Space Transportation System (STS) 130 Endeavour Crewmembers

Sensory-Motor Issues Related to Space Flight

John R. Allen, Ph.D.
Space Operations Missions Directorate
NASA Headquarters
Washington, DC

NASA HQ

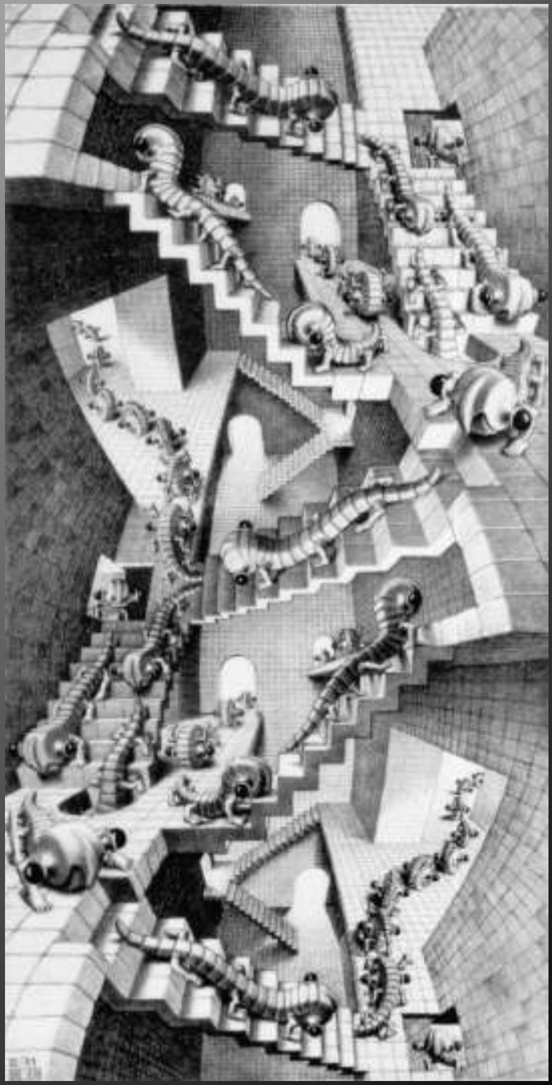
Acknowledgements

- William H. Paloski
- Charles M. Oman
- Jacob J. Bloomberg
- Millard F. Reschke
- Scott J. Wood
- Deborah L. Harm
- Brian T. Peters
- Ajitkumar P. Mulavara
- James P. Locke
- Leland S. Stone

- ***"Risk of Sensory-Motor Performance Failures Affecting Vehicle Control During Space Missions: A Review of the Evidence"***
- Journal of Gravitational Physiology, Vol 15(2), December 2008
- Exp Brain Res, February 2010 (on line)

Sensory-Motor Disorders

- Balance and Locomotor Instability
- Altered ability to visually acquire target during head movements
- Disturbances in spatial orientation and perception
- *Space Motion Sickness*



NASA’s Human Research Program

- Identified a number of potentially significant biomedical risks that might limit agency’s plans for future space exploration

Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems

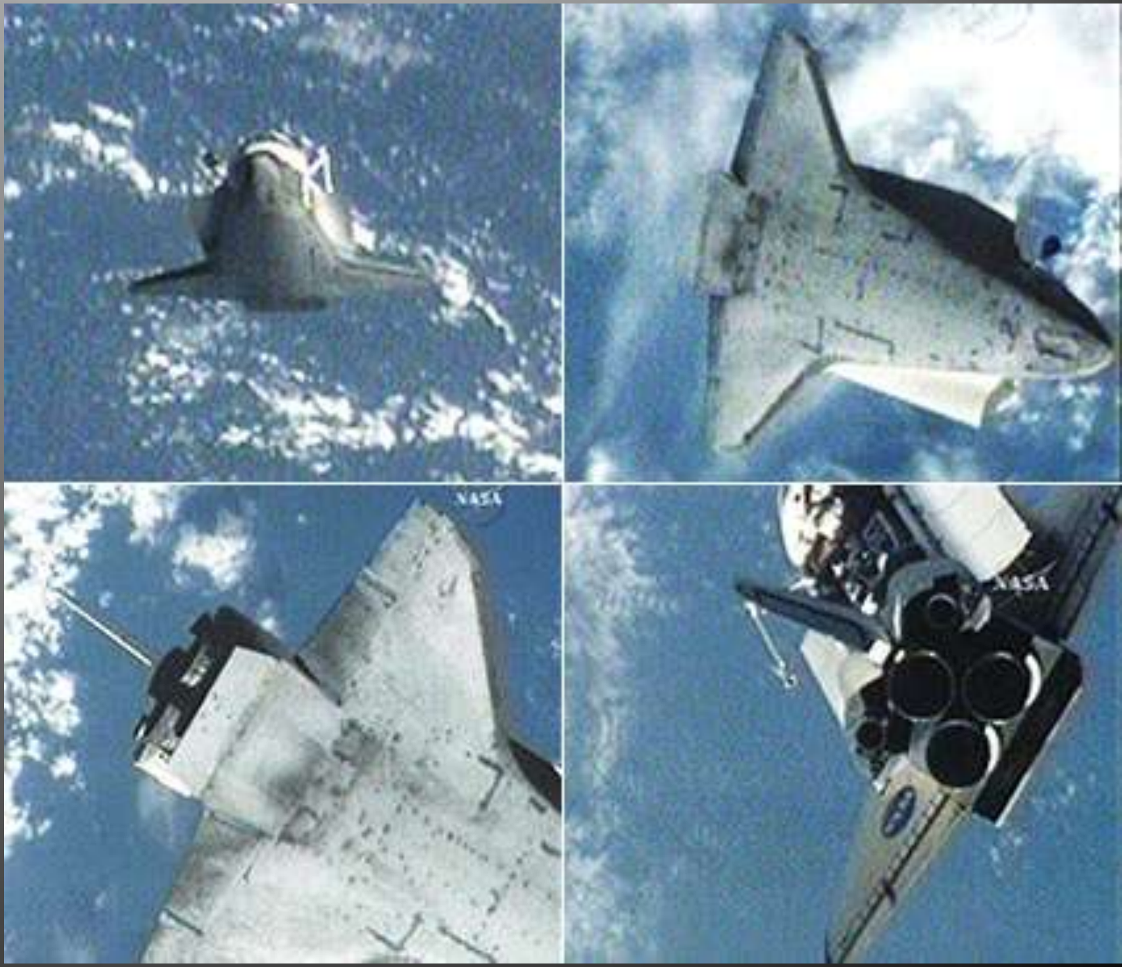
- *Space flight alters sensory-motor function*
  - *Changes in balance, locomotion, gaze control, dynamic visual acuity, eye-hand coordination, and perception.*
- *These alterations affect fundamental skills*
  - *Piloting and landing airplanes and space vehicles,*
  - *Driving automobiles and rovers,*
  - *Operating remote manipulators and other complex systems*

What Don’t We Know and Why Don’t We Know It?

- *Relationships between the physiological changes and real-time operational performance decrements not yet established due to:*
  - *Inaccessibility of operational performance data*
  - *Presence of confounding, non-physiological factors*
- *Space flight induced alterations in sensory-motor performance are of concern for future missions*
- *The greater the distance, the greater the concern*
  - *Prolonged microgravity exposure during transit, will more profoundly affect landing task performance and subsequent operation of complex surface systems*

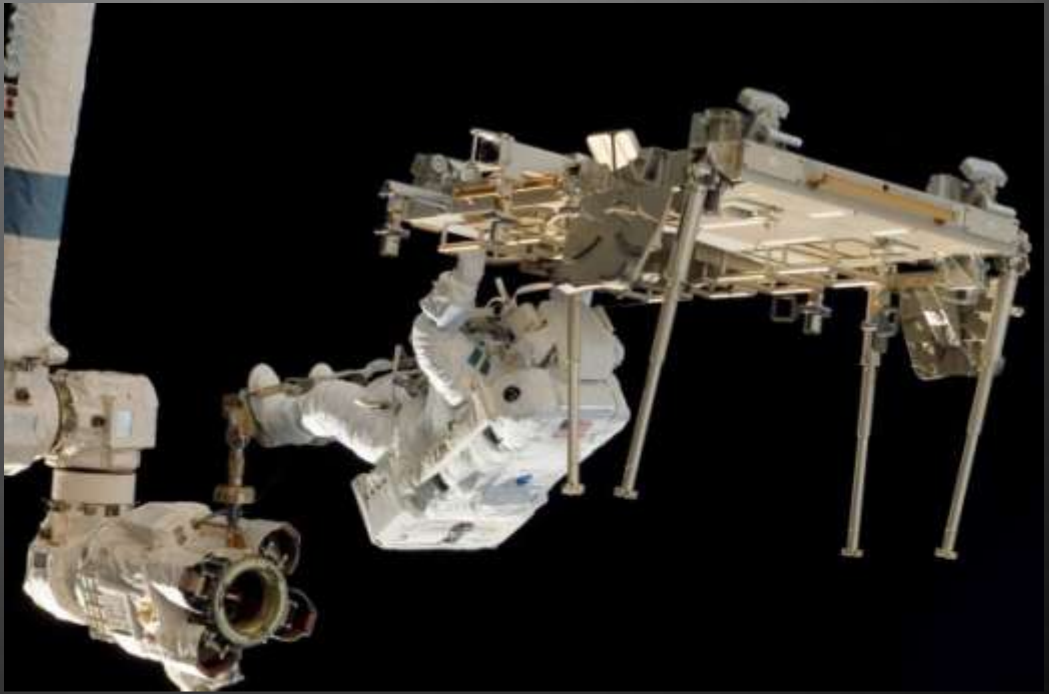
Control of Vehicles and Other Complex Systems

- Control of vehicles and other complex systems is a high-level integrative function of the central nervous system (CNS).



Control of Vehicles and Other Complex Systems

- Requires well-functioning subsystem performance
  - Good visual acuity,
  - Eye-hand coordination,
  - Spatial and geographic orientation perception,
  - Cognitive function



Control of Vehicles and Other Complex Systems

- Function of each of these subsystems is altered by removing gravity, a fundamental orientation reference…sensed by
  - vestibular,
  - proprioceptive,
  - haptic receptors and
  - used by the CNS for spatial orientation, navigation, and coordination of movements

Available Evidence

- Limited operational evidence that alterations adversely impact performance
- Research data is slim due to small “n”
- Research data is somewhat equivocal
- Data has been collected pre/post mission since 1959

Post-flight Interview

- Did you try to limit your head movements?
  - *Oh yes, definitely.*
- When you were trying to acquire the targets only, ...did you notice any difficulty in spotting the targets?
  - *Oh yeah, oh yeah.*
- Did it seem as though the target was moving or was it you?
  - *I felt that it was me. I just couldn't get my head to stop when I wanted it to.*
- So it was a head control problem?
  - *Yeah, yeah in addition to the discomfort problem it caused.*

Post-flight Interview

- So when you first got out of your seat today, can you describe what that felt like?
  - *Oh gosh, I felt so heavy, and, uh, if I even got slightly off axis, you know leaned to the right or to the left like this, I felt like everything was starting to tumble.*
- When you came down the stairs did you feel unstable?
  - *Oh yeah, I had somebody hold onto my arm.*
- Did you feel like your legs had muscle weakness, or … was it mainly in your head?
  - *It was mainly in my head.*

Post-flight Interview

- Every crewmember is interviewed on landing day (>200 crewmembers to date)
- Reported some degree of disorientation/perceptual illusion,
- Often accompanied by nausea (or other symptoms of motion sickness),
- Frequently accompanied by malcoordination, particularly during locomotion

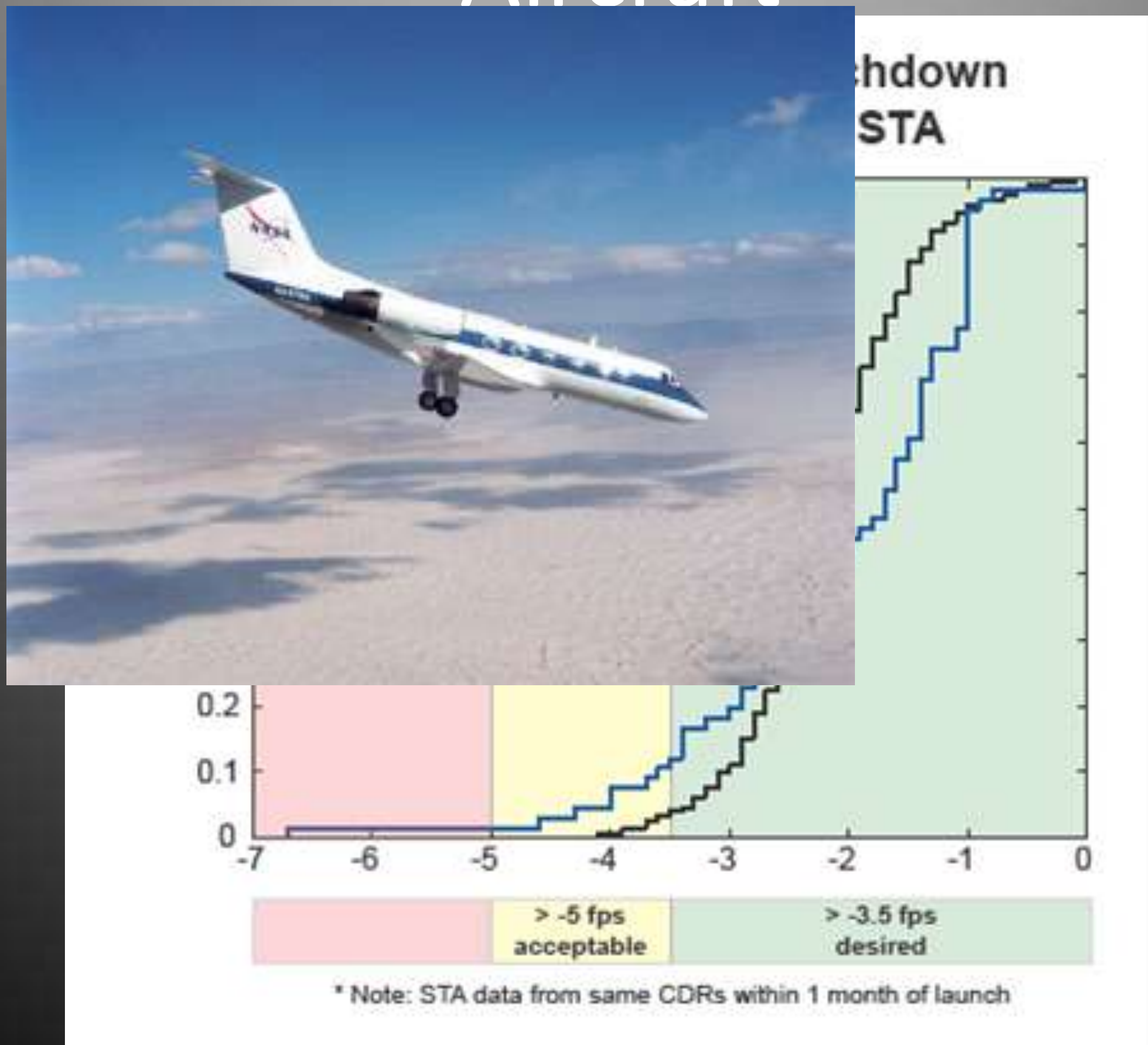
Post-flight Symptoms

- Severity and persistence of post-flight symptoms varies widely among crewmembers,
- Both tend to decrease with increasing numbers of space flight missions
- Both severity and persistence increase with mission duration
- Symptoms generally subsided within hours to days following 1-2 week Shuttle missions but persisted for a week or more following 3-6 month Mir Station and ISS missions

Shuttle Entry and Landing Spatial Disorientation (SD)

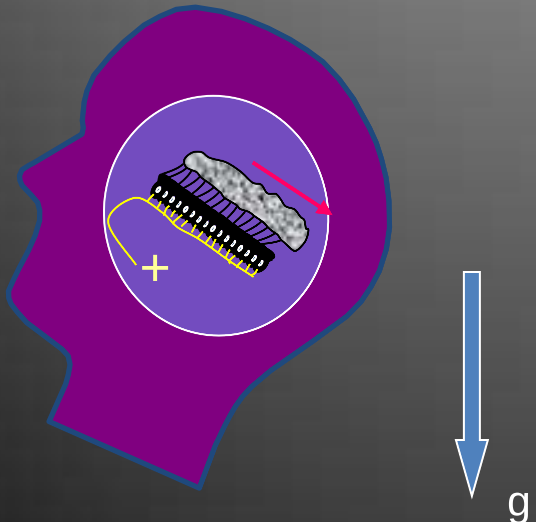
- Despite extensive training, landings have been outside performance specs
- Shuttle SD differs from aviation SD

Touchdown vs Shuttle Training Aircraft

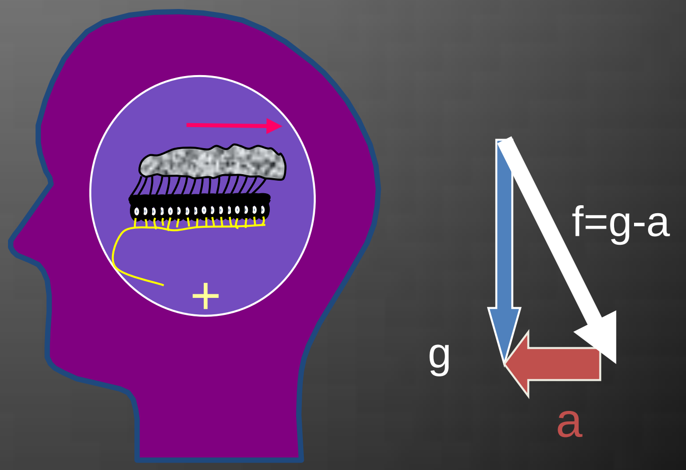


Otolith Tilt-Translation Reinterpretation

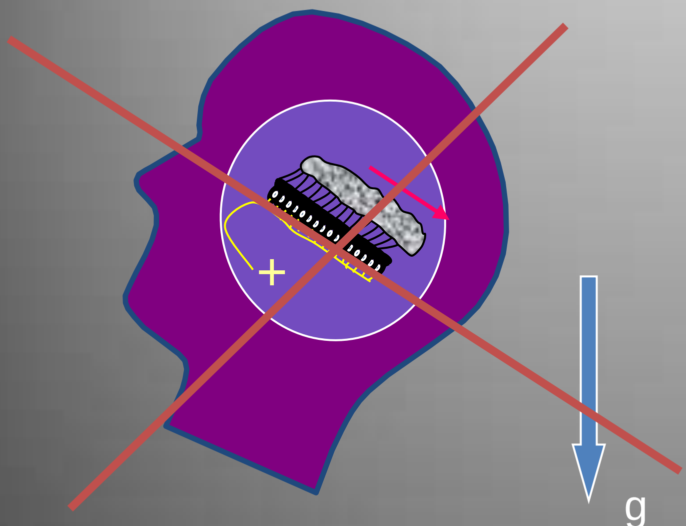
On Earth, otoliths detect both head tilt and linear acceleration



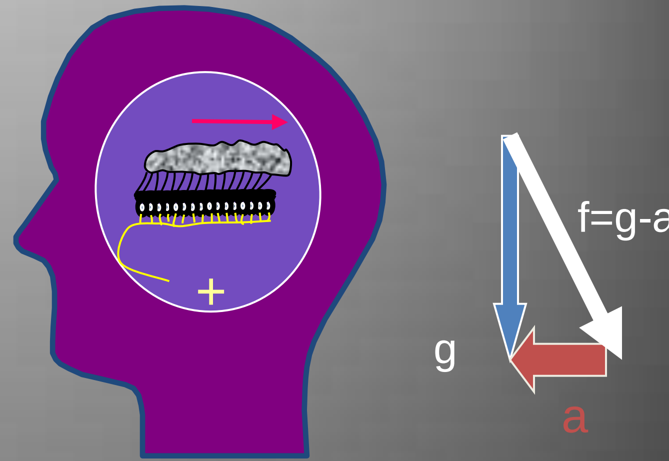
Backward Head Tilt



Forward Acceleration



Backward Head Tilt



Forward Acceleration

In microgravity otoliths detect <u>only</u> linear acceleration

Brain reinterprets all otolith input as linear acceleration

Postflight Evaluation Results

- Each crew member evaluated within hours of landing
  - Varies by location: Florida, California, Kazakhstan
- Scored for subjective symptoms, coordination, and functional motor performance
- Analyzed data from nine missions, and noted trends
  - Correlation found between touchdown sink rate and post-flight difficulty performing a sit-to-stand maneuver without using the arms
- Scores indicating neuro-vestibular dysfunction generally correlated with poorer flying performances,
  - Lower approach and landing shorter, faster, and harder

Apollo Lunar Landing Spatial Disorientation

- Apollo Lunar Module had digital autopilot capability
  - Could have done fully automated landing
  - Astronauts chose to land manually
  - Multiple challenges
    - Poor visibility
    - 1/6 g
    - Limited training with compromised vestibular function

Apollo Lunar Landing Spatial Disorientation

- None admitted to any spatial disorientation events during landing
- Later admitted feeling a little “wobbly” when stepping on the lunar surface
- Resolved in a few hours

Landing on Mars

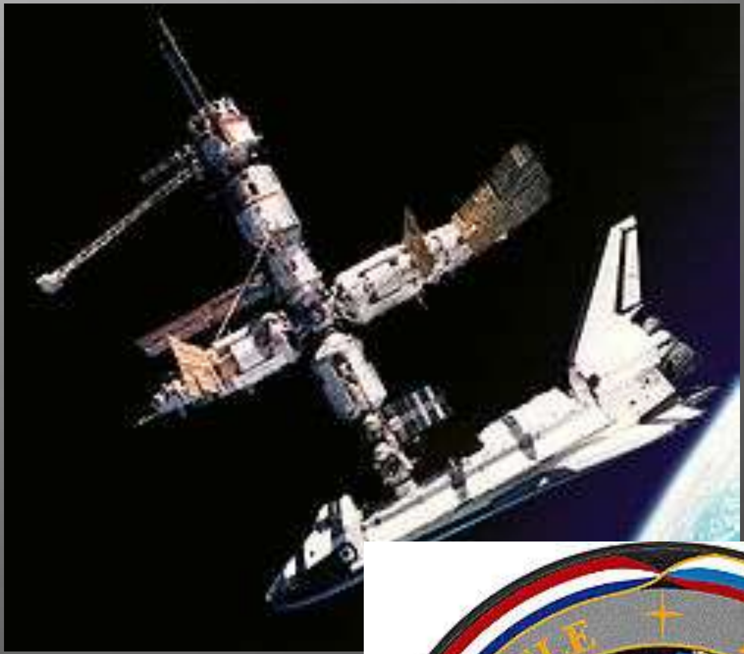
- Manual landing likely to be much greater challenge because of increased transit time in microgravity
- Landing risk compounded by more profound adaptation to microgravity and decreased training recency
- Continuous artificial gravity, created by rotating all or part of the vehicle, may mitigate this risk (as well as many of the other biomedical risks),
- Impact of prolonged exposure to a rotating environment needs to be studied

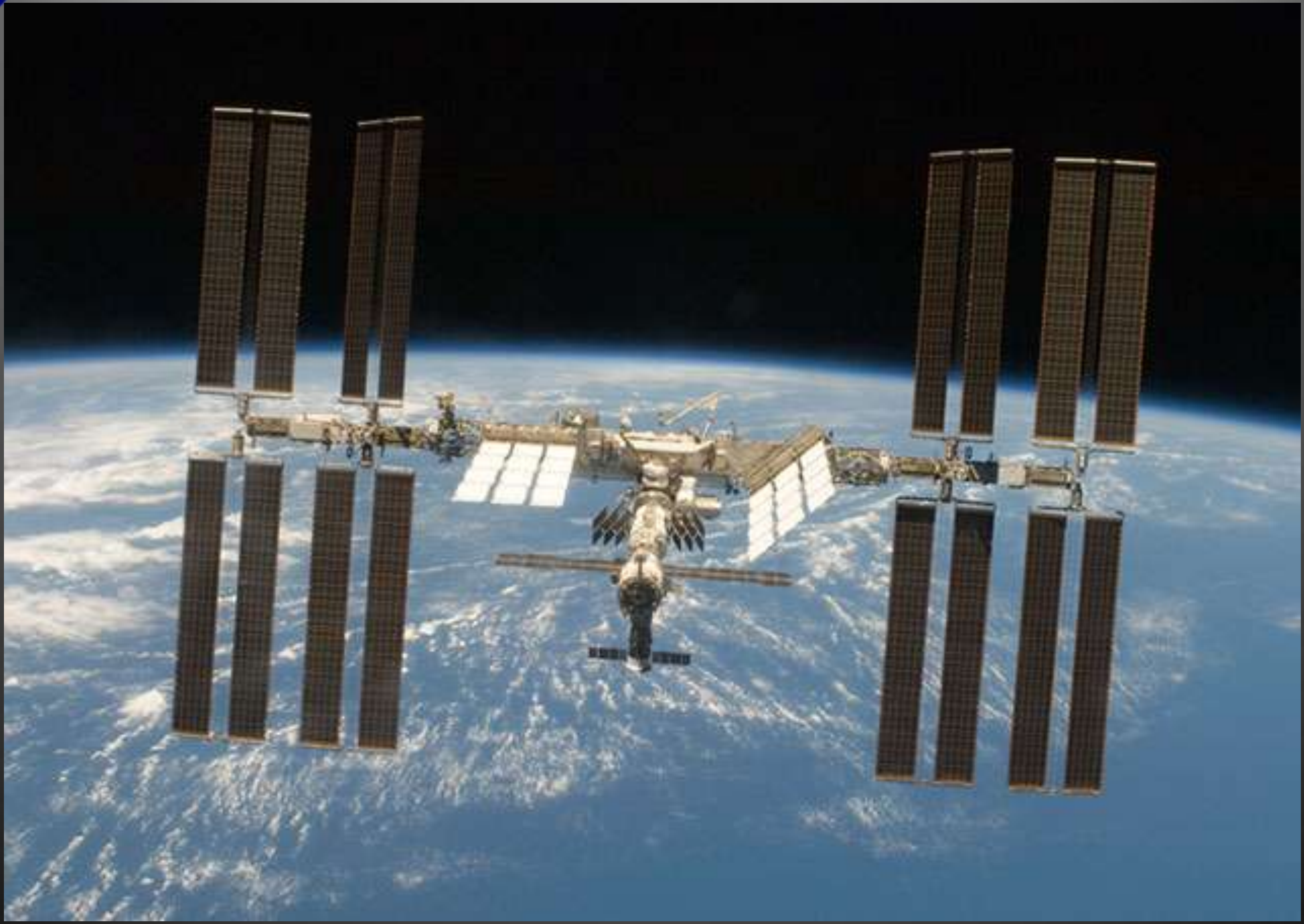
Rendezvous and Docking

- Crew and vehicle safety are paramount
- Loss of situational awareness, spatial disorientation, and sensory-motor problems, including difficulties with vision, head-hand-eye coordination, and an inability to judge distance and velocity with limited feedback likely contributed to at least one negative outcome

Rendezvous and Docking

- Target acquisition studies show
    - Dramatic changes in the speed at which target visualization can be achieved
    - Response time delayed by as much as a 1000 msec.
- Eye-hand response another full second
- Russian Institute of Biomedical Problems (IBMP) believes that the collision between Mir and Progress was caused by poor situational awareness, spatial disorientation, and sensory-motor problems





Telerobotic Activities

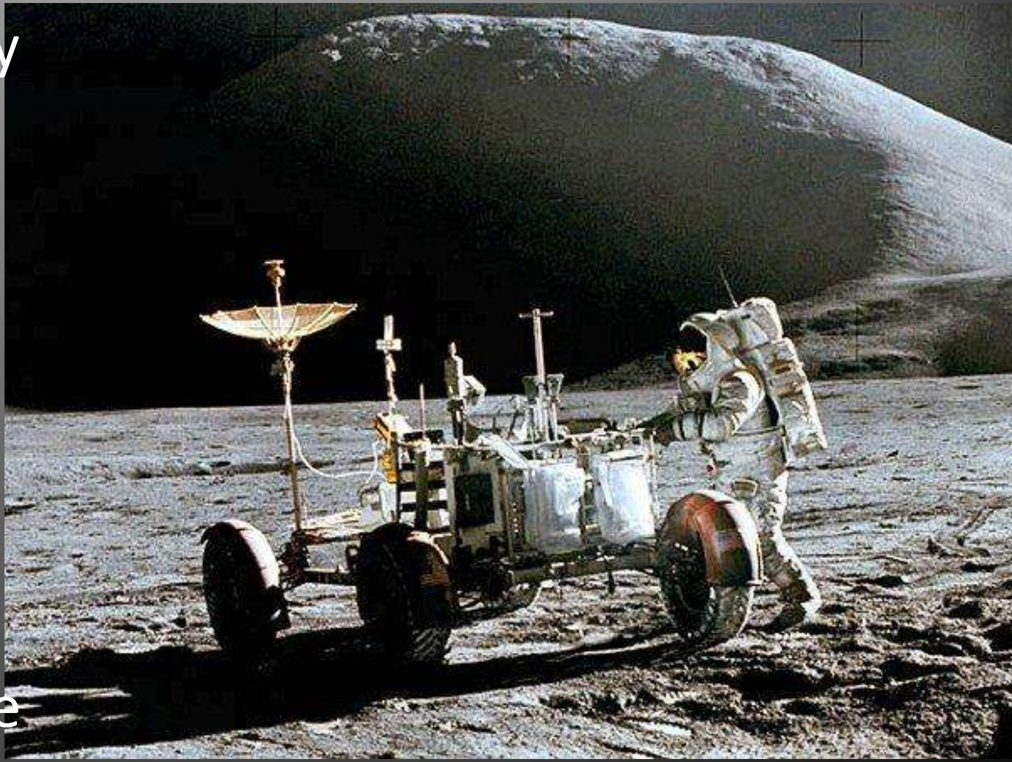
- Telerobotic operations critical to ISS construction
- Controlled with separate hand controllers
- Abilities to visualize and anticipate the three-dimensional position, motion, clearance, and mechanical singularities of the arm and moving base are critical

Driving Activities

- Vestibular patients experience difficulty in driving cars, primarily on open, featureless roads or when cresting hills (Page and Gresty, 1985)
- Vertical vestibulo-ocular reflex contributes significantly to maintaining dynamic visual acuity while driving (MacDougall and Moore, 2005)

Driving Activities

- Apollo astronauts reported driving rovers was the most dangerous activity in which they engaged
- Misperceived the angles of sloped terrain
- Bouncing from craters at times caused feeling of nearly overturning while traveling cross-slope
- Caused crewmembers to reduce their rover speed



(Apollo Summit, 2005)

Driving Activities

- Return to earth
- Concerns regarding orthostatic intolerance and overall sensory-motor status
- Restricted from driving until medically cleared

Space and Visual Acuity

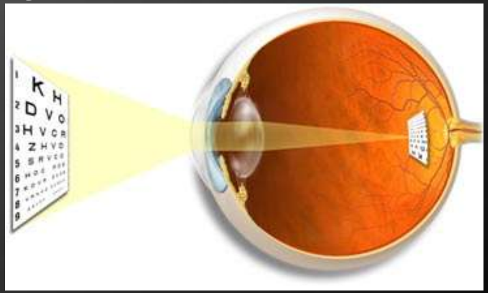
- Good visual acuity/eye movement control is important for many tasks
  - Rapidly locating and reading instrument displays,
  - Identifying suitable landing locations, free of craters, rocks, etc.,
  - Tracking the motion of targets and/or objects being manipulated

Space and Visual Acuity

- Studies show that the G-transitions associated with space flight disrupt oculomotor performance
- These include investigations into:
  - Static visual acuity,
  - Contrast sensitivity (differentiating object from background),
  - Phoria (relative directions of the eyes during binocular fixation),
  - Eye dominance,
  - Flicker fusion frequency,
  - Stereopsis (ability to perceive depth)

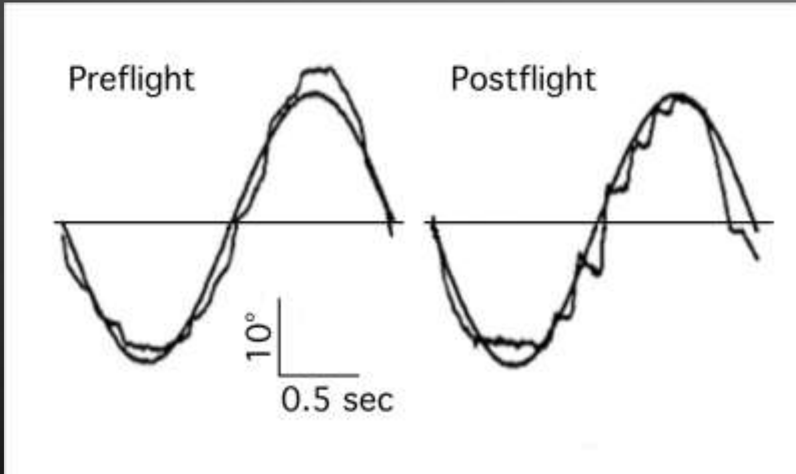
Space and Visual Acuity

- Minimal changes noted
- Only exception: contrast sensitivity
- Subjective reporting: 15% of crew members reported near vision decrements during flight (n=122)
- Likely secondary to fluid shifts or gravity related changes in ocular geometry
  – Currently being reviewed



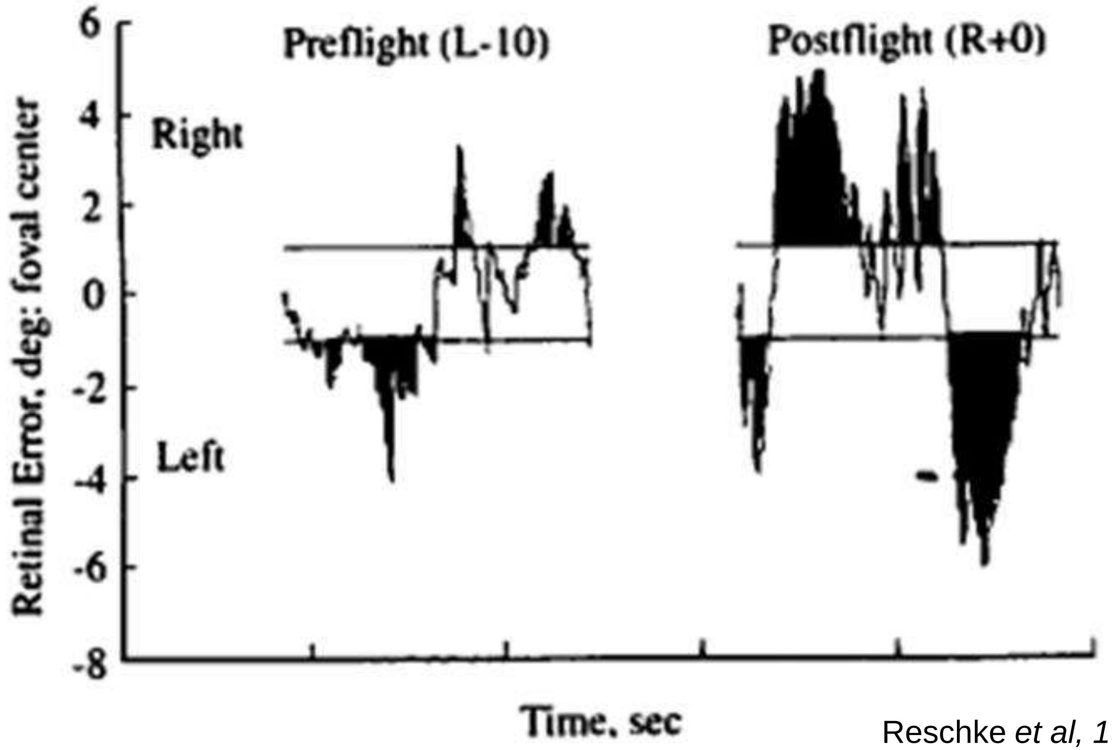
Smooth Pursuit Eye Movements

- Voluntary visual tracking of moving targets (e.g., a bird flying by) without head movements



(Reschke *et al, 1999)*

- Space flight disrupts smooth pursuit eye movements
- Functional impact: visual acuity would be degraded by inability of the oculomotor control system to keep target of interest focused on the fovea



Reschke *et al, 1999*

Cumulative time foveation is off target during the smooth pursuit-tracking task

VOR Function

- Flight experiments have demonstrated that various VOR response properties are modified during and after space flight
- VOR gain in subjects exposed to 1 Hz pitch head oscillations
  - Significantly increased 14 hrs after landing when compared with late in-flight (flight day 5 and 7) and sub-sequent postflight measurements

(Berthoz et al, 1986)

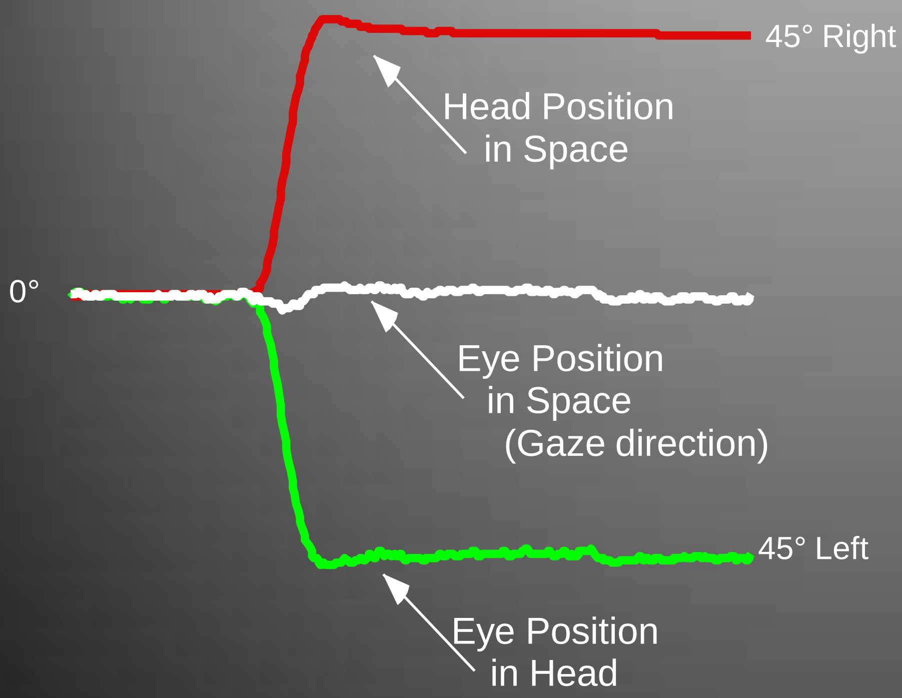
VOR Function

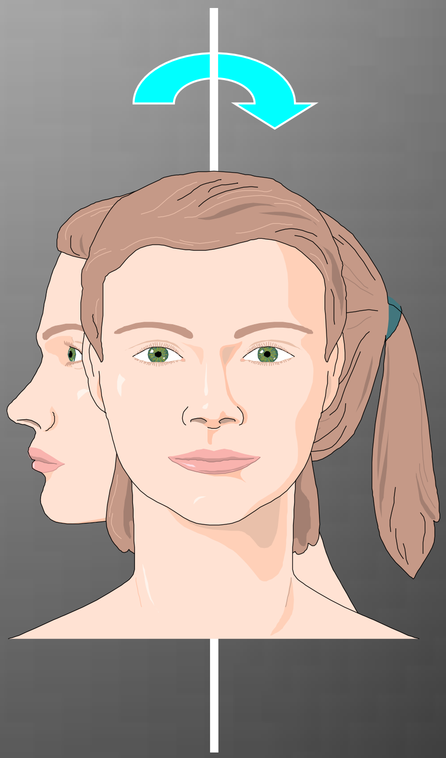
- Also reports of vertical and torsional VOR changes
- Results not conclusive, due to small “n” and other factors
  - Measurement capabilities
  - Time of assessment

Gaze

- Direction of the visual axis in three-dimensional space
- Defined as the sum of eye position with respect to the head and head position with respect to space.
- Target acquisition:
  - Coordinated eye-head movements consisting of
    - Saccadic eye movement that shifts gaze onto the target
    - VOR response that maintains the target on the fovea as the head moves to its final position

Gaze Control



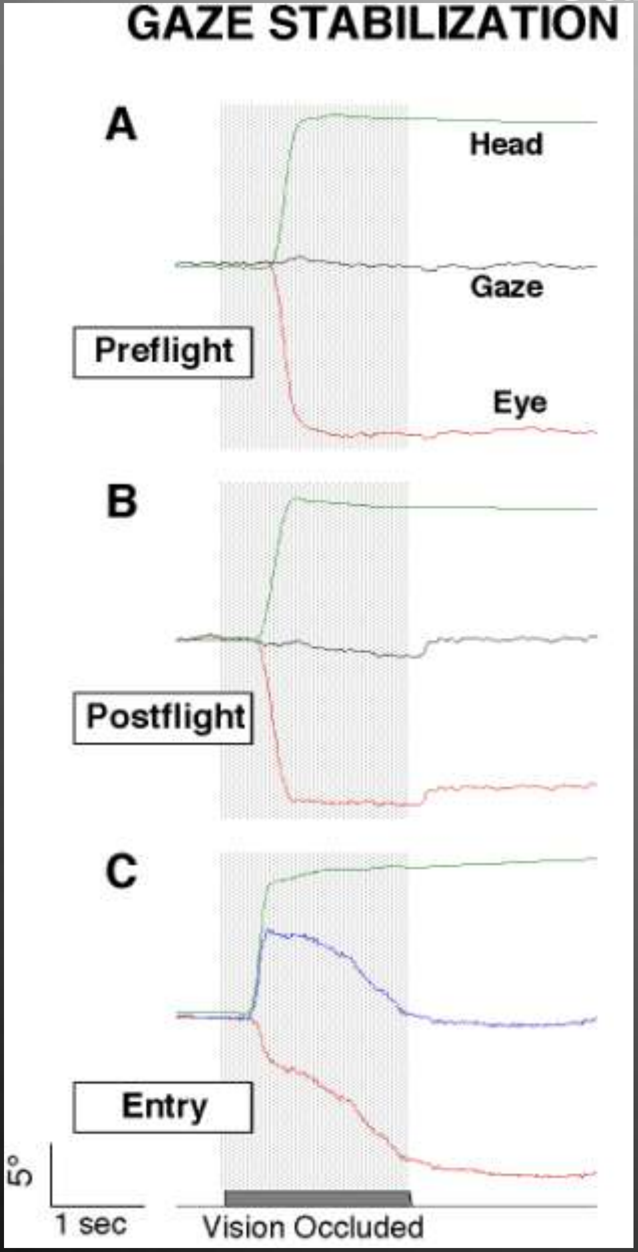


Compensatory eye movements maintain a stable retinal image during head movements

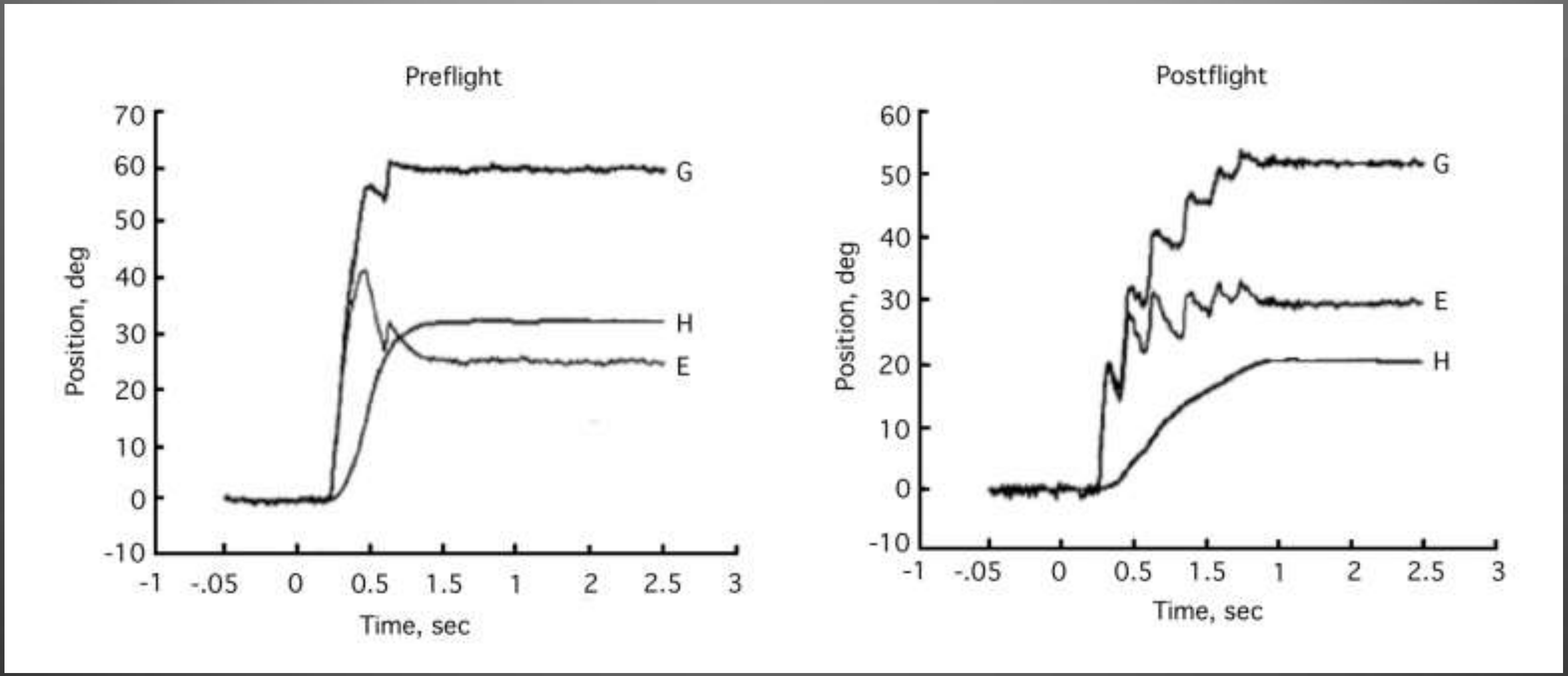
Gaze

- Reschke (1999) showed degraded eye-head coordination post flight
  - Poorest for targets outside the vertical plane
- Near doubling of the time needed to fix on a target (Grigoryan, 1986)

Gaze Stabilization During Shuttle Entry



Gaze stabilization is altered leading to reduced ability to acquire and stabilize visual targets



Head (H), eye (E), and gaze (G) movements during target acquisition beyond the effective oculomotor range before (left panel) and after (right panel) flight.

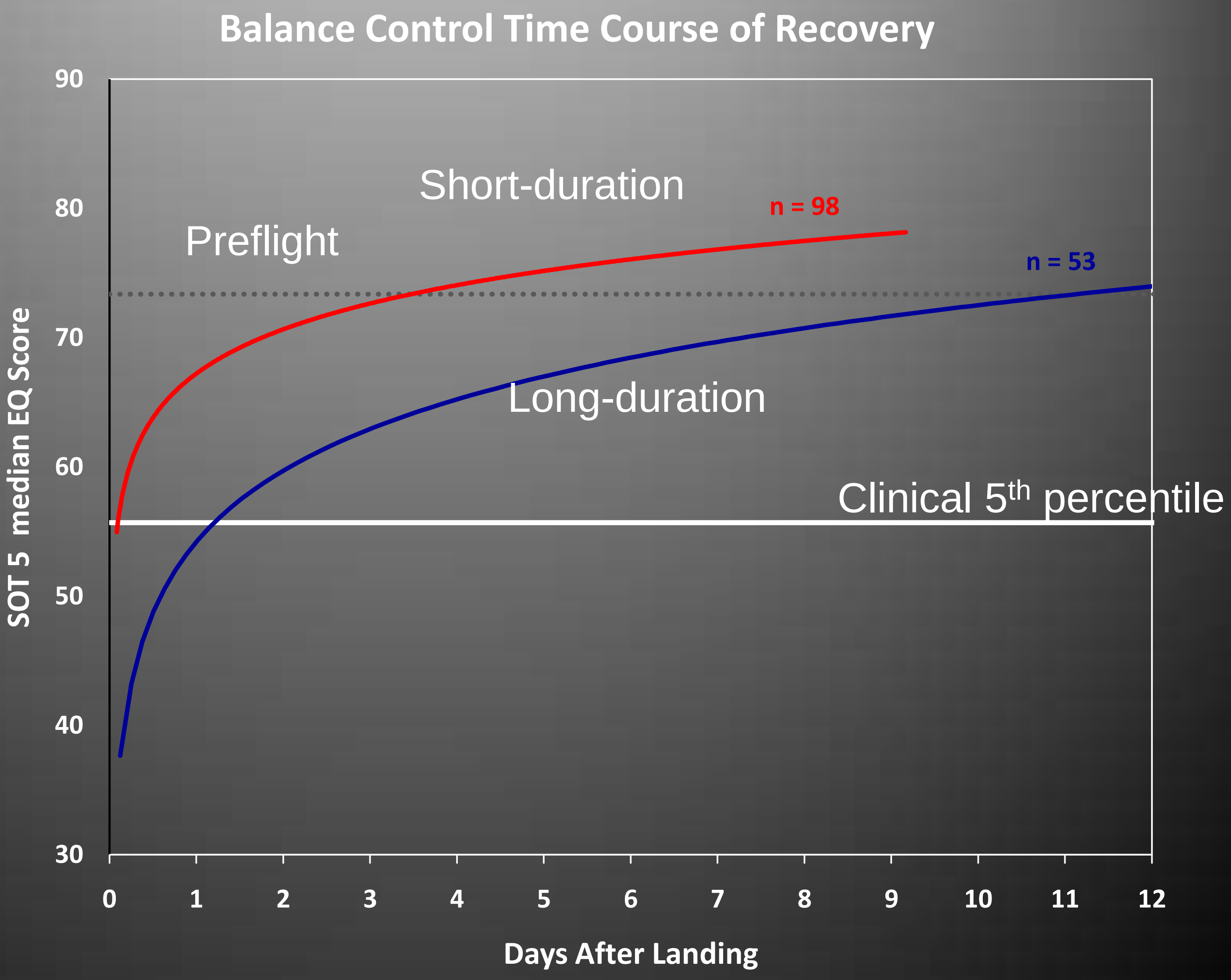
Sensory-motor dysfunction during adaptation to g-transitions

- Postural and gait instability
- Visual performance changes
- Manual control disruptions
- Spatial disorientation
- Space motion sickness

Risk Factors:
- Length of flight
- Workload and task complexity
- Crew experience
- Individual variability
- Use of medication
- Spacecraft architecture
- Suit Design

- Vehicle control
- Impaired emergency egress capability
- Falls during planetary EVAs

Recovery of Function



Severity increases and recovery is prolonged with increasing exposure time to microgravity.

Space Motion Sickness

- 0% on Mercury/Gemini, 30% on Apollo/Vostok/Soyuz/Salyut, 56% on Skylab
- 75% on Shuttle.
- Incidence is
  - highest in larger spacecraft
  - highest on days 1-2, declining on days 3-5
  - lower on second and subsequent space flights
  - unrelated to gender, or prior flying experience
  - so far, not reliably predicted by 1-G motion sickness susceptibility tests

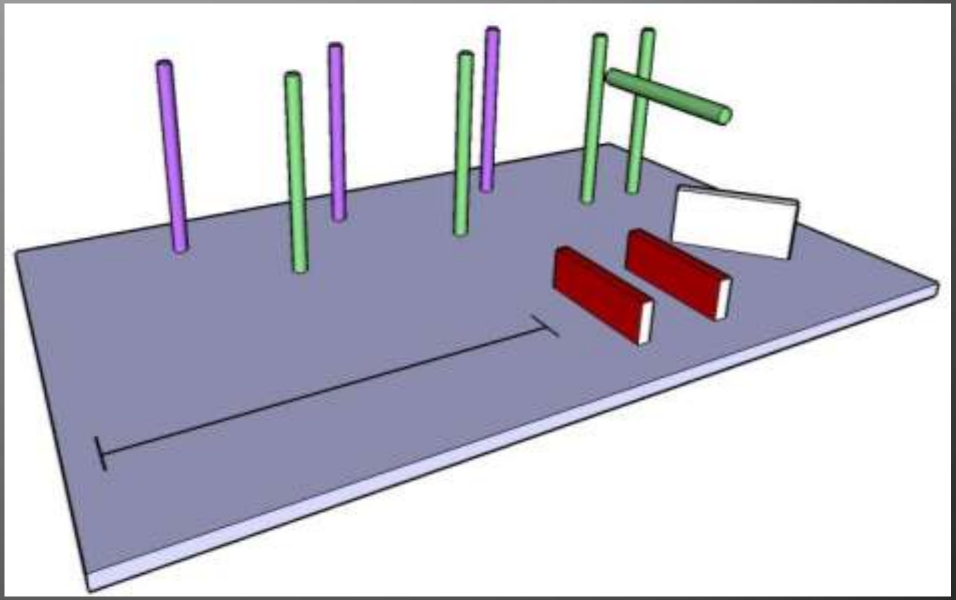
- “Earth Sickness” about 30% after 1-2 week missions, 90% after long duration flights

Courtesy of C. Oman

Locomotor Disturbances after Space Flight

- Loss of stability when rounding corners
- Deviation from a straight trajectory
- Wide stance gait to increase base of support
- More visual dependence post-flight
- Reduced visual acuity during walking
- Illusions of self and/or surround motion associated head movements
- Increased vigilance to maintain balance

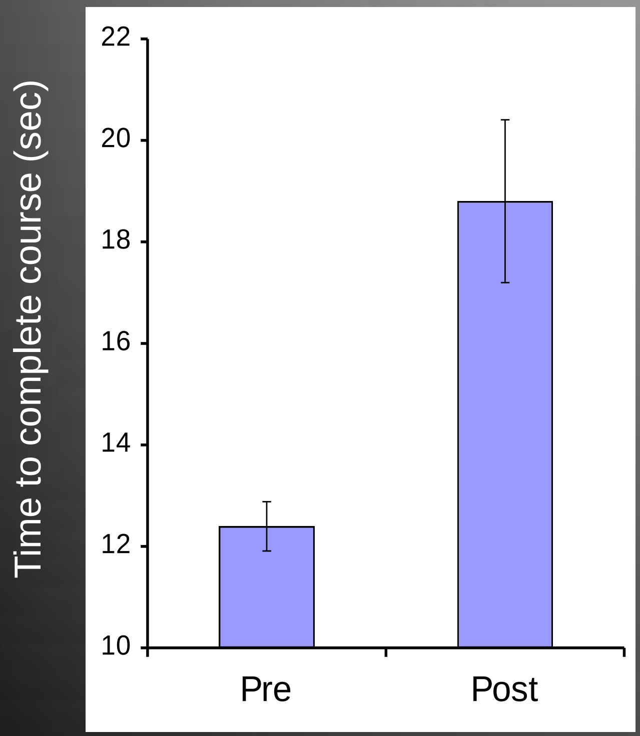
Functional Mobility Test



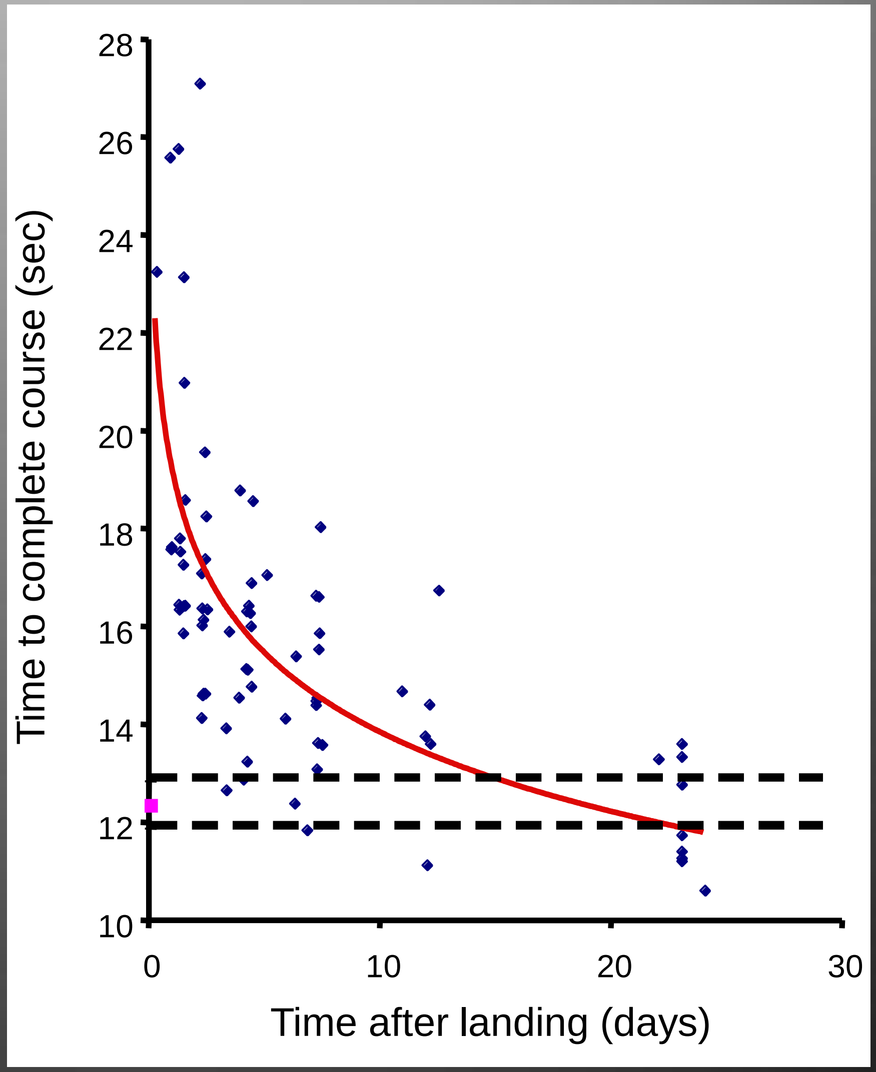
Provides information on the functional and operational implications of postflight locomotor dysfunction

Functional Mobility Test: ISS Results

n = 16



R+1



Preflight mean, 95% confidence interval

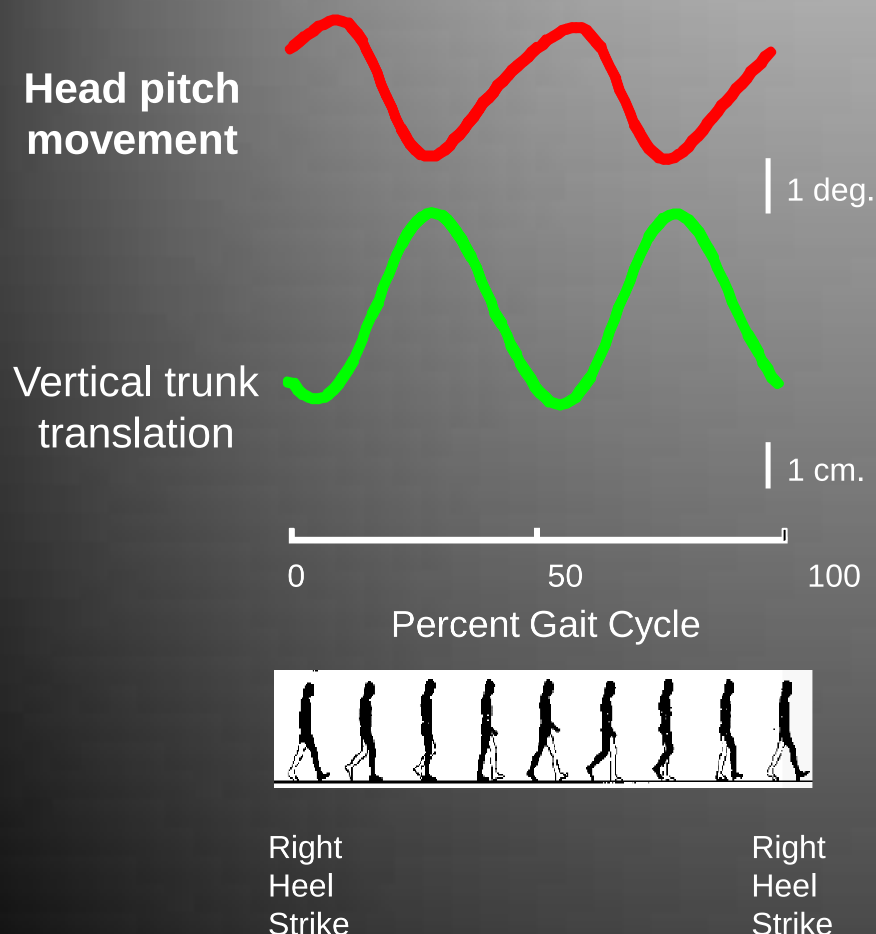
Integrated Treadmill Locomotion Test

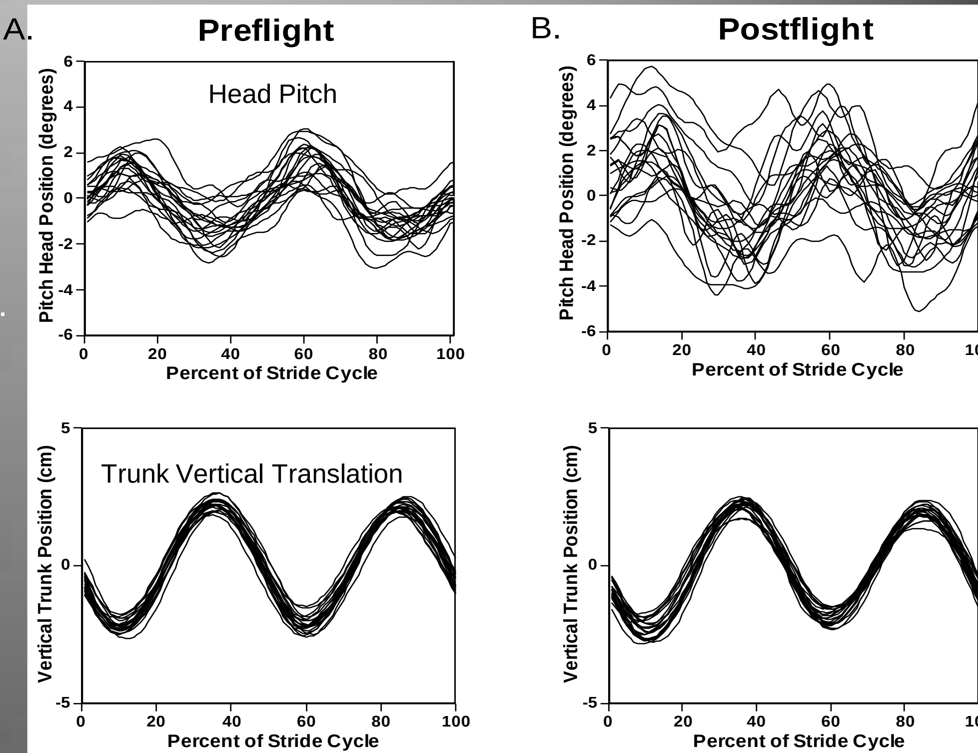
Provides information on changes in underlying sensorimotor mechanisms contributing to alterations in locomotor control.

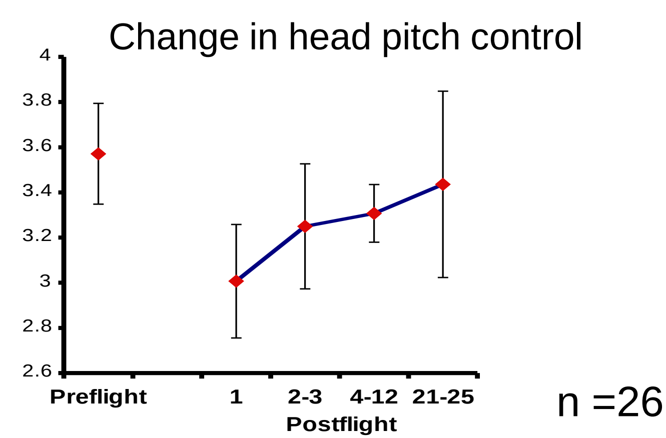
Changes observed in:

- Head-trunk coordination
- Lower limb kinematics
- Lower limb muscle activation patterns
- Gaze stabilization: dynamic visual acuity
- Gait cycle timing

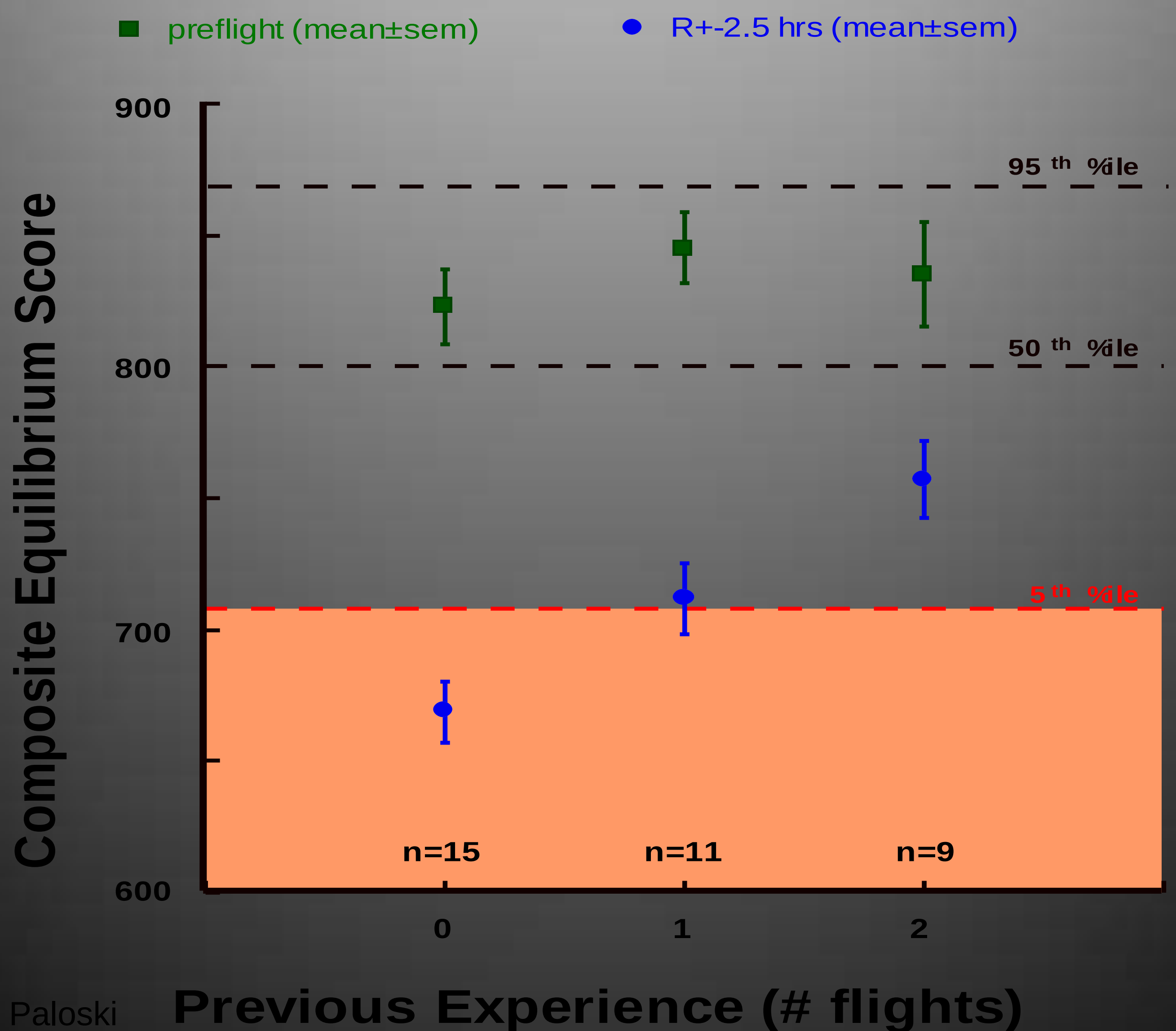
Head-Trunk Coordination During Locomotion







Effect of Previous Space Flight Experience

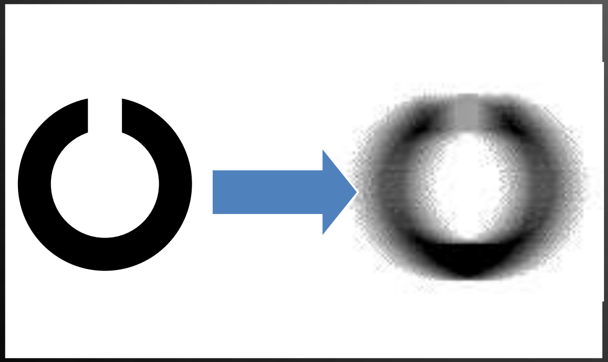


Courtesy of W.H. Paloski

Exposure to space flight

Central reinterpretation vestibular information

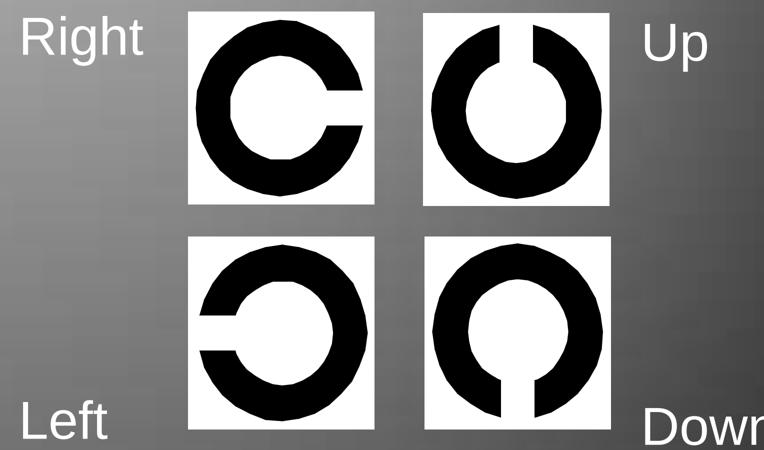
Alteration in gaze stabilization



Reduction in visual acuity during head motion

Dynamic Visual Acuity Test

Landolt-C

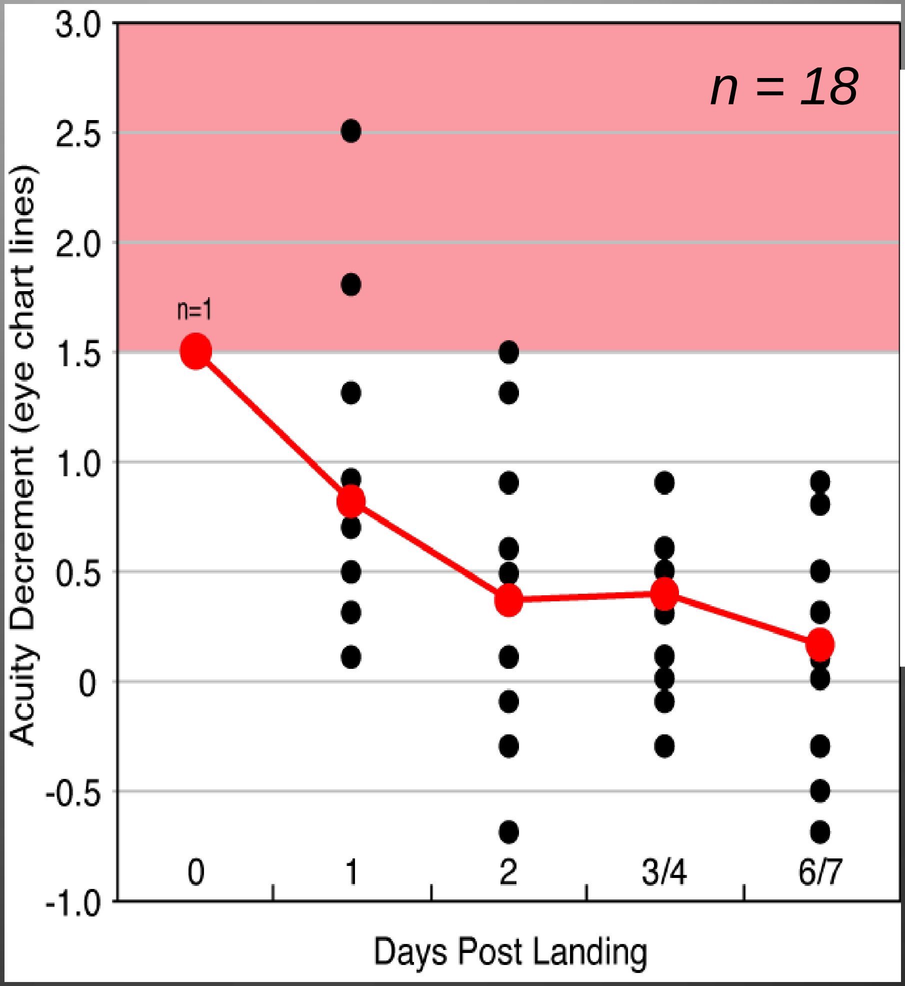


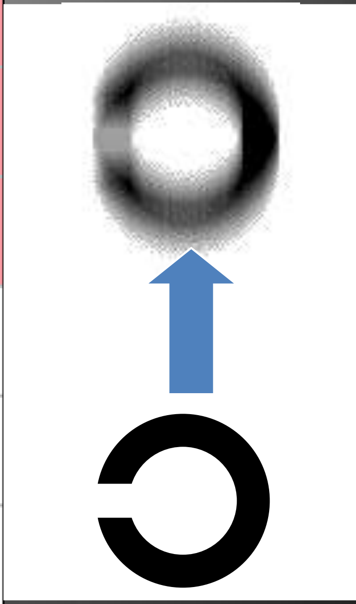
Subject walks on a treadmill at 6.4 km/h and identifies the gap position in the letter C.

- Test hones in on visual acuity threshold
- Comparison is made between static (sitting) and walking acuity

Dynamic Visual Acuity after Long-Duration Space Flight (ISS)

Astronauts show reduction in visual acuity during postflight walking due to changes in gaze control

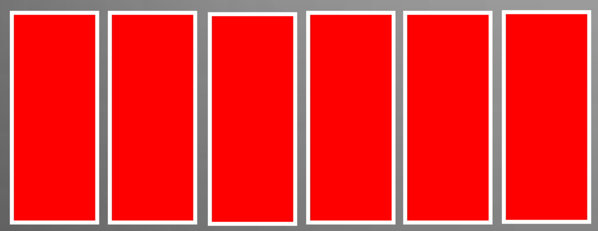




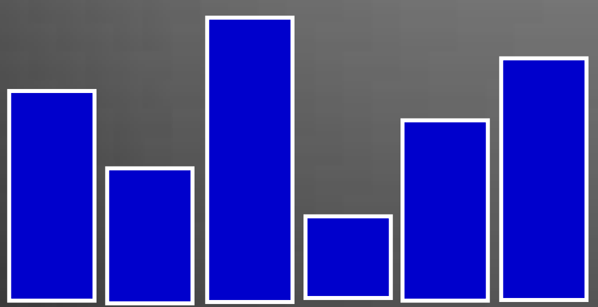
Adaptive Generalization: “learning to learn”

Training Modes

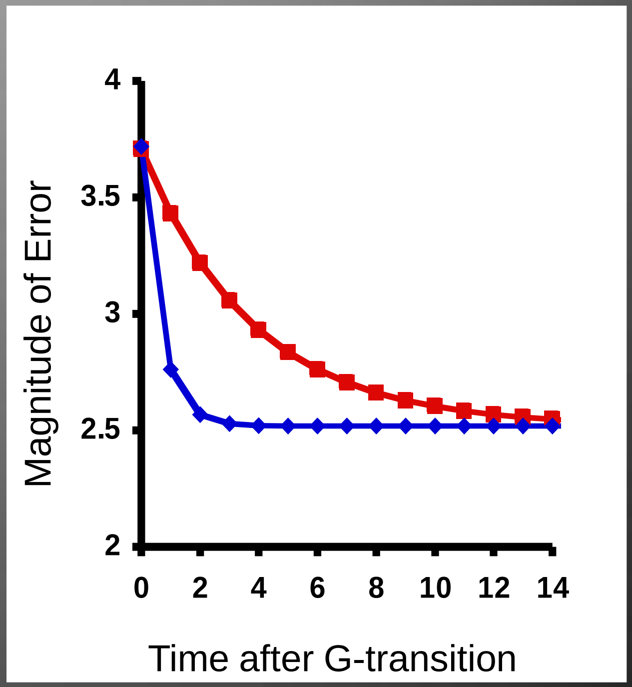
Single Sensory Challenges



Multiple Sensory Challenges



Response to <u>novel</u> sensory environment



Exposure to <u>multiple</u> sensory challenges enhances ability of CNS to adapt to <u>novel</u> environment or task (facilitates “learning to learn”).

US Sensorimotor Countermeasure Approaches

<u>Adaptability Training</u>:
Enhance ability to adapt to novel gravitational environments

<u>Sensory Supplementation</u>:
Use alternate sources of sensory information to provide feedback during adaptive phases.

<u>Artificial Gravity</u>:
Short radius, intermittent exposure

Russian Sensorimotor Countermeasures

<u>Preflight Motion Training</u>: rotating chair with coupled head movements provides desensitization training

<u>Penguin Suit</u>: provides sustained axial loading

<u>Foot Pressure Insoles</u>: maintain postural responses

Sensory-motor Adaptability Training

Goal:

- Develop a training program to facilitate rapid adaptation to different gravitational environments
- Will facilitate:
  - Adaptation to Moon/Mars environments
  - Readaptation to Earth

ASCR

ASTRONAUT STRENGTH
CONDITIONING &
REHABILITATION

ASCR Group History

- Program originally developed to aid crew members in preparing for extra vehicular activities (EVA’s)
- Program evolved to add emphasis towards physical demands for all phases of spaceflight (pre-,in-,post-)
- Expanded focus including athletic trainers

Role of an ASCR

- The ASCR team follows the traditional model used by Sports Medicine Departments

- The ASCR team consists of 6 members who are Certified Athletic Trainers (ATC) or Certified Strength and Conditioning Specialists (CSCS).
  - Four ATCs handle the musculoskeletal injuries
  - Two CSCS focuses on the physical readiness

Members of the ASCR Team

- Certified Athletic Trainers (ATC)
- Texas Licensed Athletic Trainer (LAT)
  - Injury prevention assessments
  - Injury evaluation
  - Treatment and rehabilitation of injuries

Christi Baker

Stephanie Fox (Horton)

David Hoellen

Bruce Nieschwitz

Members of the ASCR Team

- Certified Strength and Conditioning Specialists (CSCS)

Mark Guilliams

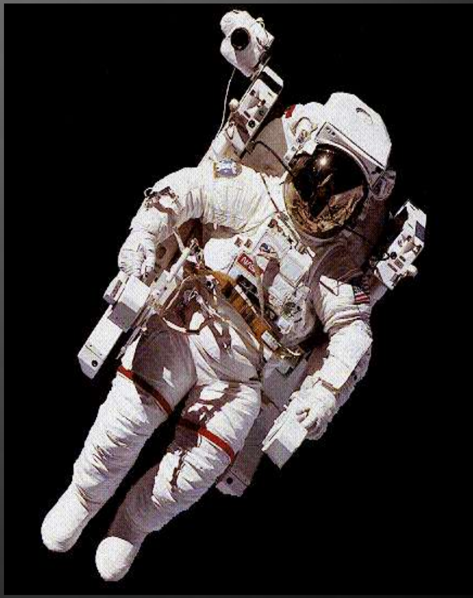
Jim Loehr

Duties of an ASCR

- Pre-Flight Workouts
- In-Flight Workouts
- Post-Flight Reconditioning and Workouts
- Advanced Resistive Exercise Device (ARED) Training
- Functional Fitness Assessment
- Annual Physical Assessment
- Prevention of Injuries
- Continuing Education

Challenges of Human Spaceflight

- Expected issues faced during spaceflight and upon return to gravity
  - Bone loss
  - Muscle atrophy
  - Orthostatic intolerance
  - Neuromuscular/proprioception changes
  - Neurovestibular changes
  - Easily fatigued



Bone Adaptations

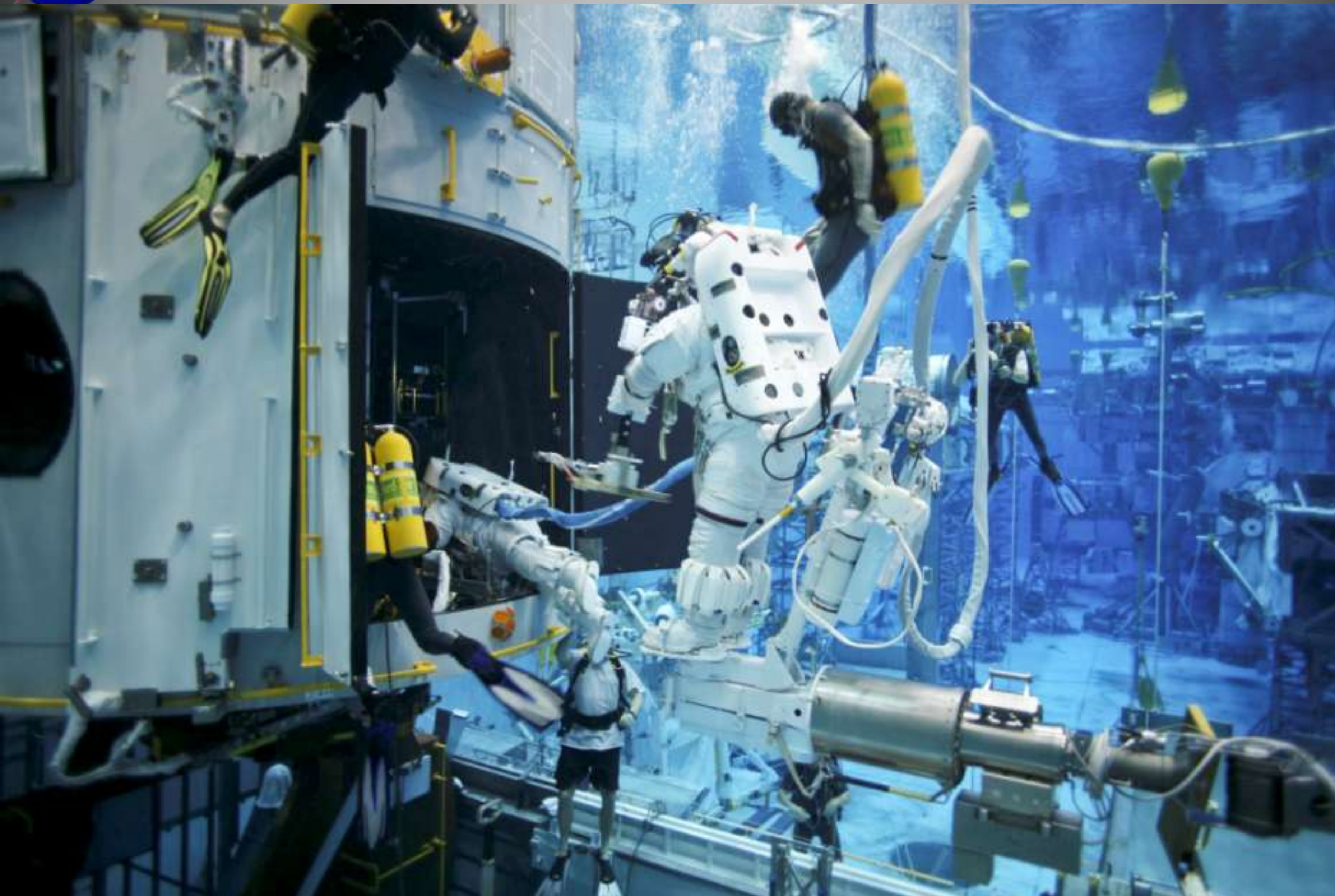
- Bone begins to remodel in as little as 3 days of microgravity
  - Over-time the changes to bone result in losses of bone mineral density (BMD)
- About 1% of total bone mass is lost per month, 12x faster than with osteoporosis
  - The changes occur faster in load bearing bones

Muscle Adaptations

- Removal of mechanical loads & less work causes changes in muscle size, strength, endurance and flexibility
- Loss of balance and agility due to lack of interpreting stimuli by the vestibular system
- Muscles of the legs, hip, trunk, and neck will require the most effort to maintain mass and function

Pre-Flight Workouts

- Develop a plan with an ASCR
- Workouts consist of:
  - Adequate warm-up and stretching routine
  - Daily workout
  - Traditional strength program
  - Cool down and stretching



EXERCISE IS ONE OF THE MOST PROMISING COUNTERMEASURES FOR MICROGRAVITY RELATED BONE LOSS AND MUSCLE ATROPHY

ISS In-Flight Exercises

- Aerobic Conditioning – Cycle Ergometer with Vibration Isolation System or Treadmill with Vibration Isolation System (CEVIS or TVIS)
  - 60 minutes
  - 6 times per week
- Resistance Training (ARED)
  - 90 minutes
  - 6 times per week
- Scheduled times may vary due to EVA, docked operations, etc.

Astronaut Don Pettit on CEVIS

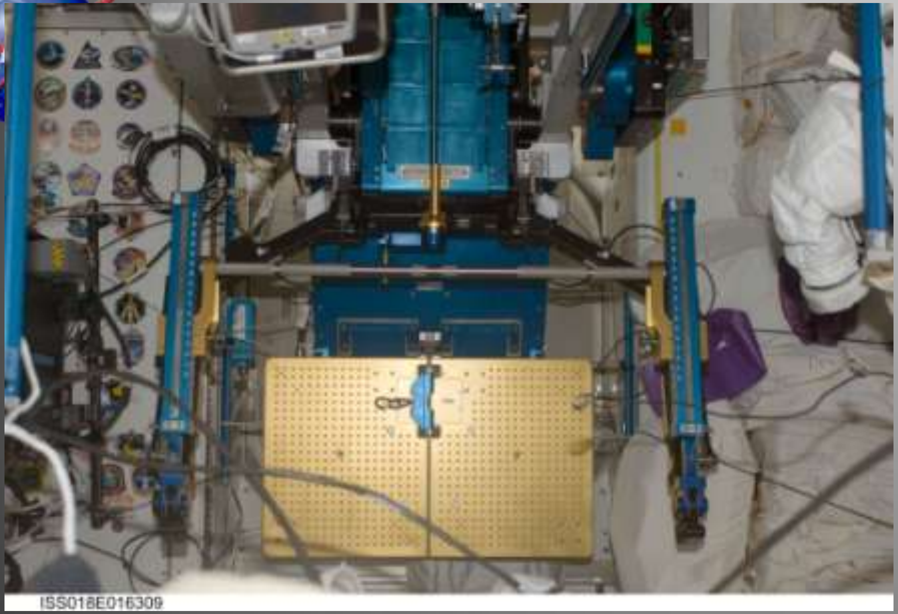
Astronaut Joe Acaba on shuttle ergometer

Astronaut Garrett Reisman on CEVIS

Astronaut Jim Voss on CEVIS & VELO

Astronaut Jeff Williams on TVIS

Astronaut Koichi Wakata on TVIS



Astronaut Lee Archambault squatting on ARED

Astronaut Koychi Wakata deadlifing on ARED

Astronaut Sandy Magnus performing SL calf raise on ARED

Astronaut Sandy Magnus performing deadlift on ARED

ISS014-E-19454 (16 April 2007) --- Flashing a thumbs up sign here, astronaut Sunita L. Williams, Expedition 14 flight engineer, circled Earth almost three times as she participated in the Boston Marathon.

During the race, Williams ran at about six miles per hour while flying more than five miles each second, as she completed the marathon on a station treadmill.

Williams' official completion time was four hours, 23 minutes and 10 seconds as she completed the race at 2:24 p.m. (EDT).

Post-Flight Reconditioning

- Long duration crewmembers go through a 45 day reconditioning phase
- This phase consists of 2 hours daily to return the crewmember to pre-flight status

Annual Fitness Assessment

- Cardiovascular fitness
  - Timed 1.5-mile run
- Sit and reach (hamstring and trunk flexibility)
- Shoulder flexibility
- Maximum push-ups in two minutes
- Maximum sit-ups in two minutes
- Maximum pull-ups (minimum requirement is two)
- Handgrip strength

- Assist in scheduling appointments with off-site consulting physicians
- Pre-surgery pre-hab
- Post-surgical rehabilitation
- Return to work evaluations
  - T-38, EMU (Extravehicular Mobility Unit)
- Orthopedic Screenings
  - EMU, Weight Room
- Preventive exercises & education programs

- Cryotherapy
  - Ice packs
  - Ice massage
  - Cold whirlpool
- Thermotherapy
  - Moist heat packs
  - Hot whirlpool
- Variable Compression
- Massage
- Electric Stim
- Iontophoresis
- Ultrasound
  - Phonophoresis

Advantages of On-site Treatment & Rehabilitation

- Help crewmembers avoid injuries through prevention techniques while decreasing the downtime when injuries occur
- Refer crewmembers to FMC in order to get physician evaluation
- Promote a constant state of physical readiness

Summary

- Spaceflight is a high risk endeavor (no pun intended)
- Deconditioning is commonplace affecting multiple systems
- One system routinely impacted is the sensory-motor system
  - The longer the mission, the greater the impact
- Safe spaceflight is dependent :
  - Pre-mission fitness
  - Fitness maintenance through countermeasures
  - Post-mission rehabilitation
- Continued research is needed

Implications for DoD and DVA

- Astronauts vs active duty
- Retired astronauts vs retired military
- De-conditioned astronauts vs audiology/ENT patients
- Impact of spaceflight vs impact of combat
- Habilitation and rehabilitation of both groups
- Potential for shared capabilities, techniques, technologies
- Potential for collaborative research

Questions?

Thanks and Good Bye!

STS-109 Astronaut Mike Massamino

John, don’t forget the goodies…

Backup Slides

Human Spaceflight Experience:

The Long and the Short of it…