre-flight results for slightly more than a week. The OCR data seems to indicate a trend toward baseline values on R+2 for subject V but not for subject Y, however the graphs, at least over the -30° to 30° range seem to show a reduced gain on both days for both subjects although subject Y did not demonstrate significance.
4. Discussion

4.1 OCR gain

Reductions in ocular counterrolling have been observed after space flight by a variety of researchers. OCR reduction was reported by Arrott and Young (1986) and by Vogel and Kass (1986) after the Spacelab 1 mission, by Dai (1994) in monkeys, and by Yakovleva (1982) after a stay on board the Salut 6 station. The cosmonauts from the last paper were found to have one-sided OCR reduction for 14 days. Data from the SLS-2 mission appears to confirm these previous observations of OCR magnitude reduction. Three out of the four subjects (T, V & W) demonstrated some statistically significant magnitude reduction post flight. For two of these subjects, V and W, there was only a significant reduction on one side, not both. Subject T displayed a reduction in OCR on R+1 and on R+2, while subjects V and W, especially W, demonstrated a return toward preflight values on R+2. The missing R+7 and R+9 data made it difficult to note any definite post-flight trends except that there was magnitude reduction on at least R+1. The change in the OCR response indicates that there was some sensory adaptation in space. In order to ensure that there were not any physical changes in the eye, Dai et al (1994) checked for a lack in mobility of the eye. They found that this was not responsible for the reduction in torsion. Fine forceps were used to measure the force required to rotate the eyeball in their monkeys- there was no difference in this force from pre- to post-flight leading them to believe that neural processing was responsible for the change.

In order to explain some of the more subtle changes in the counterrolling response, the otolith tilt translation reinterpretation hypothesis (OTTR) was formulated by Young et al (1984) and further examined in Parker et al (1985). It states that the otoliths, which can sense both linear movements and roll tilts, reinterpret the otolith generated signals in space as linear motion-induced inertial deflections rather than as partly tilt-induced, partly linear-induced motions. Since there is no net gravito-inertial force in orbit, the only otolith stimulations would come from linear accelerations. On return to earth, the eye movements seen immediately post-flight would then be expected to exhibit less counterrolling under tilt conditions; we would also expect to see more horizontal nystagmus. This implies that astronauts should improve their ability to sense linear accelerations and decrease in their ability to sense tilts with respect to gravity.

The rod and frame experiments demonstrated, with the exception of subject T, that subjects estimated the vertical poorly when tilted post-flight. The CLOAT tests revealed an improved ability to sense linear accelerations in subjects T and Y while subject V showed no change from preflight. The roll tilt CLOAT tests also confirmed a predicted performance decrement in the task in two of the four subjects, T and W. These results seem to agree with
the otolith tilt translation reinterpretation hypothesis. These results are also in agreement with similar tests that were conducted on the SLS-1 mission.

The results from this thesis also seem to match up partly with the roll tilt nulling task. In the roll tilt nulling task, subject W had returned to preflight performance levels on R+2, while subject T still showed some decrement on R+2. Interestingly there is a parallel temporal trend for subjects T and W that may be seen in the static tilt experiments. Subject T displayed static tilt-induced OCR which was reduced on R+1 and remained so on R+2. Subject W on the other hand, had OCR that was reduced on R+1, but had returned to baseline values by R+2.

In addition to the results that seem to fit previous theories and that are in accordance with previous data there are also some observations that do not quite fit in with one theory or another. For example subject T may show similar types of behaviors in the CLOAT tests and in the static tilt tests, however, the subject's good performance in the rod and frame experiments requires a separate explanation. The OTTR hypothesis would predict poor vertical judgment, instead Robinson (1995) explains the result as a "hypersensitivity" to gravity which seems to directly contradict the OTTR hypothesis. Why should there be good vertical judgment in one task and not another? One set of observations, that are missing, and that may have shed some more light on this result are comparisons of linear versus torsional eye movements in the different motion conditions (linear or rotational). Do the subjects have different ratios of torsional to linear nystagmus in the roll tasks compared to the linear tasks? A difference may indicate several types of adaptation- a slow one due to prolonged weightlessness, and a fast one in different types of stimuli perhaps.

4.2 OCR asymmetry

Two types of asymmetries have been observed in ocular counterrolling (Diamond et al 1979). There is an asymmetry in the degree of OCR between the left and right ear down tilts, and there is also an asymmetry in the OCR between the two eyes for a given tilt direction. We only examined the asymmetry in the right eye between the left and right ear down tilts. Normally, we see very little asymmetry because the differences in the otolith system are balanced out by neuro-vestibular control mechanisms. Increased left right asymmetries may appear however, when the compensation is gone; this is the case following prolonged orbit. The compensation, probably an integral part of the tilt response, may disappear due to sensory adaptation to weightlessness. Since tilt stimuli are reinterpreted by the OTTR hypothesis as linear stimuli, it would be unnecessary to balance any tilt-induced asymmetries in a zero-g environment and any left right asymmetry compensation should disappear as well. Upon return to earth most of the subjects did show some sort of asymmetrical response.

Subjects T, V, W and Y displayed asymmetries in one or more of the different statistical tests. Interestingly, subject W shows OCR that favors the left ear down orientation
rather than the right ear down one. In previously reported data, a majority of the asymmetries reported favored a right ear down bias as with subjects T, Y and V. This bias shows up in both the static tilt induced OCR and in the rod and frame experiments. Subject W however, did not show any abnormalities upon caloric testing though. Of the four subjects, a comparison of left ear down only and right ear down only gains, seemed to indicate that subject T really had the least amount of asymmetry. Perhaps the relative lack of asymmetry has some bearing on subject T’s good performance on the rod and frame tests. A set of comparisons could be made between OCR asymmetry and rod alignment error to test this. Subject W and possibly subject T hint at a possible connection between the static tilt and rod and frame experiments.

Diamond and Markham (1991, 1992) have shown that the magnitude of torsional differences tended to correlate well with previous histories of space motion sickness. They measured the torsional differences between the two eyes for a given tilt angle, whereas the data in this thesis examines the differences for one eye on opposing tilt angles. The relationship between the two types of asymmetries has not been established. However we might assume that they were correlated. If asymmetry were an indicator of SMS then the OCR data would predict subject T, with the least asymmetry, as suffering the least from SMS and subject W the most; subjects Y and V would have similar degrees of SMS. Oman reported motion sickness susceptibilities in the subjects, from least to most, as: V, T, W, then Y (Young and Merfeld 1995). It was also reported that there were very few symptoms and episodes of SMS on board the SLS-2 mission therefore it was difficult to note any correlations if any. It was noted in Merfeld (1995) that subjects who performed the best on the linear motion nulling task on post-flight were also ranked as having the most SMS. Perhaps using the linear motion results in addition to the OCR asymmetries would be a better predictor, however no attempt has been made to use both sets of information in such a way.

The appearance of large asymmetries post-flight agree with the neural compensation hypothesis and some previous data. The asymmetries also seem to appear in the perceptual rod and frame tasks indicating that there is a strong contribution by the otoliths to perception even upon immediate return from orbit. The subjects that demonstrated strong asymmetries in static OCR also performed poorly in the rod and frame experiments. Subject T, who had the least asymmetrical OCR responses however, performed very well on the rod alignment task. Curiously though, subject T did not perform well in the roll tilt nulling task. These results suggest, although one subject hardly constitutes anything significant, another hypothesis. Asymmetries may influence our absolute perception of gravity while the magnitude of the OCR may affect our relative judgment of the gravity vector. A correlation in the post-flight trends between the static tilt and the rod and frame experiments may lend some support to this hypothesis, however there are clearly more tests that need to be done. As suggested earlier in the discussion, a comparison of post-flight torsional asymmetry to vertical perception may also lend some data for this hypothesis.
5. Conclusions

Testing otolith function pre- and post-flight gives us important clues as to the nature of otolith function, neurovestibular adaptation to space, and finally the readaptation process upon return to earth. The changes observed in static ocular counterrolling both agree with previous observations and data, and seem to agree with existing hypotheses. The two hypotheses examined in this thesis were the otolith tilt translation reinterpretation hypothesis and the asymmetry compensation hypothesis. The OCR data clearly indicated that the magnitude of torsion had been reduced post-flight, at least on R+1. The subjects also demonstrated the existence of left right asymmetries in their OCR. The three subjects that had large asymmetries displayed those asymmetries in the rod and frame experiments and in the same direction. It was particularly notable that subject W’s left ear biased asymmetry also showed up in the rod and frame experiments. These were the strongest findings of this paper, however there were some other trends that were weak though interesting. The readaptation time course in the different tasks were not the same on the whole, however there was a correlation between the static tilt induced OCR and the roll tilt nulling task for two subjects. In the future, data collected in between R+2 and R+9 may help illustrate a clearer correlation if any in these post-flight trends. Finally, a comparison of the relative amounts of torsional and linear nystagmus between roll and linear motion conditions may reveal perceptual changes in the interpretation of otolith signals.
6. Sources


Crites, Troy A. Circularvection and ocular counterrolling in visually induced roll supine and in weightlessness, (1980) S.M. Thesis Massachusetts Institute of Technology


Kornhuber, H. H. ed., Handbook of Sensory Physiology, volume VI/1 and VI/2 Springer-Verlag, New York 1974


Miller, E.F.,II. and Graybiel, A., “Ocular counterrolling measured during eight hours of sustained body tilt.” (1972) NASA T-81633


47


Young, L.R., “Human neurovestibular adaptation to weightlessness (experiments performed on the Spacelab SLS-2 mission)”, abstract presented at Life Sciences and Space Medicine Conference and Exhibition, Houston, April 3-5, 1995

7. Appendix

7.1 VDAC Automated video oculography system

7.1.1 System overview

The VDAC system was developed by Kwanjae Sung, Johnson Space Center Houston, Texas. He may be reached by email, ksung@PLATO.JSC.NASA.GOV, or by the following address: The system consists of hardware and software components. A 3/4 inch SONY UMATIC VCR, model number VO-9600 equipped with a BKU-701 frame accurate controller/computer interface board, is used to play the 3/4 UMATIC video tapes. A Macintosh PowerPC 7100/80 is used to control the VCR, and to sample the video data. A two page monitor (1152x870x256grays screen resolution) is required in order to display all of the menus. A video acquisition card manufactured by SCION, model LG-3 equipped with 16MB of on board RAM was used to accurately capture the video frames. Future versions of the software will be designed to run on PowerPC Macintoshes with a PCI bus based video card; the LG-3 currently being used uses the older NUBUS bus. Also, the LG-3 and other PCI video cards maybe equipped with up to 64MB (or more for PCI cards) of RAM to speed up data acquisition and analysis. The VDAC software (version 1.4.1 (ppc)_16mb) is written specifically for the PowerPC processor for maximum performance. The VDAC software controls both the VCR and the video capture board so that frame accurate capturing is performed. Linear eye movements as well as torsional eye movements are recorded along with a time stamp. The data is output in Matlab® format as a series of vectors. Pupil diameter and percentage of pupil visible are also included in the output.

7.1.2 Video data format

7.1.2.1 Grayscale video

The software uses only grayscale information, therefore it is not necessary to capture with a color video camera. A high resolution grayscale camera is preferable. High frequency color information can also cause some visible banding in an image which has been captured as a grayscale image.

7.1.2.2 Timecode

In order to synchronize to the VCR and properly capture video frames, the software searches for a timecode stamp on the video. It is necessary to record timecode on the video as data is being recorded. A timecode generator should be placed in between the camera and the recorder preferably, however a timecode may be later placed on the video by copying onto another tape. This will cause some video degradation however.
7.1.2.3 Linear eye movements

For linear eye movement tracking, the pupil needs to be in full view because the center of the pupil is located for tracking the eyeball. There should be good contrast between the pupil and the surrounding iris and sclera. This is necessary because a threshold operation is used to isolate the mostly black pupil. Reflections in the pupil should be minimized as much as possible also.

7.1.2.4 Torsional eye movements

Stricter constraints need to placed on the video data in order to measure ocular torsion. The constraints above also apply since the center of the pupil needs to be consistently located. Since iris patterns are used to calculate torsion angles, they need to be in focus and in high contrast. The iris should fill up as much of the video frame as possible in order to maximize the information available for analysis, and the pupil should be as small as possible. Lighting should just graze the eye to avoid any shadows that may be cast by eyelashes on the iris. Since the software searches for patterns at fixed distances from the center of the pupil, the pupil should not change diameter. A bright steady source of light and a fixation target may be enough to maintain a small fixed pupil diameter, however there are drugs that may be administered to guarantee a fixed and constricted pupil. One such drug is pilocarpine hydrochloride (Curthoys et al 1992), and its effects last for an hour or so; the dosage may be varied for more or less effective time.

7.1.3 Setup

The LG-3 framegrabber must be placed in one of the nubus slots inside the PowerMac. A digitizing cable plugs into the framegrabber and the other BNC connector plugs into the video out of the VCR. An RS232 port on the VCR is the controller port for the VCR. This must be connected to the modem port of the PowerMac. A secondary video out from the VCR should be connected to a monitor for convenient scanning, though not necessary. Before you start the program, make sure that the VCR is on, and that it is connected to the computer via the modem port, otherwise the program may lock up. It is also a good idea to have a tape in the VCR with timecode. If you do not, then the program gives you a random error which you may ignore.
7.1.4 Main screen

Upon startup, the windows shown above should appear. An image will appear if there is a tape in the VCR. The graph window displays linear and torsional data as it is collected. The graph window has scaling and offset buttons on the right side. The "message 2" window displays statistics such as brightness and contrast, "FG bri." and "FG cont.", as well as framecode information, the current data values, and the pupil threshold setting. The Main menu shown above only has four useful buttons, Track, Live, Pref, and Quit. Quit is self explanatory. The others are explained below.

7.1.5 Capturing an initial baseline frame

A baseline frame is required in order to determine the dimensions of the iris and the pupil and to grab a template for torsion measurements. The software can be used to control the playback of the VCR. The controls may be found in the Live menu (shown below) which can be reached from the Main menu. The top row of controls are, from left to right, eject, stop, rewind, play, fast forward, pause, goto timecode, and reset timecode sync buttons.

The computer must be synched to the timecode on the tape before any frame accurate functions, including the goto timecode button and automated data collection, can be performed. The tape is automatically synched upon startup of the program, however the sync
may be lost in a variety of ways including fast forwarding and ejecting tapes, therefore the “Reset” button is included to find the sync again.

7.1.5.1 Timecodes and frame codes

It is important to realize that timecode is a number on the particular videotape whereas, there is also a number called the framecode which is a number internal to the VCR. The framecode is displayed on the VCR counter. The VCR actually uses the framecode to find a particular frame of video. Upon reset, the timecode on the tape is synched to the framecode. The timecode is used by the program to calculate framecode numbers which are actually used to forward, rewind or play the tape to a particular user specified timecode. It is possible, if the frame counter is near its minimum or maximum value, to generate errors in searching for a particular timecode; resetting the frame counter by ejecting the tape maybe necessary.

7.1.5.2 Capturing a frame

While you play the video tape through the software, brightness and contrast (found in the live menu) should be adjusted to maximize pupil contrast as well as iris contrast for torsion. When an acceptable series of images appear, “pause” may be pressed to freeze the image for analysis.

7.1.5.3 Pupil threshold and iris boundary definition

The next step is to go to the Pref menu from the Main menu. Do not go to the pref menu from any other menu, this may cause some problems.

![Image of menu options]

The significance of the “track” submenu (not shown) is not clear, although for the record, I arbitrarily set Eye Orientation to “rot” instead of “normal”. Choose the “iris1” submenu, and the following will appear:
The first thing that needs to be done is to determine the pupil tracking threshold level. The “Auto T” and “Retrack” buttons on the upper left hand corner are used for this. For a good start, pick “Auto T”. This usually picks a good threshold value, and a cross hair should appear centered on the pupil (if you look at the eye picture above, you will see a cross hair—ignore it since it is an artefact of the timecode generator). The cross hair should appear as below:

If the cross-hair is not centered or there is poor tracking during data collection, the threshold level can be manually adjusted in the box next to “Retrack”. A binary image will display the results of the thresholding. Ideally, only the pupil should be seen in black. Click on the “Retrack” button when you are done to regenerate the cross-hair.

The next step is to define the iris boundary. First click on the “Manual Register” button, located below the threshold buttons. Then click on twelve points around the edge of the iris. I usually pick six on each side. Once you are finished, click on “Calculate”.
This generates a circular fit around the iris. You may click on the boxes immediately below “Calculate” to show the graphical results of the fitting. This is unnecessary though. The final step that needs to be done in this window is to click on “Memorize Current Results” and then on “OK” to leave the menu.

### 7.1.5.4 Pupil Search region

Choose the “cent” submenu from the Pref menu. This defines the region over which the pupil will be tracked.

Make sure that you allow for some horizontal and vertical movement in the region. Click on “OK” when you are done.

### 7.1.5.5 Setting baseline search region or arcs for torsion measurements

The “iris2”, “p1”, and “p2” submenus do not have a purpose. The “save” and “load” buttons are not completely clear to me, so use with discretion. The “head” and “roll” buttons are used to pick the regions of the iris where torsion will be calculated. If you plan on only collecting linear eye movements, the rest of this section is unnecessary. The “head” menu allows you to define a 2-D dimensional region for torsion calculations.
The region sizes and positions may be entered. The regions may be moved together by first clicking on "Move by Cursor" then clicking and dragging the regions in the image window. The search region is larger than the search region to allow the correlation to have overlap (its better this way). Both search and template regions should be selected by choosing "Both". To activate the two dimensional regions click on "Operational". The "Normalize Template" option may or not may not improve things- I'm not sure. This method is several times slower than the search arcs described below since it uses two-dimensional correlations. Click on "OK" to proceed.

Click on the "roll" submenu to select the 1-D search arcs. The following should appear:

Pick a four or seven set of arcs with the "4 wings" or "7 wings" button. Use the + and - buttons to adjust the radius ("Rad In" and "Rad Out") of the arcs so that they are in an interesting region of the iris. You can see the arcs on the image window as shown below:
After a satisfactory set of arcs have been placed, click on "Current->Base" to use the area under the arcs as the templates for cross-correlations. The "Calc Torsion" button will calculate the torsion of the current frame. Click on "OK" to proceed.

### 7.1.6 Automated data collection- the Track menu

When you have finished preparing the first frame, go to the Track menu from the Main menu.

Choose the "Batch" submenu to set the trial length and output filename.

It is necessary to first choose "Add" to pick an output filename. It is probably wise to include a .mat ending to the file so that both you and Matlab® recognize it as a Matlab® file. You must enter the timecode times for the start and stop time, not the framecode. Look at the picture of the image window above. At the top center, you can see the timecode; it reads "012 11:52:56.464". The 012 is a day number, so ignore it. 11 is the hour, 52 the minutes, and 56.464 the seconds. The requester does not allow decimal points so start and stop points
need to be rounded to the nearest second. The “yes, to” box should be checked off to use
the pupil threshold value always, and the “Roll” box should be checked off if torsion is
being recorded (I think - I always checked it off). You can add more trials. Click “OK”
when done.

Just click on “Start” when you are ready to collect data and sit back. You can watch
the values pop up on the graph. If necessary, it is possible to use the “pause” submenu in
Track to pause data collection so that you can change the threshold with the “thr+” and
“thr-” buttons. The “set” button needs to be pressed after you change the threshold. Press
“Pause” again to continue. You may also “Stop” the data collection. The file will contain
all of the data up to when you stopped it.
7.2 Matlab® artefact removal script for torsion data

The screen shots below demonstrate an interactive window-based artefact removal and data analysis script. You may pick up to three trials, zoom into a region, cut out a region, or select a region for which the mean and standard deviation will be given. Note that for file1, the vertical eye position is also plotted above the torsion data to help locate blinks. The Matlab® script given below uses the uicontrol function to make buttons that execute the lines of code that precede it. The code is made into a string, which is executed by the uicontrol button every time it is pushed.

To run the script just type “octor” in the control window of Matlab®. The program will ask you for an initial range. Input the timecode as you did in the VDAC software: [hours minutes seconds] for the start and stop times. The script will let you zoom in from those limits Two windows will appear. The one on the left contains buttons for loading up to three torsion files, along with zoom, cutting, and analysis buttons. The window on the left gives histograms for the data in the left window; file1 is in the upper left, file2 upper right, file3 lower left, and the total in the lower right. The buttons are fairly self-explanatory. Once a suitable range has been selected, the print stats button will give the mean and standard deviation for the three separate files and the total mean and standard deviation. These are printed in the control window. See the screen shots below to see the code at work.
7.2.1 Screen shots

Commands to get started: intro, demo, help help
Commands for more information: help, what is, info, subscribe

Enter start time, [hours minutes seconds]: [12 22:23]

Enter stop time, [hours minutes seconds]: [12 23:5]

1
Commands to get started: intro, demo, help help
Commands for more information: help, whatisnew, info, subscribe

octave

Enter start time, [hours minutes seconds]: [12 22 23]

Enter stop time, [hours minutes seconds]: [12 23 5]
Stats: [mean std samples]
for file:
urp105
Mean: 1.0326
Std: 0.8110
Samples: 336.0000

Stats: [mean std samples]
for file:

Warning: Divide by zero

Warning: Divide by zero

100 0 0
7.2.2 Ocular torsion analysis script
An explanation of the script is given at the beginning of section 7.2.

clear
clf
x1 = [];
x2 = [];
x3 = [];
t1 = [];
t2 = [];
t3 = [];
y1 = [];
xla = [];
x2a = [];
x3a = [];
tla = [];
t2a = [];
t3a = [];
yla = [];
file1 = [];
file2 = [];
file3 = [];

hr1 = input('Enter start time, [hours minutes seconds]: ');
hr2 = input('Enter stop time, [hours minutes seconds]: ');
figure(1)
set(gcf,'Position', [0 420 560 420])
figure(2)
set(gcf,'Position', [580 420 560 420])
figure(1)

s1 = ['[file1, path] = uigetfile(''*'',''Choose an ocular torsion file to analyze.'');');
s1 = [s1 'if ~isstr(file1),'';'];
s1 = [s1 't1 = []; Tla = [];'';'];
s1 = [s1 'x1 = []; Xla = [];'';'];
s1 = [s1 'y1 = []; Yla = [];'';'];
s1 = [s1 'plot(xla,tla,''-''',x2a,t2a,''-''',x3a,t3a,''-''',xla,yla/10-5,'''');'';'];
s1 = [s1 'else,'';'];
s1 = [s1 'cd(path);'';'];
s1 = [s1 'load(file1);'';'];
s1 = [s1 'a = find(timeData > hrs(hr1(l), hr1(2), hr1(3))) & timeData <= hrs(hr2(1), hr2(2), hr2(3)));'';'];
s1 = [s1 't1 = torData(a); Tla = t1;'';'];
s1 = [s1 'x1 = timeData(a); Xla = x1;'';'];
s1 = [s1 'y1 = yData(a); Yla = y1;'';'];
s1 = [s1 'plot(xla,tla,''-''',x2a,t2a,''-''',x3a,t3a,''-''',xla,yla/10-5,'''');'';'];
s1 = [s1 'end'';'];
ucicontrol('Units','normal','Position',[0 .1 .06],'String','File 1','callback',s1);
s1=[];
s1 = ['[file2, path] = uigetfile(''*'',''Choose an ocular torsion file to analyze.'');'';'];

61
si = [si 'if ~isstr(file2),'
];
si = [si 't2 = []; t2a = [];
];
si = [si 'x2 = []; x2a = [];
];
si = [si 'plot(xla,tla,''-',t2a,t2a,''-',x3a,t3a,''-.'',xla,yla/10-5,'':'');'
];
si = [si 'else,'
];
si = [si 'cd(path);'
];
si = [si 'load(file2);'
];
si = [si 'a = find(timeData > hms(hrl(1), hrl(2), hrl(3)) & timeData <= hms(hr2(1),
hr2(2), hr2(3)));
'];
si = [si 't2 = torData(a); t2a = t2a;
];
si = [si 'x2 = timeData(a), x2a = x2a;
];
si = [si 'plot(xla,tla,''-',x2a,t2a,''-',x3a,t3a,''-.'',xla,yla/10-5,'':'');'
];
si = [si 'end'
];

uicontrol('Units', 'normal', 'Position', [.1 0 .1 .06], 'String', 'File 2', 'callback', sl);
s1 = [si]

s1 = [file1, path] = uigetfile('''','Choose an ocular torsion file to
analyze.'');
]
s1 = [si 'if ~isstr(file3),'
];
s1 = [si 't3 = []; t3a = [];
];
s1 = [si 'x3 = []; x3a = [];
];
s1 = [si 'plot(xla,tla,''-',x2a,t2a,''-',x3a,t3a,''-.'',xla,yla/10-5,'':'');'
];
s1 = [si 'else,'
];
s1 = [si 'cd(path);'
];
s1 = [si 'load(file3);'
];
s1 = [si 'a = find(timeData > hms(hrl(1), hrl(2), hrl(3)) & timeData <= hms(hr2(1),
hr2(2), hr2(3)));
'];
s1 = [si 't3 = torData(a); t3a = t3a;
];
s1 = [si 'x3 = timeData(a), x3a = x3a;
];
s1 = [si 'plot(xla,tla,''-',x2a,t2a,''-',x3a,t3a,''-.'',xla,yla/10-5,'':'');'
];
s1 = [si 'end'
];

uicontrol('Units', 'normal', 'Position', [.2 0 .1 .06], 'String', 'File 3', 'callback', s1);
s1 = [s1]

s3 = 'figure(1);'
]
s3 = [s3 'text(yrange(4), yrange(4), ''Pick the min x range'');'
];
s3 = [s3 's1 = ginput(1);'
];
s3 = [s3 's1(2) = s1(1);
'];
s3 = [s3 'hold on, plot(sl,yrange(3:4),''w:'',''erase'',''none''); hold off;'
];
s3 = [s3 'text(yrange(4), (yrange(4)-yrange(3))/4, ''Pick the max x range'');'
];
s3 = [s3 's2 = ginput(1);'
];
s3 = [s3 's2(2) = s2(1);
'];
s3 = [s3 'hold on, plot(s2,yrange(3:4),''w:'',''erase'',''none''); hold off;'
];
s3 = [s3 'pause(2);'
];
s3 = [s3 'sx(sl(l),s2(l));'
];
s3 = [s3 'a = find(xla > sl(l) & xla <= s2(1));'
];
s3 = [s3 'tla = tla(a);'
];
s3 = [s3 'xla = xla(a);'
];
s3 = [s3 'yla = yla(a);'
];
s3 = [s3 'a = find(x2a > sl(l) & x2a <= s2(1));'
];
s3 = [s3 't2a = t2a(a);'
];
s3 = [s3 'x2a = x2a(a);'
];
s3 = [s3 'a = find(x3a > sl(l) & x3a <= s2(1));'
];
s3 = [s3 't3a = t3a(a);'
];
s3 = [s3 'x3a = x3a(a);'
];
s3 = [s3 'figure(1);'
];
s3 = [s3 'plot(xla,tla,''-',x2a,t2a,''-',x3a,t3a,''-.'',xla,yla/10-5,'':'');'
];
s3 = [s3 'figure(2);'
];
s3 = [s3 'subplot(221);'
];
s3 = [s3 'hist(t1a,20);'
];
s3 = [s3 'if ~isempty(t2a),'
];
s3 = [s3 'subplot(222);'
];
s3 = [s3 'hist(t2a,20);'
];
s3 = [s3 'end;'
];
s3 = [s3 'if ~isempty(t3a),'
];
s3 = [s3 'subplot(223);'
];
s3 = [s3 'hist(t3a,20);'
];
s3 = [s3 'end;'
];
s3 = [s3 'if ~isempty([t1a'' t2a'' t3a'']),'
];
s3 = [s3 'subplot(224);'
];
s3 = [s3 'hist([t1a'' t2a'' t3a''],20);'
];
s3 = [s3 'end;'
];

uicontrol('Units', 'normal', 'Position', [.3 0 .12 .06], 'String', 'Pick Range', 'callback', s3);
s3=[];
s3 = [s3 'figure(1);'
];
s3 = [s3 'yrange = axis;'
];
s3 = [s3 'text(yrange(1), yrange(4), ''Pick the min x range'');'
];
s3 = [s3 'sl = ginput(1);'
];
s3 = [s3 's1(2) = sl(1);'
];
s3 = [s3 'hold on, plot(sl,yrange(3:4), ''w:'',''erase'',''none''); hold off;'
];
s3 = [s3 'text(sl, yrange(4), ''Pick the max x range'');'
];
s3 = [s3 's2 = ginput(1);'
];
s3 = [s3 's2(2) = s2(1);'
];
s3 = [s3 'hold on, plot(s2,yrange(3:4), ''w:'',''erase'',''none''); hold off;'
];
s3 = [s3 'pause(2);'
];
s3 = [s3 'sx(s1(1),s2(1));'
];
s3 = [s3 'if ~isempty(t1a),'
];
s3 = [s3 'a = find(xla > s1(1) & xla <= s2(1));'
];
s3 = [s3 't1a(a)=[;]'
];
s3 = [s3 'xla(a)=[];'
s3 = [s3 'yla(a)=[];

s3 = [s3 'end;

s3 = [s3 'if ~isempty(t2a),'

s3 = [s3 'a = find(x2a > sl(l) & x2a <= s2(l));'

s3 = [s3 't2a(a)=[];

s3 = [s3 'x2a(a)=[];

s3 = [s3 'end;

s3 = [s3 'if ~isempty(t3a),'

s3 = [s3 'a = find(x3a > s1(l) & x3a <= s2(l));'

s3 = [s3 't3a(a)=[];

s3 = [s3 'x3a(a)=[];

s3 = [s3 'end;

s3 = [s3 'figure(l);

s3 = [s3 'plot(xla,tla,''-.'',x2a,t2a, ''--'' ,x3a,t3a, ''-.'',xla,yla/10-5, ''':'');

s3 = [s3 'figure(2);

s3 = [s3 'subplot(221);

s3 = [s3 'hist(tla,20);

s3 = [s3 'subplot(222);

s3 = [s3 'hist(t2a,20);

s3 = [s3 'end;

s3 = [s3 'if ~isempty(t3a),

s3 = [s3 'subplot(223);

s3 = [s3 'hist(t3a,20);

s3 = [s3 'end;

s3 = [s3 'ttot = [tla'' t2a'' t3a''];''

s3 = [s3 'disp(''Stats: [mean std samples]'');'

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file1);

s3 = [s3 'disp([mean(tla) std(tla) length(tla)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file2);

s3 = [s3 'disp([mean(t2a) std(t2a) length(t2a)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file3);

s3 = [s3 'disp([mean(t3a) std(t3a) length(t3a)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for total:'');

s3 = [s3 'disp([mean(ttot) std(ttot) length(ttot)]);

s3 = [s3 'disp(''Print Stats'','callback',s3)];

s3 = [s3 '

s3 = [s3 'hr1 = input(''Enter start time, [hours minutes seconds]: '');''

s3 = [s3 'hr2 = input(''Enter stop time, [hours minutes seconds]: '');''

s3 = [s3 'uicontrol(''Units',''normal',''Position', [.54 0 .12 .06],''String',''Clip Range',''callback',s3);

s3 = [s3 'ttot = [tla'' t2a'' t3a''];''

s3 = [s3 'disp(''Stats: [mean std samples]'');'

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file1);

s3 = [s3 'disp([mean(tla) std(tla) length(tla)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file2);

s3 = [s3 'disp([mean(t2a) std(t2a) length(t2a)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for file:'');

s3 = [s3 'disp(file3);

s3 = [s3 'disp([mean(t3a) std(t3a) length(t3a)]);

s3 = [s3 'disp(''Stats: [mean std samples]'');

s3 = [s3 'disp(''for total:'');

s3 = [s3 'disp([mean(ttot) std(ttot) length(ttot)]);

s3 = [s3 'disp(''Print Stats'','callback',s3)];

s3 = [s3 ''];

s3 = [s3 'hr1 = input(''Enter start time, [hours minutes seconds]: '');''

s3 = [s3 'hr2 = input(''Enter stop time, [hours minutes seconds]: '');''

s3 = [s3 'uicontrol(''Units',''normal',''Position', [.54 0 .12 .06],''String',''New Range',''callback',s3);

s3 = [s3 ''];
s3 = 'a = find(t1<-100); t1(a)=[];';
s3 = [s3 'x1(a)=[];'];
s3 = [s3 'y1(a)=[];'];
s3 = [s3 'a = find(t2<-100); t2(a)=[];'];
s3 = [s3 'x2(a)=[];'];
s3 = [s3 'a = find(t3<-100); t3(a)=[];'];
s3 = [s3 'x3(a)=[];'];
uicontrol('Units','normal','Position',[.9 0 .1 .06],'String','De-Spike','callback',s3);
7.3 Photoshop® analysis method

Photoshop® 3.0 optimized for a PowerPC Macintosh was used for image analysis. A Power Mac 7100/80 was used for the task. The Scion LG-3 framegrabber used in the VDAC system used above was used to grab frames of the video data. The Scion Image program shipped with the LG-3 framegrabber allowed single frame grabbing. Two frames for each tilt angle were grabbed. Care was taken to take images toward the end of the trials and far between blinks to allow an torsional transients to die away.

The images were imported into Photoshop® one at a time. Each image underwent the following sequence of processing.

7.3.1 Cropping

The cropping tool was used to select only the area including the entire iris.
7.3.2 Unsharp mask filtering

A variety of different filters may be used to enhance features in the iris for easier identification. Edge detection algorithms are commonly used, however, I personally liked the results of the unsharp masking. This filter is in the "Sharpen" submenu of the "Filter" menu. This filter essentially subtracts out the low frequency information from the picture. The settings that I used were, Amount = 500%, pixel radius 10, and a threshold of 0.

7.3.3 Increase image resolution

The image resolution was increased so that "finer" lines could be drawn and rotated for comparison. Choose the "Image Size" item from the "Image" menu. I increased the resolution from 72 dpi to 120 dpi. The choice was arbitrary, but was convenient for navigating around the image when enlarged. A larger resolution could also have been used for a little more accuracy, however the inherent noise in the images must be considered when increasing the resolution too much; speed and ease of scrolling decrease with very large images.

7.3.4 Pupil center location

The selection tool can be set to either a rectangle or an ellipse. I chose an ellipse and used it to help define the boundaries of the pupil. The ellipse was fit around the pupil using three points on the pupil edge. The points chosen were the width and height maxima (there are two for each, so I picked one or the other from each), and an arbitrary point depending on the subject.
The center of the selection ellipse could then easily be identified and marked with cross-hairs. The center was thus located.

7.3.5 Landmark identification

I chose at least three landmarks in each of the 0° baseline images for comparison so that if one or another was not present in the trial images for whatever reason (noise, occlusion, etc...) there were other landmarks to use. On the baseline image, a second image layer was made. On this layer, arrows were drawn from the center of the
pupil to the landmarks. These arrows were copied to the clipboard. On the trial images, the arrows were drawn on the image to the landmarks as before. The arrows from the baseline image were then taken from the clipboard and placed on top of the trial images.

7.3.6 Arrow vector alignment

While leaving the baseline vectors selected, the arbitrary rotation function was applied. A requester allowed exact numerical rotation values to be entered.

Rotation of different amounts (using steps of .1°) were tried until the vectors would line up as well as possible. This rotation angle corresponded to the torsion angle for a given trial.