Space and the Vestibular System

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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 $\sim 10\%$ (i.e., $45^\circ$ head tilt $\rightarrow$ $\sim 4^\circ$ torsion)
- Each utricle contributes more to OCR in ipsilateral than contralateral eye
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

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

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
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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.

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.

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
  - Substantial population with latent vestibular disorders (35% age 40+)
    - Agrawal, Carey, Della Santina, Schubert, Minor (2009)
  - 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