Space and the Vestibular System

Mark Shelhamer
Depts. of Otolaryngology and BME
210 Pathology Bldg.
×4-6302
mjs@dizzy.med.jhu.edu
Sensorimotor Problems of Space Flight

- Sudden loss of stable g vector
- Nausea, motion sickness (SMS)
- Visual orientation illusions
- Coordination deficits
- Post-flight deficits in posture & locomotion
- Lethargy, reduced performance
- Impact on performance (piloting)
SMS

- Mercury, Gemini: confined, little movement, few problems reported
- Apollo: more spacious, SMS more prevalent (11 of 33 astronauts)
- Shuttle (first 36 missions):
  - 38% moderate or severe SMS on first flight
  - 16% moderate or severe SMS on subsequent flights
  - Onset usually within first hour
  - Resolves within 3-6 days
- Terrestrial motion sickness not a predictor (even parabolic flight)
- Head movements, disorienting visual cues are contributors
Possible Solutions

• Screening
  – No correlation between terrestrial motion sickness & SMS
  – No consistent predictors of SMS

• Drugs
  – Side effects
  – Only partially effective
  – May delay adaptation
  – Difficult to do controlled studies

• Preflight training

• Artificial gravity
Vestibular System

Sense of orientation and motion

- Semicircular canals (rotation)
- Otolith organs (translation, tilt)
- Vision
- Proprioceptive, kinesthetic
Otolith Organs

- Linear acceleration transducers
- Utricle: mainly lateral motion
- Saccule: mainly vertical motion
- Gravity is a linear acceleration
- Reasons to suspect otoliths in SMS:
  - Counterrolling asymmetry
  - Tilt-translation ambiguity
Mechanism I: Sensory Conflict

- Sense of orientation and motion provided by combination of sensory inputs:
  - Semicircular canals (rotation)
  - Otolith organs (translation, tilt)
  - Vision
  - Proprioceptive, kinesthetic

- Stored patterns of relationship between senses

  **Sensory Conflict in Space**

- Head tilt
  - Vision & canals sense tilt (correctly)
  - Otoliths do not sense tilt (wrong)
  - Intersensory conflict based on experience

- Exacerbated by head movements
Motion Sickness: Theories

- Sensory conflict: primary theory at this time
- Adverse response to stimuli outside the adaptive capabilities of the sensorimotor systems
- Epiphenomenon: network of functional responses (autonomic, volitional, emetic, coordination, etc.) can lead to unwanted interactions
Mechanism II. Tilt-Translation: OTTR

Otolith Tilt-Translation Reinterpretation

• Tilt-translation ambiguity
• In space, there is no such thing as tilt
• CNS learns that all otolith stimulation is due to translation
• Frequency-specific (low freq = tilt)
Horizontal & Torsional Eye Movements During Interaural Translation

Pure translation stimulus produces:

Translation response (horizontal eye movement)

Tilt response (torsion)

Neurolab OTTR Experiment (1998)

- Centrifugation during flight
- Interaural, 1 g & 0.5 g

**Pre-flight:**
- perception of roll tilt
- OCR

**In-flight (16 days):**
- Only acceleration stimulus is due to centripetal force
- OTTR predicts a *translation* response
- Subjects have OCR and perceive *tilt*:
  - $45^\circ \rightarrow 83^\circ$ @ 1g
  - $42^\circ \rightarrow 48^\circ$ @ 0.5g
Neurolab (cont.)

• So is OTTR dead?

• Problems with Neurolab experiment:
  – Mental set (translation out the side of the spacecraft?)
  – Tactile cues (indicating upright orientation)
  – Extensive pre-flight experience (context-specificity)
  – Frequency:
    • Centrifugation is “0 Hz”
    • Tilt-translation interaction may be a low-frequency phenomenon, with a tilt “singularity” at DC

• Nevertheless, the OCR results in particular are compelling and present a challenge to OTTR
Mechanism III. Otolith Asymmetry

- Ocular counterrolling (OCR)
- Compensatory response to head tilt
- Torsional eye movement
- Gain $\approx 10\%$ (i.e., $45^\circ$ head tilt $\rightarrow \approx 4^\circ$ torsion)
- Each utricle contributes more to OCR in ipsilateral than contralateral eye

![Diagram](image)
Otolith Asymmetry (cont.)

- Postulated anatomic or physiologic asymmetry in otoliths
- Normally compensated by neural pathways in 1g
- In hyper-g or hypo-g, compensation is no longer appropriate
- Measure torsional disconjugacy:
  - find difference in torsional position between two eyes
  - slope of this difference from 1.8 g to 0 g = disconjugacy (°/g)
Otolith Asymmetry (cont.)

- Disconjugacy (°/g) vs. subject
- Dark bars: no SMS
- Gray bars: SMS
Otolith Asymmetry (cont.)

• Promising

• Problems:
  – Does not explain importance of head movements in SMS
  – Does not explain role of visual orientation illusions in SMS
  – No correlation of SMS in space with SMS in parabolic flight
Solution I: Artificial Gravity

• Centripetal acceleration in rotating spacecraft
  – $a = \omega^2 r$
  – Large radius ($r$): expensive
  – Rapid rotation ($\omega$): expensive
AG (cont.)

Problems

• What is minimum g level needed to avoid deconditioning of physiological systems?
• Disorientation due to cross-coupled angular accelerations (Coriolis)
• What are limits of human adaptability to rotating environments? (SRR)
AG problem: “Coriolis”

- “Cross-coupled angular accelerations

![Diagram of head with cross-coupled angular accelerations]

Fig. 1. Schematic illustration of cross-coupling stimulation. If an individual rotating clockwise at constant velocity tilts his head forward 90° in pitch, his “horizontal” semicircular canal will signal a counter-clockwise velocity impulse and his “vertical” semicircular canal will indicate a clockwise velocity impulse. For a more detailed treatment (12,25,26).

- Skylab (1973-1974): immunity in flight
Solution II: Preflight Adaptation Trainer (PAT)

• Subjective reports from astronauts regarding translation sensation during head tilt
• Labile, readapts quickly, difficult to describe
• Attempt to pre-adapt responses:
  – Tilt at low frequency
  – Translation at high frequency
PAT

IG - PITCH: OTOLITH DISPLACEMENT (TILT)

OG - PITCH: NO OTOLITH DISPLACEMENT (TILT)

IG or OG - FORWARD TRANSLATION: OTOLITH DISPLACEMENT
Solution III: Context-Specific Adaptation

- Humans undergo significant adaptation upon exposure to space environment
- Must re-adapt upon return to earth (or Mars)
- Impaired function during transitions
  - Weightless / gravity
  - Artificial gravity / weightless / planetary g
- Can CNS maintain reflex calibrations appropriate for two different environments simultaneously, and switch between them based on a context cue (gravity)?
Parabolic Flight
Pitch Vestibulo-Ocular Reflex

• Head pitch activates canals and otoliths.
• Expect gain to be increased in 2g and reduced in 0g, before adaptation.
• If adaptation is context-specific, expect gains adjusted back to normal level in each g level.

• VOR gain = eye excursion ÷ head excursion.
  – measure eye movements during pitch head movements at ~0.1-1.0 Hz
  – head-mounted video system
Pitch Vestibulo-Ocular Reflex

- Head pitch activates canals and otoliths.
- Expect gain to be increased in 2g and reduced in 0g, before adaptation.
- If adaptation is context-specific, expect gains adjusted back to normal level in each g level.
Gain of the vestibulo-ocular reflex during head pitch
• New flyers initially – higher in 2g than in 0g
• New flyers adapted – little difference in gain between 2g and 0g
• Experienced flyers – little difference in gain between 2g and 0g
  ➔ This vestibular-mediated response rapidly adapts to correctly incorporate two different gravity levels.
CSA

- Responses show g-level dependence early in flight which decreases with experience.
- This supports the hypothesis of a context-specific adaptation of each response to each g level.
- Also true in experienced flyers.
The Space Program is not Over

ISS long-duration flight

NASA “Flexible Path” for exploration missions

Commercial spaceflight
Virgin Galactic

• 4-5 minutes 0g
• $200,000
• Flights in 2013?
What can we do for Suborbital Passengers?

• Precedent: parabolic flight [Vomit Comet]
  – About 50% of first-time flyers are sick
  – Adaptation is rapid (1-3 flights)

• Neurovestibular Issues
  – Motion sickness, nausea, dizziness
  – Migraine: ~25% of population, ~20% dizziness component (motion sensitivity)
  – Benign positional vertigo: BPPV
  – Mal de debarquement: disembarkment syndrome
  – Screening, detection of undiagnosed vestibular disorders, pre-adaptation
Relevant Concepts from Adaptation Studies

• Context-specific adaptation
  – store two sensorimotor programs
  – switch between them based on context
  – gravity can serve as a context cue
  – a set of 0g-appropriate sensorimotor programs might be learned and stored before flight

• Adaptive generalization
  – ability to rapidly adapt to a new stimulus arrangement by repeated adaptations to similar settings
  – 0g is a unique environment that is difficult to mimic adequately on the ground for pre-flight adaptation
  – may be helpful to expose passengers to a series of unusual sensorimotor rearrangements that call into play the adaptive mechanisms that are needed in 0g