An Agenda for Sensorimotor Research in Sub-Orbital Flight

Faisal Karmali, Harvard/MEEI
Mark Shelhamer, Johns Hopkins

Supported by: NSBRI, NIH, NSERC (Canada)
Special thanks: Ondrej Juhasz, Michelle Zwernemann, John Yaniec, Noel Skinner and our research subjects
How can we:

- Make sub-orbital flight more safe?
- Make sub-orbital flight more enjoyable?
- Benefit humans on Earth through sub-orbital flight experiments?
Sensorimotor disruptions

- Autonomic
  - Motion Sickness
  - Orthostatic intolerance

- Eye movements
  - Vestibulo-ocular reflex
    - Pitch
    - Roll
    - Torsional
    - Vertical
  - Eye alignment
    - Nystagmus
    - Saccade accuracy
  - Gait
    - Head-body-eye coordination
  - Manual joystick control
  - Inversion illusion

- Postural stability
- Motor coordination
- Orientation illusions

- Eye alignment
- Saccade accuracy
- Gait
- Manual joystick control

- Eye movements
- Vestibulo-ocular reflex
- Pitch
- Roll
- Torsional
- Vertical

- Vision-related motor control
- Motor coordination
- Orientation illusions

- Sensorimotor coordination
- Postural stability
- Manual joystick control

- Orientation illusions
- Motor coordination
- Head-body-eye coordination

- Sensorimotor disruptions
- Motion Sickness
- Orthostatic intolerance

- Eye movements
- Vestibulo-ocular reflex
- Pitch
- Roll
- Torsional
- Vertical

- Sensorimotor system
- Autonomic
- Eye movements
- Postural stability
- Motor coordination
- Orientation illusions
## Goals

<table>
<thead>
<tr>
<th>Sub-orbital passengers</th>
<th>Sub-orbital pilots</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Maximize enjoyment (maximize corporate revenue via customer referrals)</td>
<td>• Safely pilot the aircraft during both nominal and emergency situations Without interference from sensorimotor disruption</td>
</tr>
<tr>
<td>• Accomplish research tasks</td>
<td></td>
</tr>
</tbody>
</table>

**Sub-orbital passengers**

- Maximize enjoyment (maximize corporate revenue via customer referrals)
- Accomplish research tasks

**Sub-orbital pilots**

- Safely pilot the aircraft during both nominal and emergency situations Without interference from sensorimotor disruption
# Overcoming sensorimotor disruptions

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Orbital flight</th>
<th>Sub-orbital passengers</th>
<th>Sub-orbital pilots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptation</td>
<td>*****</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Re-adaptation</td>
<td>**</td>
<td>*</td>
<td>*****</td>
</tr>
<tr>
<td>Pre-adaptation</td>
<td>***</td>
<td>****</td>
<td>**</td>
</tr>
<tr>
<td>Pharmaceutical</td>
<td>***</td>
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<td>**</td>
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<tr>
<td>Cognitive training</td>
<td>*****</td>
<td>****</td>
<td>***</td>
</tr>
</tbody>
</table>
How quickly do we adapt?

Difference between 0 g and 1.8 g in pitch vestibuloocular reflex gain (deg/deg)
# Recommendations

<table>
<thead>
<tr>
<th>Operators</th>
<th>Researchers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use pre-adaptation in parabolic flight for sub-orbital passengers</td>
<td>Study the effectiveness of parabolic flight as a tool to pre-adapt sub-orbital passengers</td>
</tr>
<tr>
<td>Emphasize recency of experience for sub-orbital pilots</td>
<td>Find sensorimotor symptoms caused by the unique sub-orbital flight trajectory, and ways to mitigate them</td>
</tr>
<tr>
<td>Develop and conduct a neurological examination for sub-orbital pilots</td>
<td>Study the correlation between sensorimotor disruption and pilot performance and appropriate countermeasures.</td>
</tr>
<tr>
<td>Consider screening of passengers for latent and undiagnosed neurovestibular problems before sub-orbital flight</td>
<td></td>
</tr>
</tbody>
</table>

*Recommendations for operators and researchers regarding pre-adaptation and health screening for sub-orbital flights.*
<table>
<thead>
<tr>
<th>Adaptation</th>
<th>Seconds - Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Research Goals

<table>
<thead>
<tr>
<th>Sub-orbital passengers</th>
<th>Sub-orbital pilots</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Allow passengers to fully focus on the flight experience without distraction of sensorimotor disruption</td>
<td>• Ensure that sensorimotor disruption does not interfere with the ability to pilot the aircraft during both nominal and emergency situations</td>
</tr>
<tr>
<td>• Allow passengers to complete a set of personal tasks within a short period of time, such as movement in 0 g, flips, looking out the window, and interacting with other passengers</td>
<td>• Quantify re-adaptation capability by study the effect of gaps in sub-orbital exposure on functional neurological tests and actual flight performance metrics</td>
</tr>
<tr>
<td>• Allow scientist-passengers to complete scientific tasks quickly and accurately</td>
<td></td>
</tr>
<tr>
<td>• Consider any interactions between flight phases specific to sub-orbital flight</td>
<td></td>
</tr>
</tbody>
</table>
Adaptation of otolith-ocular responses to parabolic flight

Faisal Karmali, Ondrej Juhasz, Michelle Zwernemann, Mark Shelhamer

Presented by:
Faisal Karmali
Research Fellow
JVPL / MEEI / HMS

October 14, 2008

Supported by: NSBRI, NIH, NSERC (Canada)
Take-home points

- In parabolic flight, certain otolith-dependent ocular responses improve over the course of 3 days of flying.

- Pilots (non-parabolic) had similar responses to experienced parabolic fliers, suggesting that certain experiences can prepare one for parabolic flight.

- Adaptation of otolith-dependent pitch responses transfers to otolith-dependent translation responses.
Naïve subjects had significantly different results compared to both pilots and experienced subjects on day 1 \((p<0.04)\), but not subsequent days.
Gain of pitch vestibuloocular reflex (deg/deg; ideal gain is 1.0)

Naive subjects (n=3)
Pilot subjects (n=2)
Experienced parabolic flyers (n=4)
Take-home points

- In parabolic flight, certain otolith-dependent neurological responses improve over the course of 3 days of flying.

- Pilots (non-parabolic) had similar responses to experienced parabolic fliers, suggesting that certain experiences can prepare one for parabolic flight.

- Adaptation of otolith-dependent pitch responses transfers to otolith-dependent translation responses.
Measuring static eye position

- OCR
- Torsional alignment
- Vertical alignment

- Nikon D70 digital camera
- Subjects’ head upright/tilted
Measuring pitch VOR gain

- Active sine-like head movements
  - 0.3-1.6 Hz. Results based on 0.6-1.3 Hz
  - 20-30º
  - 40-90º/sec

- Fixating stationary point in the light.

- Eye movements were recorded using a head-mounted video system (Chronos).

- Gain computed by least-squares fitting of eye velocity to head velocity, for each cycle of motion.
Adventures in weightlessness:

Adaptation of otolith-dependent ocular responses to parabolic flight

Faisal Karmali, Ondrej Juhasz, Michelle Zwernemann, Mark Shelhamer

Presented by:
Faisal Karmali
Research Fellow
JVPL / MEEI / HMS

MEEI Vestibular Seminar
March 24, 2008
The bottom line...

1. Parabolic flight consists of specific flight trajectories that provide periods of 0 g and 1.8 g.

2. Subjects experience sensorimotor disruption when initially exposed to parabolic flight, specifically in the pitch vestibuloocular reflex and torsional alignment.

3. Over the course of three days in parabolic flight, responses became appropriate in 0 g, 1 g and 1.8 g.

4. Responses in 1 g were not affected by adaptation in 0 g and 1.8 g, suggesting context-specific adaptation (rather than generalized sensory rearrangement).
Outline

- Background: Parabolic flight
- Background: Science
- Methods: Recording eye position
- Results
- Conclusions
Background
Parabolic Flight
Mercury astronauts training aboard a C-131B (1959)
- Play movie: C:\Faisal\kc-135\Skew\KC135_March2002_Day3_MarkFaisal.avi
- Play movie: C:\Faisal\kc-135\Pictures\Aug2006\walkingupsidedown.mov
$g = gia = \text{gravitoinertial acceleration} \Rightarrow \text{the occupants’ perceptions of gravity}$
• Play movie:
c:\Faisal\kc-135\Pictures\Apr2006\HPIM2161.MPG
It is not zero gravity!

- In parabolic flight, the plane accelerates downwards to match gravity, so the net force is zero.
- Even in orbit, there is still gravity (~9.37 m/s² at 300 km)

**Preferred terms**

- freefall
- weightlessness
- microgravity
- zero gravity
- zero g
- gravitoinertial acceleration (gia)

**Less correct**
Why doesn’t everybody fall to the front of the plane?

Aircraft g level (gravito-inertial acceleration) during two parabolas (aircraft coordinates)

- 350 KT IAS, Mach 0.83
- 510 KT TAS, 24000 ft

- 225 KT IAS, Mach 0.61
- 360 KT TAS, 45° nose up

- MAX UPWARD VELOCITY
- 140 KT IAS, Mach 0.43
- 245 KT TAS, 34000 ft

- BELOW UNACCELERATED STALL SPEED

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Altitude</th>
<th>Vertical g level (g)</th>
<th>Longitudinal g level (g)</th>
<th>Lateral g level (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Rotational dynamics

- The aircraft is rotating through 90° every 30 seconds

<table>
<thead>
<tr>
<th>Angular velocity</th>
<th>Centripetal acceleration of 0.006 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>of 3 °/s</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular acceleration of 2 °/s² during transitions between 0 g and 1.8 g</th>
<th>Tangential acceleration of 0.07 g</th>
</tr>
</thead>
</table>

- Our paper claims these are “barely at the threshold of detection” of the semicircular canals!

Karmali F, Shelhamer M. *The dynamics of parabolic flight: flight characteristics and passenger percepts.* Acta Astronautica (In press)
Otolith stimulation
Why they call it the “Vomit Comet”

- Approximately 40-60% of participants get sick on their first flight. The next day, most are fine.

- A sensorimotor rearrangement has occurred. This learning is retained for months.

- We want to improve our understanding of these adaptive processes.

- Studied a range of sensorimotor responses at different neural levels: brainstem through to perceptual
  - based on design MVL Spacelab experiments
Background
Vestibular-Ocular Reflexes

- **Otolith organs** measure linear acceleration and gravity (contains utricle and saccule)
- **Semicircular canals (SCC)** measure angular velocity

- Eye movements opposite of head movements
- **Conjugate**: eyes move together
- **Disconjugate**: difference between left and right eyes

VOR gain = Eye velocity / head velocity
Eye movements and otolith organs

- Eye misalignments occur in parabolic flight and whole-body pitch rotation – otolith implicated (Markham, Diamond, Karmali)

- Ocular counterroll is reduced after space flight (Clarke 2000, Moore 2003, Vogel 1986).

- Pitch VOR still exists when canals deactivated (Angelaki)

- Otolith-dependent misalignments can be adapted with static head positioning using a visual-vestibular mismatch (Schor)
Hypotheses

1. Context-specific adaptation: learning a set of specific responses that is calibrated for each g level.
   - Example: initially inappropriate otolith-driven responses, which eventually become appropriate (correctly calibrated) in each g level.

2. Generalized adaptation: learning a set of general responses, each of which is simultaneously appropriate for multiple g levels.
   - Example: gradual decrease in otolith-driven responses, reflecting overall lack of reliability of otolith information as g level varies.
Experimental design

- Three consecutive days of flying per subject
- Responses tested:
  - Pre-parabolas
  - Early
  - Late
  - Post-parabolas
- 14 subjects: 5 experienced, 6 naïve, 3 pilots
- Measurements:
  - torsional alignment
  - ocular counterroll
  - vertical alignment
  - pitch VOR gain – active & passive
  - Also tried linear VOR, SVV, SPV
- No medication for motion sickness
## Experimental design

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-parabolas</td>
<td>Pre-parabolas</td>
<td>Pre-parabolas</td>
</tr>
<tr>
<td>Early (first 10 parabolas)</td>
<td>Early (first 10 parabolas)</td>
<td>Early (first 10 parabolas)</td>
</tr>
<tr>
<td>Late (last 10 parabolas)</td>
<td>Late (last 10 parabolas)</td>
<td>Late (last 10 parabolas)</td>
</tr>
<tr>
<td>Post-parabolas</td>
<td>Post-parabolas</td>
<td>Post-parabolas</td>
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Measuring pitch VOR gain

- Active sine-like head movements
  - 0.3-1.6 Hz. Results based on 0.6-1.3 Hz
  - 20-30°
  - 40-90°/sec

- Fixating stationary point in the light.

- Eye movements were recorded using a head-mounted video system (Chronos).

- Gain computed by least-squares fitting of eye velocity to head velocity, for each cycle of motion.
Measuring static eye position

- OCR
- Torsional alignment
- Vertical alignment

- Nikon D70 digital camera
- Subjects’ head upright/tilted
Results

- Torsional alignment instability
- Ocular counterroll (response to head tilt)
- Active pitch VOR
Naïve subjects had significantly different results compared to both pilots and experienced subjects on day 1 ($p<0.04$), but not subsequent days.
Instability of torsional alignment (deg)

Motion sickness score

- Naive subjects (n=6)
- Pilots subjects (n=3)
- Experienced subjects (n=4)
Conjugate torsional eye position (+CW; degrees) vs. g level.

- Black line: Naive subjects (n=6)
- Blue line: Pilots subjects (n=3)
- Red line: Experienced subjects (n=4)
Eye & head position

VOR Gain

g level

1.8 g  0 g
Day 1
Early

Gain of pitch vestibuloocular reflex (deg/deg; ideal gain is 1.0)

- Naive subjects (n=3)
- Pilot subjects (n=2)
- Experienced parabolic flyers (n=4)
Gain of pitch vestibuloocular reflex (deg/deg; ideal gain is 1.0)

Day 1
Late

Naive subjects (n=3)
Pilot subjects (n=2)
Day 3

Gain of pitch vestibuloocular reflex (deg/deg; ideal gain is 1.0)

- Naive subjects (n=3)
- Pilot subjects (n=2)
Conclusions

- All responses showed a g-level dependence early in flight, which decreased with experience.

- Rate of adaptation varied between reflexes: torsional disconjugacy is fastest, then pitch VOR, then ocular counterroll.
  - Torsional alignment instability rapidly reduced upon exposure to parabolic flight, and adaptation is retained between flights. The relatively rapid adaptation may be because errors in torsional alignment have greater functional offsets than conjugate changes in torsional eye position and changes in the pitch VOR.
  - Pitch VOR gain initially dropped in 0 g and increased in 1.8 g, consistent with an otolith contribution. Difference between g levels decreased with experience and eventually disappeared, showing that the different otolith contributions in the different g levels are correctly processed after adaptation.
  - Ocular counterroll is initially larger in 1.8 g and smaller in 0 g. Differences between g levels do not change within 3 days, although pilots show more appropriate responses in 1 g. An explanation for this slow adaptation may be that a well-tuned OCR gain is not critical; it is not compensatory in normal circumstances.
  - None of the mechanisms show a change in response to 1 g after exposure to parabolic flight. This suggests that adaptation is context specific.

- Upon adaptation, torsion, torsional alignment and pitch VOR are correctly calibrated in each g level, supporting the hypothesis of a context-specific adaptation of each response.
Acknowledgements

- Advisor: Dr. Mark Shelhamer
- Undergraduate researchers: Ondrej Juhasz, Michelle Zwernemann, Anton Aboukhalil
- Technical assistance: Adrian Lasker, Dale Roberts, Dr. Andy Clarke
- NASA staff: Noel Skinner, John Yaniec
- Scientific advise: Dr. Mark Walker, Dr. Howard Ying, SPH Biostats Clinic
- Moral support: Zee lab, friends & family
- Funding: NSBRI, NIH, NSERC
- Compare t-test significance of day 1 vs day 3 naïve
- Change bar graphs to std err instead of std
- Review adapt. Spaceflight
- See MJS PPT
- Inc cool videos
- ~45 slides
Otolith ambiguity – same sensor transduces tilt and translation of head

Transduced signal during tilt differs dramatically in weightlessness / high g environments, and changes in otolith-dependent reflexes occur

Designing a countermeasure to speed adaptation or pre-adapt reflexes could reduce adverse problems during space missions, return to Earth or visiting other celestial bodies

Characterizing the adaptive characteristics of otolith-dependent reflexes and the relationship between adaptation of translation and tilt important for the design of countermeasures

To learn more about these pathways, we studied the vestibulo-ocular reflex

Specifically interested in the pitch VOR, because this is the most common type of head movement in which the otolith organs transduce a changing direction of gravity

During pitch head movements, three (or more) sensory signals available: otolith-transduced head position; SCC-transduced head velocity; eye position

Goals:
- to adapt VOR and show that adaptation is otolith-organ dependent
- Show that adaptation of VOR transfers from tilt to translation
- Characterize how the brain processes otolith organ information using the characteristics of the transfer of adaptation

With pitch head movements, during translation and tilt, the compensatory eye movement is vertical. Makes it impossible to distinguish adaptation that is dependent on eye- vs. head- motion-dependent adaptation. Using vertical eye misalignment allows dependency on velocity and position to be better discriminated.

Methods
- How to adapt VOR / eye misalignment?

Results / Discussion

Conclusions
- The evidence that Cartesian components of the g vector are used as adaptive cues is important because it suggests that countermeasures on Earth can adapt some responses without changing the magnitude of the g vector. That means adaptation of otolith-dependent reflexes could occur in a 1 g field, which allows longer, cheaper adaptation sessions than jet or parabolic flight.
Transfer of oculomotor adaptation between otolith-dependent tilt and translation reflexes

Faisal Karmali
Post-doctoral fellow
JVPL / MEEI / HMS

MVL, MIT
November 14, 2007
The bottom line...

1. A vertical misalignment between the eyes can be adapted that is dependent on otolith-transduced head tilt during pitch head rotation using a visual-vestibular mismatch

2. Modification of the response to otolith-transduced head tilt also modifies the response to vertical translation

3. Modeling shows that for adaptation, the brain processes the g vector as Cartesian components, rather than in polar coordinates
Background
Vestibular-Ocular Reflexes

- **Otolith organs** measure linear acceleration and gravity (contains **utricle** and **saccule**)
- **Semicircular canals (SCC)** measure angular velocity

- **Eye movements opposite of head movements**
- **Conjugate**: eyes move together
- **Disconjugate**: difference between left and right eyes

\[
\text{VOR gain} = \frac{\text{Eye velocity}}{\text{head velocity}}
\]
Eye movements and otolith organs

- Eye misalignments occur in parabolic flight and whole-body pitch rotation – otolith implicated (Markham, Diamond, Karmali)

- Amount of misalignment decreases with experience in parabolic flight – shows adaptation of pathway occurs

- Pitch VOR gain changes with g level – otolith implicated

- Pitch VOR still exists when canals deactivated (Angelaki)

- Otolith-dependent misalignments can be adapted with static head positioning using a visual-vestibular mismatch (Schor)
Previous studies of transfer between translation and rotation

- Yaw adaptation affects interaural translation response (Koizuka et al.)
- Interaural adaptation affects yaw response (Koizuka et al.)
- Yaw adaptation affects response to constant-velocity pitch rotation (Petropoulos, Wall III, Oman)

These studies suggest adaptation of a pathway common to the SCC and otolith reflexes

In contrast, we find adaptation specific to the otolith pathway
Pitch VOR gain is dependent on g level in parabolic flight

Day 1, early

Day 1, late

Gain of pitch vestibular reflex (deg/deg; ideal gain is 1.0)

- Naive subjects (n=3)
- Pilot subjects (n=2)
- Experienced parabolic flyers (n=4)
Experimental Design
Aims

1. Show that a misalignment between the eyes can be adapted that it dependent on otolith-transduced tilt during dynamic pitch rotation using a visual-vestibular mismatch

2. Determine if modification of the response to otolith-transduced head tilt also modifies the response to vertical translation

3. Develop a model to understand how the brain processes otolith information during adaptation of otolith-ocular responses
Motion profiles

Active pitch rotation

Vertical sled translation

Time (seconds)
## Sensory environment during motion profiles

<table>
<thead>
<tr>
<th>Sensory receptor</th>
<th>Active pitch rotation</th>
<th>Vertical translation</th>
<th>Linear acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otolith organs</td>
<td>Changing orientation relative to gravity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semicircular canals (SCC)</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Orbital eye position</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Collic (neck) reflex</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
## Sensory environment during motion profiles

<table>
<thead>
<tr>
<th>Sensory receptor</th>
<th>Passive pitch rotation (full body)</th>
<th>Active pitch rotation</th>
<th>Vertical translation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otolith organs</td>
<td>Changing orientation relative to gravity</td>
<td>Changing orientation relative to gravity</td>
<td>Linear acceleration</td>
</tr>
<tr>
<td>Semicircular canals (SCC)</td>
<td>Only before vestibular time constant exceeded</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Orbital eye position</td>
<td>Yes, due to counterpitch response</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Collic (neck) reflex</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cognitive intent</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cognitive anticipation</td>
<td>Some situations</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Study procedures

The *pitch plasticity study*

**Pre-test Pitch (monocular targets)** ➔ **Adapt Pitch (20 min)** ➔ **Post-test Pitch (monocular targets)**

The *vertical translate study*

**Pre-test Vertical (monocular target)** ➔ **Pre-test Pitch (monocular target)** ➔ **Adapt Pitch (15 min)** ➔ **Post-test Pitch (monocular target)** ➔ **Adapt Pitch (5 min)** ➔ **Post-test vertical (monocular target)**
Scleral contact lens coils

- Coil frame in a cube that consists of three orthogonal magnetic fields oscillating at different frequencies
- Coil acts as antenna that picks up a linear combination of the three that depends on its orientation
- Accuracy <0.01°
- Wire is fragile, and often breaks
- Small coil frame used on vertical sled – data for pitch not usable during the *vertical translate study*
Generalized Estimating Equations

- $t$-test is often used to compare time-series data in two different conditions.

- $t$-test assumes independence between measures, which is not usually the case with rapidly-changing, sampled data such as eye position.

- GEE is a more correct and stringent technique that takes into account the correlation of the data with itself.

- $t$-test will sometimes indicate significance when GEE does not.


Pitch plasticity study

- Goal: understand the nature of central compensation
- Study the ability of the brain to learn an otolith organ-dependent misalignment during dynamic head movements
- Subject performs active pitch rotation
- Induced a vertical misalignment of the eye by presenting a visual disparity between the left and right eyes
- Subject wears red-blue glasses
- Real-time head position is fed to laptop which projects a field of dots onto a screen
- The dots have a vertical disparity between left and right eyes
- Regular & eye-head dissociation paradigms
Pitch plasticity study

Pre-adaptation

Post-adaptation

Head position (degrees; + up)

Vertical eye positions (degrees; + up)

Vertical misalignment (degrees; right-left; + up)

Misalignment gain

Time (seconds)

-20
0
20

-40
-20
0
20

-1
0
1
2
3

-1
0
1

-0.1
0
0.1

-1
0
1

-0.1
0
0.1

95 100 105 110 115 120
1645 1650 1655 1660 1665 1670
1645 1650 1655 1660 1665 1670
1645 1650 1655 1660 1665 1670
95 100 105 110 115 120
95 100 105 110 115 120
1645 1650 1655 1660 1665 1670
1645 1650 1655 1660 1665 1670

Misalignment vs. head position for three target positions (subject J)

Vertical misalignment (degrees; right-left; + up)

Head position (degrees; + up)

Post-adaptation

Pre-adaptation
Vertical misalignment (degrees; right-left; + up)

Head position (degrees; + up)
Eye position (deg; + down)

Subject H
Subject H
Subject H
Subject H

Subject J
Subject J
Subject J
Subject J

Subject L
Subject L
Subject L
Subject L

Subject M
Subject M
Subject M
Subject M

Subject B
Subject B
Subject B
Subject B

Subject Y
Subject Y
Subject Y
Subject Y

Subject B*
Subject B*
Subject B*
Subject B*
Position-dependent misalignment increased in most experiments

Coefficient of change in position-dependent misalignment from pre to post (deg/deg)

** p<0.01; GEE

* eye-head dissociation paradigm
Ideal results demonstrating **head** position-dependent adaptation

![Graph showing head position-dependent adaptation](image)

Ideal results demonstrating **eye** position-dependent adaptation

![Graph showing eye position-dependent adaptation](image)
Example: misalignment dependent on head position

Misalignment vs. head position for three target positions (subject H)

Vertical misalignment (degrees; right-left; + up)

Head position (degrees; + up)

Misalignment vs. eye position for three target positions (subject H)

Vertical misalignment (degrees; right-left; + up)

Eye position (degrees; + down)

index of head-position-dependent adaptation = \frac{MS_{\text{eye}} - MS_{\text{head}}}{MS_{\text{eye}} + MS_{\text{head}}}

Example: misalignment partly dependent on eye position

Misalignment vs. head position for three target positions (subject H)

Misalignment vs. eye position for three target positions (subject H)
Is adaptation dependent on eye or head?

- Compare mean sum-of-squares of regression for misalignment on eye, and misalignment on head

Subject exhibits head-position-dependent adaptation

Subject exhibits eye-position-dependent adaptation
Pitch plasticity study – summary

- Position-dependent misalignments were adapted in all subjects

- Head position was implicated as the adaptation cue in most subjects

- Otolith organs or SCC could be driving adaptation

- In the next study, we performed the same adaptation and also tested in *vertical translation*, which stimulated the otolith organs but not the SCC
Vertical translate study

- Pre-test Vertical (monocular target)
- Pre-test Pitch (monocular target)
- Adapt Pitch (15 min)
- Post-test Pitch (monocular target)
- Adapt Pitch (5 min)
- Post-test vertical (monocular target)
0.95 Hertz

±0.7 g peak acceleration
Response to vertical translation

Pre-adaptation response (subject J)

Post-adaptation response (subject J)
Sensitivity to vertical translation increases after adaptation of pitch response

- Increase in sensitivity increases for 4 of 5 subjects
- Change statistically significant in all subjects (GEE)
Sensitivity to vertical translation increases after adaptation of pitch response.
Vertical translate study – summary

- Head-position-dependent adaptation of misalignment during pitch rotation was otolith organ dependent

- Adaptation transferred from otolith-dependent tilt response to otolith-dependent translation response

- Misalignment is a tool to study the otolith-ocular pathway: it allows questions to be asked about tilt/translation which are difficult to answer using conjugate eye movements
What model of otolith organ information processing explains the transfer of adaptation from *pitch* to *vertical translation*?

Polar coordinates

Cartesian components
Pitch Plasticity Study

Misalignment predicted by

\[ \text{Cartesian NO only} \]
\[ \text{Cartesian NO and VT (non-optimal)} \]
\[ \text{Cartesian (single knob)} \]

Vertical Translate Study

Misalignment predicted by

\[ \text{Cartesian NO only} \]
\[ \text{Cartesian NO and VT (non-optimal)} \]
\[ \text{Cartesian (single knob)} \]
Modeling – summary

- Otolith organ information is processed in Cartesian components
- Adaptation affects all g vector components equally
Conclusions

- Otolith-dependent eye misalignments can be adaptively created during dynamic pitch rotation using a visual-vestibular mismatch

- Adaptation transfers from otolith-transduced tilt responses to translation responses

- Components of the g vector are used to determine the ocular response; adaptation affects all components equally
Application to countermeasures

- Adapting otolith reflexes during weightlessness is expensive and of a short duration

- Countermeasures can focus on adapting responses of individual Cartesian components

- When appropriate g vector cannot be provided using translation, it can be provided using tilt
Future work

- Test for transfer when adapted Cartesian components are the same

- The relationship between head position and misalignment in the adaptive paradigm was linear – a parabolic relationship would separate otolith and SCC contributions

- Transfer of adaptation from vertical translation to pitch rotation
## Future work

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<td>rotation axis</td>
<td>g vector components stimulated</td>
<td>rotation axis</td>
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<td>Pitch upright</td>
<td>VT &amp; NO</td>
<td>Roll onside</td>
</tr>
<tr>
<td>Roll upright</td>
<td>VT &amp; IA</td>
<td>Pitch supine</td>
</tr>
<tr>
<td>Yaw supine</td>
<td>NO &amp; IA</td>
<td>Pitch upright</td>
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Acknowledgements

- Advisor: Dr. Mark Shelhamer
- Committee members: Drs. Paul Fuchs, David Solomon, David Zee, Kechen Zhang
- Technical assistance: Adrian Lasker, Dale Roberts, NASA staff, Dr. Andy Clarke
- Scientific advise: Dr. Mark Walker, Dr. Howard Ying, School of Public Health Biostats Clinic
- Funding: NSBRI, NIH, NSERC
Vertical eye misalignments during pitch rotation and vertical translation: Evidence for bilateral asymmetries and plasticity in the otolith-ocular reflex

Dr. Faisal Karmali
MEEI
September 10, 2007
Publications

- 12 conference abstracts
- Peer-reviewed publications


- Karmali F, Shelhamer M. *Compensating for camera translation in video eye movement recordings by tracking a landmark selected automatically by a genetic algorithm*. (submitted)

- Karmali F, Shelhamer M. *The dynamics of parabolic flight: flight characteristics and passenger percepts*. (submitted)


Background
The Vestibular System

- “Sixth sense” that keeps us balanced
- Stops us from falling when we stumble
- Helps move eyes (“gaze stabilization”)

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<th>Patients with Vestibular Disease or stroke</th>
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Vestibular-Ocular Reflexes

- **Otolith organs** measure linear acceleration and gravity (contains **utricle** and **saccule**)

- **Semicircular canals (SCC)** measure angular velocity

- **Eye movements opposite of head movements**

- **Torsion** is rotation of eye about the line of sight

- **Conjugate**: eyes move together

- **Disconjugate**: difference between left and right eyes
The otolith organ: a mass on a lever

Temporal bone of the head

The lever is a hair cell that measures deflection

The mass is called the otoconia and deflects when acted upon by external forces

g vector: the sum of linear acceleration and gravity

1 g of downward gravity is indistinguishable from 1 g of upward acceleration of the head
Vertical misalignments during parabolic flight

Otolith Asymmetry Hypothesis

Central Compensation

Left Eye

Right Eye

Left Otolith

Right Otolith

g vector
“Over 50% of utricular-activated, second-order vestibular neurons received commissural inhibition from the contralateral utricular nerve.”

“Almost all the saccular-activated, second-order vestibular neurons exhibit no response to stimulation of the contralateral saccular nerve.”

Uchino, 2004
Implications of otolith asymmetry

1. It can predict space sickness: a better understanding of the mechanisms may help to improve screening and produce simpler screening tests
2. It may reduce task performance by creating a sensory conflict or misaligning the eyes
3. Understanding how it adapts may be useful in training including partial adaptation before flight
Experimental Design
# Sensory environment during motion profiles

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<th>Motion profile</th>
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<tr>
<td><strong>Passive pitch rotation</strong> (full body)</td>
<td><strong>Active pitch rotation</strong></td>
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<tr>
<td>Otolith organs</td>
<td>Changing orientation relative to gravity</td>
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<td>Only before vestibular time constant exceeded</td>
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<td>Orbital eye position</td>
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<td>Linear acceleration</td>
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<td>Cognitive intent</td>
<td>No</td>
</tr>
<tr>
<td>Cognitive anticipation</td>
<td>Some situations</td>
</tr>
</tbody>
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The *pitch innate study*

- Slow test Pitch
- Medium test Pitch
- Fast test Pitch

The *pitch plasticity study*

- Pre-test Pitch (monocular targets)
- Adapt Pitch (20 min)
- Post-test Pitch (monocular targets)

The *vertical translate study*

- Pre-test Vertical (monocular target)
- Pre-test Pitch (monocular target)
- Adapt Pitch (15 min)
- Post-test Pitch (monocular target)
- Adapt Pitch (5 min)
- Post-test vertical (monocular target)
Scleral contact lens coils

- Coil frame in a cube that consists of three orthogonal magnetic fields oscillating at different frequencies
- Coil acts as antenna that picks up a linear combination of the three that depends on its orientation
- Accuracy <0.01°
- Wire is fragile, and often breaks
- Small coil frame used on vertical sled – data for pitch not usable during the *vertical translate study*
Generalized Estimating Equations

- $t$-test is often used to compare time-series data in two different conditions.
- $t$-test assumes independence between measures, which is not usually the case with rapidly-changing, sampled data such as eye position.
- GEE is a more correct and stringent technique that takes into account the correlation of the data with itself.
- $t$-test will sometimes indicate significance when GEE does not.

Pitch innate study
**Static alignment**

Subject A

Vertical misalignment (Degrees, right-left, +down)

- $0^\circ$ ($\tau$ = 3.26 s)
- $270^\circ$ ($\tau$ = 0.35 s)
- $180^\circ$ ($\tau$ = 0.00 s)
- $90^\circ$ ($\tau$ = 0.32 s)
- least-squares fit

Subject T

Vertical misalignment (Degrees, right-left, +down)

- $0^\circ$ ($\tau$ = 0.00 s)
- $270^\circ$ ($\tau$ = 0.00 s)
- $180^\circ$ ($\tau$ = 0.00 s)
- $90^\circ$ ($\tau$ = 0.00 s)
- least-squares fit

Subject S

Vertical misalignment (Degrees, right-left, +down)

- $0^\circ$ ($\tau$ = 0.43 s)
- $270^\circ$ ($\tau$ = 0.59 s)
- $180^\circ$ ($\tau$ = 0.91 s)
- $90^\circ$ ($\tau$ = 0.37 s)
- least-squares fit

Subject E

Vertical misalignment (Degrees, right-left, +down)

- $0^\circ$ ($\tau$ = 0.52 s)
- $270^\circ$ ($\tau$ = 0.50 s)
- $180^\circ$ ($\tau$ = 0.00 s)
- $90^\circ$ ($\tau$ = 0.00 s)
- least-squares fit

Subject Q

Vertical misalignment (Degrees, right-left, +down)

- $0^\circ$ ($\tau$ = 5.85 s)
- $270^\circ$ ($\tau$ = 1.26 s)
- $180^\circ$ ($\tau$ = 0.59 s)
- $90^\circ$ ($\tau$ = 0.42 s)
- least-squares fit
**Slow rotation – 6°/sec**

Vertical misalignment during slow pitch rotation (6 deg/sec)

- **Right eye**
- **Left eye**

Chair position (degrees)

- **Backward Rotation**
- **Forward Rotation**

Time

Slow rotation – 6°/sec
Medium rotation – 60º/sec

- Vertical eye positions (degrees, +down)
- Vertical misalignment (degrees, right-left, +down)
- Vertical misalignment (degrees, right-left, +down) vs Chair position (degrees)

Graphs showing eye movements and vertical misalignment with chair position over time.
Fast rotation – 2 second steps

Vertical eye positions (degrees, +down)
- Right eye
- Left eye
- Chair position (inverted)

Vertical misalignment (degrees, right-left, +down)
- Fixation target off
- Fixation target on

Vertical eye velocity (deg/s, +down)

Misalignment velocity (deg/s, right-left, +down)
Fast rotation – 2 second steps
Fast rotation – 2 second steps
Summary of vertical eye misalignments for static orientation and slow, medium and fast pitch rotations

Vertical misalignment (Degrees, right-left, +down)

Subject

- A
- E
- Q
- R
- S
- T

- Static orientation: misalignment differential
- Slow: peak vertical misalignment (forward)
- Slow: peak misalignment (backward)
- Medium: misalignment differential (forward)
- Medium: misalignment differential (backward)
- Fast: significance of orientation dependence - peak misalignment (forward)
- Fast: significance of orientation dependence - peak misalignment (backward)
- Fast: significance of orientation dependence - peak misalignment velocity (forward)
- Fast: significance of orientation dependence - peak misalignment velocity (backward)
**Pitch innate study - summary**

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Misalignment determined by</th>
<th>Average misalignment difference between upright &amp; upside-down</th>
<th>Number of significant subjects (p&lt;0.01; GEE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Orientation</td>
<td>0.99°</td>
<td>3/5</td>
</tr>
<tr>
<td>Slow</td>
<td>Orientation</td>
<td>1.74°</td>
<td>3/3</td>
</tr>
<tr>
<td>Medium</td>
<td>Orientation</td>
<td>0.39°</td>
<td>3/4</td>
</tr>
<tr>
<td>Fast</td>
<td>Angular velocity</td>
<td>1.86° (peak misalignment) (orientation significant in 1/5 subjects)</td>
<td></td>
</tr>
</tbody>
</table>

- Orientation-dependent misalignments implicate asymmetry in otolith pathway
- Velocity-dependent misalignments implicate SCC pathway

- Otolith asymmetry acts in both:
  - pitch rotation - g vector direction changing
  - vertical acceleration - g vector magnitude changing
Pitch plasticity study

- Goal: understand the nature of central compensation
- Study the ability of the brain to learn an otolith organ-dependent misalignment during dynamic head movements
- Subject performs active pitch rotation
- Induced a vertical misalignment of the eye by presenting a visual disparity between the left and right eyes
- Subject wears red-blue glasses
- Real-time head position is fed to laptop which projects a field of dots onto a screen
- The dots have a vertical disparity between left and right eyes
- *Regular & eye-head dissociation* paradigms
Pitch plasticity study

Pre-adaptation

- Head position (degrees; + up)
- Vertical eye positions (degrees; + up; Right eye and Left eye)
- Vertical misalignment (degrees; right-left; + up)
- Misalignment gain

Time (seconds)

Post-adaptation

- Head position (degrees; + up)
- Vertical eye positions (degrees; + up)
- Vertical misalignment (degrees; right-left; + up)
- Misalignment gain

Time (seconds)
Misalignment vs. head position for three target positions (subject J)

Vertical misalignment (degrees; right-left; + up)

Head position (degrees; + up)

Post-adaptation

Pre-adaptation
Position-dependent misalignment increased in most experiments.

** Coefficient of change in position-dependent misalignment from pre to post (deg/deg)

** p<0.01; GEE

* eye-head dissociation paradigm
Ideal results demonstrating **head** position-dependent adaptation

Ideal results demonstrating **eye** position-dependent adaptation
Example: misalignment dependent on head position

Misalignment vs. head position for three target positions (subject H)

- Vertical misalignment (degrees; right-left; + up)
- Head position (degrees; + up)

Misalignment vs. eye position for three target positions (subject H)

- Vertical misalignment (degrees; right-left; + up)
- Eye position (degrees; + down)

Index of head-position-dependent adaptation = $\frac{MS_{\text{eye}} - MS_{\text{head}}}{MS_{\text{eye}} + MS_{\text{head}}}$
Example: misalignment partly dependent on eye position

Misalignment vs. head position for three target positions (subject H)

Misalignment vs. eye position for three target positions (subject H)
Is adaptation dependent on eye or head?

- Compare mean sum-of-squares of regression from misalignment on eye and misalignment on head.
Position-dependent misalignments were adapted in all subjects.

Head position was implicated as the adaptation cue in most subjects.

Otolith organs or SCC could be driving adaptation.

In the next study, we performed this experiment and tested in *vertical translation*, which stimulated the otolith organs but not the SCC.
Vertical translate study

The *vertical translate study*

Pre-test Vertical (monocular target) → Pre-test Pitch (monocular target) → Adapt Pitch (15 min) → Post-test Pitch (monocular target) → Adapt Pitch (5 min) → Post-test vertical (monocular target)
Vertical sled movement characteristics

- **Vertical acceleration (m/s²)**
  - Upward
  - Downward

- **Vertical velocity (m/s)**

- **Vertical position (m)**

**Notes:**
- **0.95 Hertz**
- **±0.7 g peak acceleration**
Response to vertical translation

Pre-adaptation response (subject J)

Post-adaptation response (subject J)
Sensitivity to vertical translation increases after adaptation of pitch response

- Increase in sensitivity increases for 4 of 5 subjects
- Change statistically significant in all subjects (GEE)
Sensitivity to vertical translation increases after adaptation of pitch response.
Vertical translate study – summary

- Head-position-dependent adaptation of misalignment during pitch rotation was otolith organ dependent

- Adaptation transferred from otolith-dependent tilt response to otolith-dependent translation response

- Misalignment is a tool to study the otolith-ocular pathway: it allows questions to be asked about tilt/translation which are difficult to answer using conjugate eye movements
Modeling

- What is the nature of the central compensation?
- What model of otolith organ information processing explains the transfer of adaptation from pitch rotation to vertical translation?
Model overview

Additive
Multiplicative
Context-specific adaptation

Head tilt and translation

Sensorimotor processing

Central compensation

Eye plant

L_{comm} + L_{eye}

Left eye position

Vertical eye misalignment

Visual processing of misalignment

Right eye position

Sensorimotor processing

Left otolith organ

R_{comm} + R_{eye}

Right otolith organ

L_{aff}

R_{aff}

Commissure

-k

-k

L_{eye}

-k

-
Additive vs. Multiplicative Compensation

Otolith organ afferents

Neuronal firing rate

$R_{aff} = q * g$

$L_{aff} = g$

Pre-commissural additive

$R_{comm} = (q * g)$

$L_{comm} = g$

Pre-commissural multiplicative

$R_{comm} = (q * g - a)$

$L_{comm} = g$

Post-commissural additive

$R_{comm} = (q * g)$

$L_{comm} = g$

Post-commissural multiplicative

$R_{comm} = (q * g)$

$L_{comm} = g$

G level (g)

Pre-commissural neurons

No compensation

$R_{eye} = (q * g) - k * g$

$L_{eye} = g - k * (q * g)$

Pre-commissural additive

$R_{eye} = (q * g) - k * g$

$L_{eye} = g - k * (q * g)$

Post-commissural neurons

Pre-commissural multiplicative

$R_{eye} = (q * g - k) * g$

$L_{eye} = g - k * (q * g)$

Post-commissural additive

$R_{eye} = (q * g) - k * g$

$L_{eye} = g - k * (q * g)$

Post-commissural multiplicative

$R_{eye} = d * ((q * g) - k * g)$

$L_{eye} = g - k * (q * g)$
What model of otolith organ information processing explains the transfer of adaptation from *pitch* to *vertical translation*?
- Eye torsion with head tilted during change g level
- Torsion changes even though g vector direction does not change
- Suggests the g vector component determines torsion
Pitch Plasticity Study

Head pitch angle (degrees)

g vector components (g = 9.81 m/s/s)

Misalignment predicted by g vector model

Misalignment predicted by g vector model (non-optimal)

Misalignment predicted by g vector components model

Vertical Translate Study

g vector components model

Time (seconds)
Modeling – summary

- Context-specific adaptation is a likely candidate for central compensation
- Otolith organ information is processed in g vector components
- Adaptation affects all g vector components equally
Conclusions

- Vertical eye misalignments that are dependent on the otolith organs occur during pitch rotation.
- Vertical eye misalignments that are dependent on the SCC occur during fast pitch rotation.
- Otolith-dependent misalignments can be adaptively created during dynamic pitch rotation using a visual-vestibular mismatch.
- Context-specific adaptation is a likely candidate for central compensation.
- Components of the g vector are used to determine the ocular response; adaptation affects all components equally.
Implications

- Understanding central compensation in the otolith-ocular pathway can improve the design of adaptation regiments for both astronauts and patients.
- Understanding how otolith information is used by the brain can guide the selection of motion profiles used for adaptation paradigms.
- The ability to measure innate misalignments using pitch rotation may help in assessing risks during spaceflight.
Future work

- Model a SCC asymmetry by having canal planes that are slightly different in the left and right ear
- The relationship between head position and misalignment in the adaptive paradigm was linear – a parabolic relationship would help to separate otolith and SCC contributions
- In fast rotation, SCC-dependent misalignments were implicated – further investigation is required
- Transfer of adaptation from vertical translation to pitch rotation
- Transfer of adaptation between otolith-dependent tilt and translation with conjugate eye movements
Future work

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| Pitch upright                     | Roll onside       | Yaw onside        |
| VT & NO                           | VT (&IA)          | NO (&IA)          |
| Roll upright                      | Pitch supine      | Yaw supine        |
| VT & IA                           | VT (&NO)          | IA (&NO)          |
| Yaw supine                        | Pitch upright     | Roll upright      |
| NO & IA                           | NO (&VT)          | IA (&VT)          |
Acknowledgements

- Advisor: Dr. Mark Shelhamer
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- Collaborators: Dr. Stefano Ramat, Dr. Dominik Straumann, Zurich University Hospital students & staff
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- Undergraduate researchers: Ondrej Juhasz, Anton Aboukhalil, Tiffany Chen, Michelle Zwernemann
- Moral support: Zee lab, friends & family
- Funding: NSBRI, NIH, NSERC
Control of motion and posture
The Vestibular System

- “Sixth sense” that keeps us balanced
- Stops us from falling when we stumble
- Helps move eyes (“gaze stabilization”)

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- Studying astronauts will help us cure people on the ground
Background & Significance

- Astronauts and others exposed to unusual acceleration environments get sick.
- Torsional misalignment found in parabolic flight and may be due to otolith asymmetry.
- Motion sickness correlated with torsional misalignment.
- Motion sickness correlated with an otolith mass asymmetry in fish.
- In pitch head movements, the otoliths detect a changing g vector and contribute to eye movements.
Vestibular-Ocular Reflexes

- **Otoliths** measure linear acceleration and gravity (contains utricle and saccule)
- **Semicircular canals (SCC)** measure angular velocity

- Eye movements opposite of head movements
- **Torsion** is rotation of eye about the line of sight
- **Conjugate**: eyes move together
- **Disconjugate**: difference between left and right eyes

Eye misalignment between L and R eye position

Visual disparity between what is seen by L and R eye
The otoliths: a mass on a lever

The lever is a hair cell that measures deflection.

The mass is called the otoconia and deflects when acted upon by external forces.

Temporal bone of the head

Gravito-inertial acceleration (g level): the sum of linear acceleration and gravity. 1 g of downward gravity is indistinguishable from 1 g of upward acceleration of the head.
Otolith Asymmetry Hypothesis

Central Compensation

Left Eye

Left Otolith

Right Otolith

Right Eye

g level (GIA)
Implications of otolith asymmetry

1. It can predict space sickness: a better understanding of the mechanisms may help to improve screening and produce simpler screening tests
2. It may reduce performance by misaligning the eyes
3. Understanding how it adapts may be useful in training including partial adaptation before flight
Hypotheses

- An otolith asymmetry will manifest as ocular misalignments when the magnitude and orientation of the g vector is unusual.
- An otolith asymmetry will imbalance the otolith contribution to the pitch VOR, resulting in ocular misalignment.
- A reduction in misalignment will occur with experience in an environment, and this adaptation occurs within the central compensation mechanism.
Experimental Methods: Parabolic Flight
Experimental Methods: Video eye movement recording

- Binocular (both eyes)
- 50 Hz
- Accelerometers and rate sensors
- Subjects in darkness
- Software finds pupil in image and computes gaze direction
**Experimental Methods: Summary**

**Parabolic flight**
- Otolith: vertical; change in magnitude (0-1.8 g) but not direction
- Pitch rotation: 3 °/s
- Roll rotation: 0 °/s
- Yaw rotation: 0 °/s

**Centrifugation**
- Otolith: rotates in roll to vertical; change in magnitude 1-2 g and direction
- Pitch rotation: 0 °/s
- Roll rotation: 1 °/s
- Yaw rotation: 0 °/s to 100 °/s

**Pitch rotation**
- Otolith: continuously rotating in pitch; fixed magnitude g
- Pitch rotation: up to 90 °/s
- Roll rotation: 0 °/s
- Yaw rotation: 0 °/s
Perceptual Observation

- Operator: “Did you notice the light diverging at all?”
- Subject: “The little light… diverged, and I couldn’t get it to come back together again when I was looking off to the right. The two divergent red lights were not always in the same relation to each other.”
- Operator: “Did they separate completely horizontally, completely vertically or something in between?”
- Subject: “…It was mostly vertically, but the bottom one would move across, moving horizontally more than the top one”
- Subject: “I tried to focus them back on top of each other. They were always vertically separated but I tried to get them horizontally aligned.”
- Subject #2: “For right targets, one moved up and to the left. For left targets one moved down and to the right.”
- Subject #2: “At the end I didn’t notice it as much at all.”
Gravity
Vertical Skew induced by Changing GIA

- Vertical eye positions (degrees)
  - Left Eye
  - Right Eye

- Compensated vertical eye positions (degrees)
  - Left Eye
  - Right Eye

- Gravitoinertial acceleration (g)

Time (seconds)  Trial: B2
**Goal**

Develop a method to detect vertical translation of the camera relative to the eye using features in the video image

*... using an automatically selected landmark*

**Algorithm**

- Automatically select a smaller rectangular landmark
- Find in each video frame using cross-correlation
- “Temporal feature-selection”
Co-correlation

- Metric to estimate motion of a landmark relative to other landmarks
Co-correlation predicts landmark tracking accuracy

- First iteration
- Worthy (most accurate) landmarks
- Second iteration
- Worthy (most accurate) landmarks

Mean error compared to benchmark (degrees)

Co-correlation with other time-series

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
3: How is disconjugacy influenced by target distance and position?

- The magnitude of g-dependent vertical skew does not depend on the horizontal or vertical displacement of the fixation target (ANOVA; p>0.4)
- Vertical skew is significantly smaller for far targets compared to near targets ($t$-test; p<0.1)

<table>
<thead>
<tr>
<th>Target</th>
<th>Near (12 cm)</th>
<th>Far (30 cm)</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>+1.54°±1.13° (n=18)</td>
<td>+0.99°±1.04° (n=4)</td>
<td>+1.44°±1.16° (n=22)</td>
</tr>
<tr>
<td>Left</td>
<td>+0.99°±0.63° (n=9)</td>
<td>+0.70°±0.65° (n=3)</td>
<td>+0.92°±0.62° (n=12)</td>
</tr>
<tr>
<td>Center</td>
<td>+0.90°±0.67° (n=9)</td>
<td>+1.15°±0.00° (n=1)</td>
<td>+0.93°±0.63° (n=10)</td>
</tr>
<tr>
<td>Up</td>
<td>+1.20°±0.91° (n=4)</td>
<td>- (n=0)</td>
<td>+1.20°±0.91° (n=4)</td>
</tr>
<tr>
<td>Overall</td>
<td>+1.24°±0.93° (n=40)</td>
<td>+0.90°±0.79° (n=8)</td>
<td>+1.18°±0.93° (n=48)</td>
</tr>
</tbody>
</table>
Influence of flight experience on magnitude of skew differential

Parabolic flight experience in current campaign (flights)

Magnitude of skew differential between 0 g and 1.8 g (degrees)

- Significant trial (p<0.005)
- Not significant
- Exponential fit (τ=3.69 flights, p<0.034)
Summary Aim 1: Determine how binocular alignment is disrupted during linear acceleration

- The results provide evidence for vertical skew related to g level, possibly as a consequence of otolith asymmetry
- The skew is does not varies with target position (comitant) but reduces with target distance
- Vertical skew and torsional disconjugacy is reduced with exposure to parabolic flight
- The relationship between vertical and torsional disconjugacies will be studied
Aim 2: Pitch Rotations

Methods

- Rotate full body in the pitch direction
- Slow, medium, fast paradigms
- Eye movements recorded with scleral search coils
Slow pitch rotation

- Torsional eye positions (degrees)
- Vertical eye positions (degrees)
- Chair position (degrees)

Graph showing the eye positions and chair position during slow pitch rotation.
Medium pitch rotation

60 °/sec
Target flashes every 7 seconds resetting skew
Skew changes by 0.94°.
Will attempt to reduce noise by finding and removing fast phases
Summary of Aim 2: Determine how binocular alignment is disrupted during dynamic tilt (pitch VOR)

- Vertical skew occur in pitching with different motion profiles
- Torsional disconjugacy occurs in slow pitching; will look in medium, fast
- Will look for correlation between vertical/torsional
- Will perform regression of all experimental data to determine dependency on motion variables
Aim 4: Model how otolith asymmetry could contribute to disruption of binocular alignment under these different motion scenarios

- Can an anatomically-based otolith asymmetry model explain the vertical and torsional disconjugacies?
- Does a model suggest that the pathway is a direct otolith-vertical or that it is otolith-torsion-vertical?
- Does the model correctly predict changes in disconjugacy with different vestibular and visual inputs?
- Can the model predict adaptation? How are adaptation and central compensation related?
B: Does a model suggest that the pathway is: direct otolith-vertical or otolith-torsion-vertical?

A direct pathway is suggested by evidence that damage to the otolith pathway will result in vertical skew.

Torsion about an axis other than an optical axis will result in vertical movement.

It has been shown that torsion results from otolith asymmetry.

The model incorporated the geometry of how torsion about different axes would cause vertical movements. We will use experimental data to determine which axis is consistent.
D: How to model influence of central compensation on vestibular nuclei
D: How to model influence of central compensation on vestibular nuclei

- Context-specific adaptation
Acknowledgements

- Advisor: Dr. Mark Shelhamer
- Parabolic flight studies: Dr. Stefano Ramat, Ondrej Juhasz, Michelle Zwernemann, Anton Aboukhalil, Tiffany Chen, NASA staff
- Pitch rotation: Dr. Dominik Straumann, Dr. Stefano Ramat, Zurich University Hospital staff
- Scientific insights / moral support: Dr. David Zee & the lab
Recruitment

- The lab is looking for new students – rotations, Masters, Ph.D.s
- Mark Shelhamer
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Otolith asymmetry: Implications for disruption of human binocular alignment in unnatural gravito-inertial environments

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October 11, 2006