

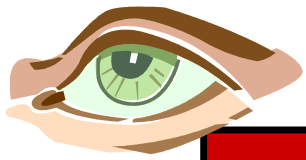
Sensorimotor adaptation during and following spaceflight: Lessons learned for characterization and management of fall risks

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NASA JSC Neuroscience Laboratory

Objectives

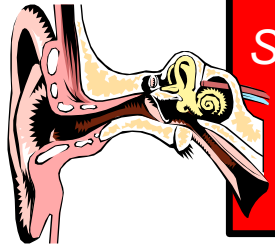
- Sensorimotor adaptation
 - G-transitional nature of risk
 - Clinical assessments
 - Research findings
- Countermeasures
 - Landing & egress
 - Reconditioning
- Lessons learned



VISUAL
 Central (foveal)
 Peripheral

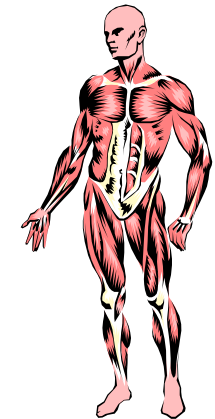


**Control of
 Movement**



INNER EAR
 Semi-circular canals
 Otoliths
 Auditory

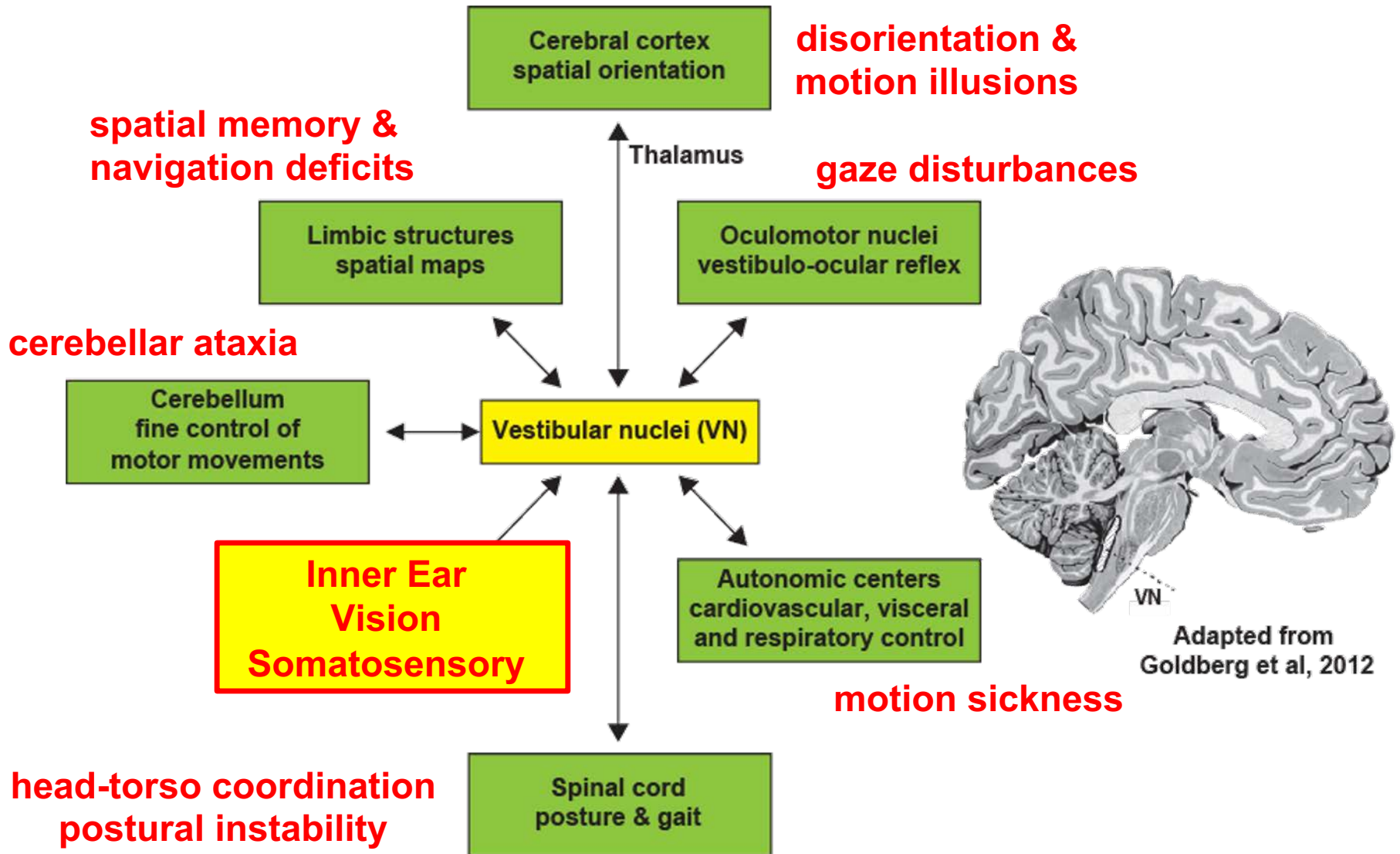
**CENTRAL
INTEGRATION OF
 SENSORY INPUT**



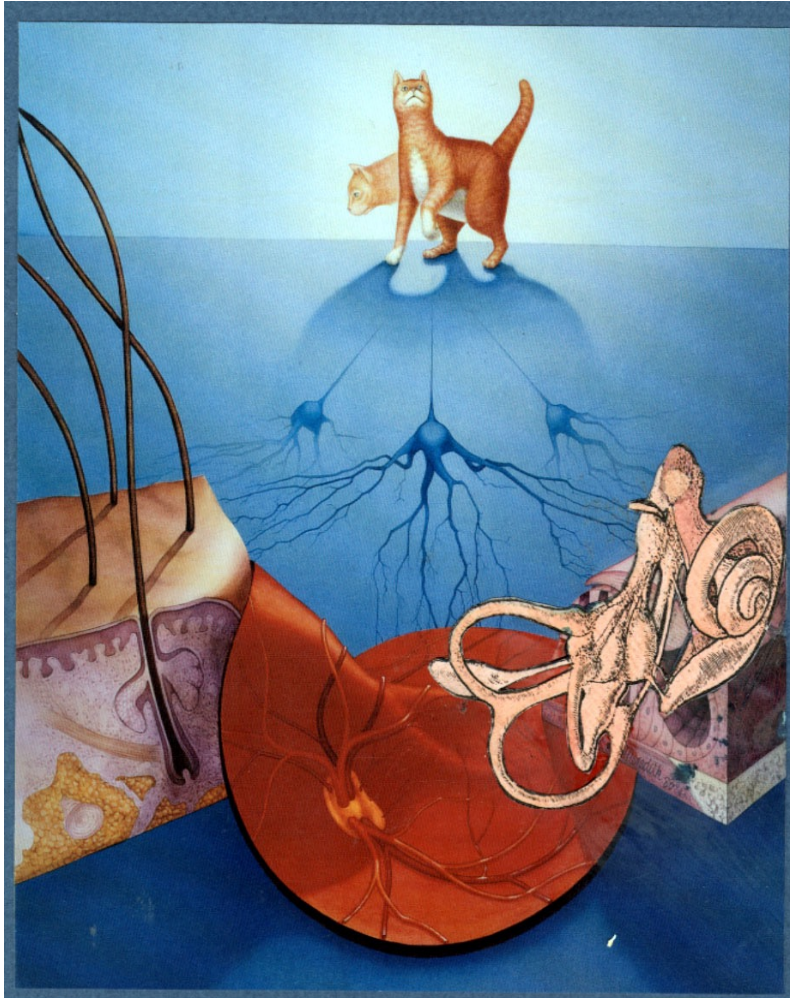
SOMATOSENSORY
 Proprioception (joint),
 Exteroception (tactile),
 Interoception (viscera)

**Brain integrates visual, vestibular and somatosensory
 input to control body movement**

Vestibular signs/symptoms



Multisensory integration



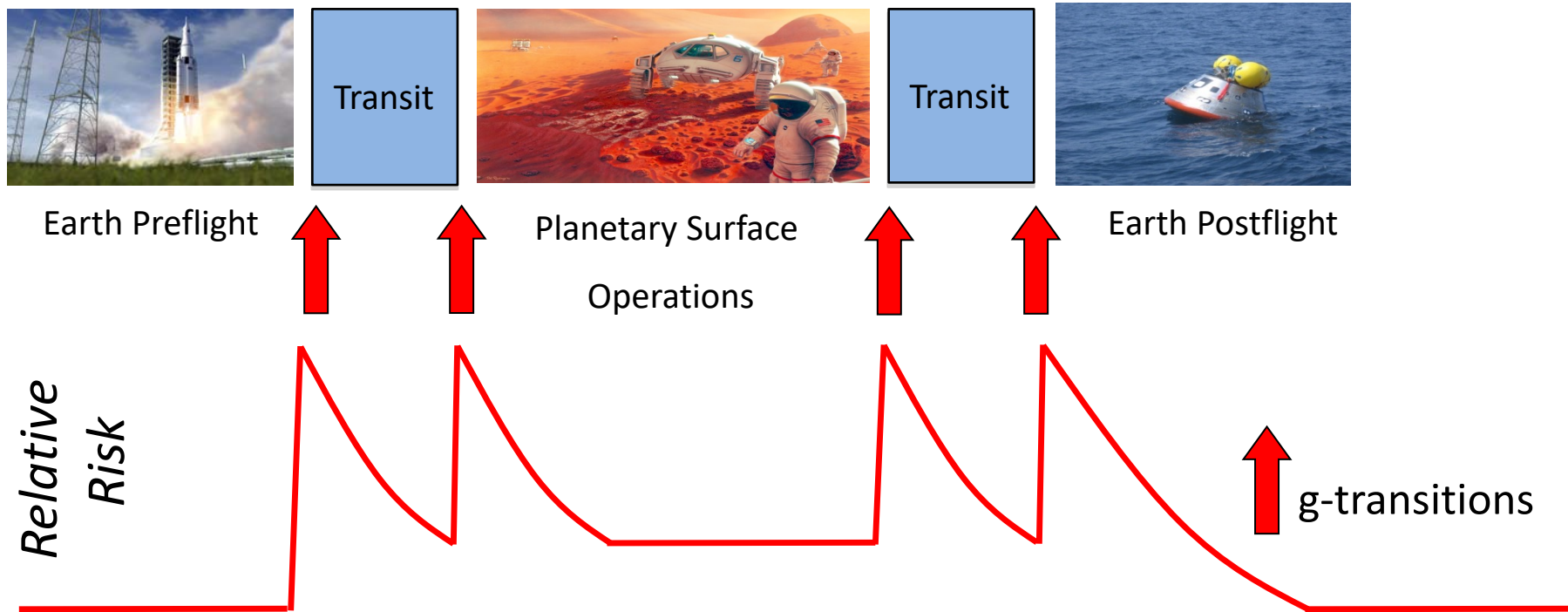
- Our ability to sense motion and orientation depends on a learned ability to interpret the continuous input of multiple sensory signals
- Redundancy means that one system can compensate for limitations in another
- Redundancy also sets up potential for sensory conflict through aging, pathology or environmental change

Mechanisms of adaptation

- Gravitational unloading
 - Altered proprioception for mass discrimination and force control
 - Deconditioning
 - Changes in sensor morphology
- Multisensory integration
 - Different patterns of sensory cues, e.g., otolith cues during head tilt
 - Interaction with support surfaces for locomotion and orientation
- Adaptive for microgravity ...
maladaptive for transition to new gravitoinertial state



SM Risk greatest at G-transitions



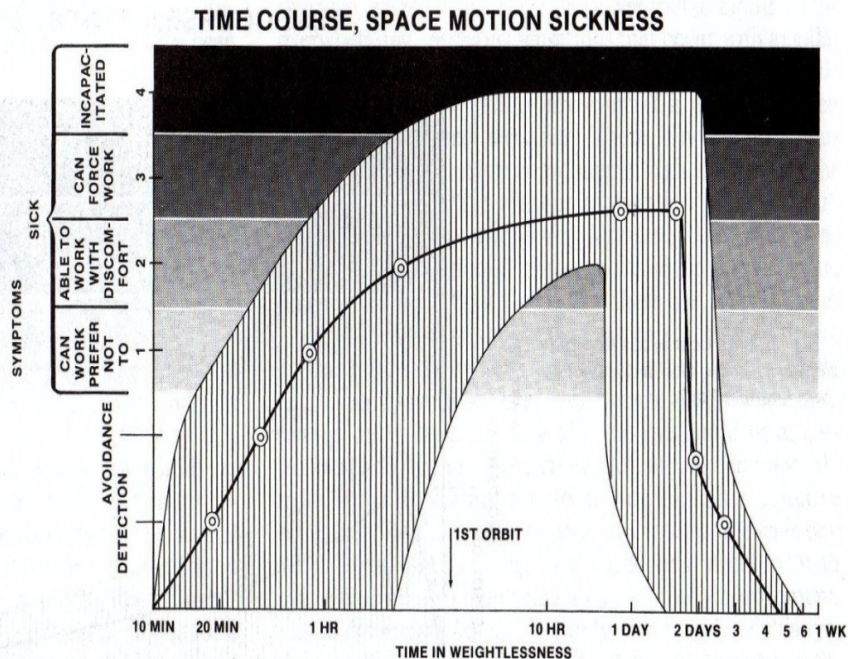
- Adaptive changes that optimize sensorimotor function in one gravity environment are maladaptive for transitions to other gravity states
- High degree of intersubject variability, and level of functional decrements and time of recovery vary as a function of flight duration

Other risk factors

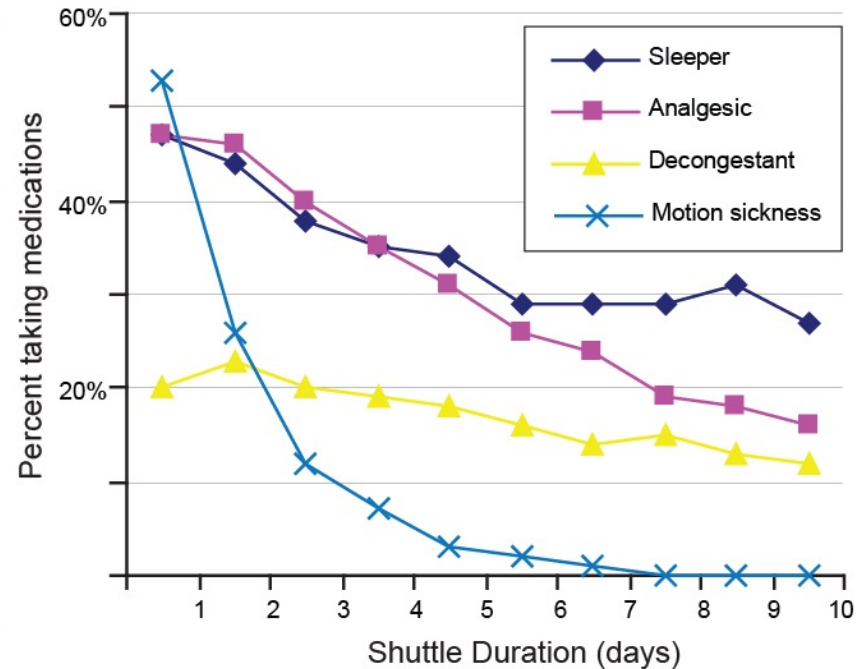
- **Individual variability**
- **Length of flight**
- **Workload and task complexity**
- **Crew experience**
- **Use of medication**
- **Suit design**
- **Spacecraft architecture**



Space Motion Sickness (SMS)



Thornton et al., 1987



Putch a et al, 1999

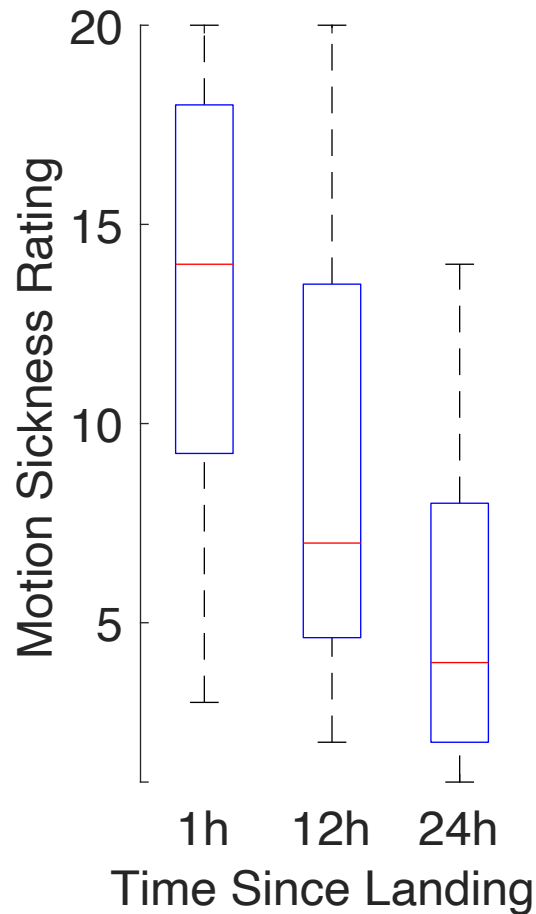
- Inflight space motion sickness (SMS) incidence ~70%, developing within hours and resolving within 2-3 days but may persist in a few (Jennings, 1998, Reschke et al, 2018)
- SMS severity highly variable across crews, with decreased incidence in repeat flyers (Davis et al, 1988)

Space Motion Sickness (SMS)

- Symptoms alleviated by:
 - Medications (e.g., IM Phenergan)
 - restriction of early activities
 - maintain familiar orientation wrt visual environment
 - maintain contact cues
- Difficult to predict susceptibility from terrestrial analogs
 - Most promising: reversing prisms (Oman et al., 1986), torsional disconjugacy (Markham & Diamond, 1993), 90m exposure to 3Gx (Bles et al., 1997)
- “Re-entry Sickness” on return ~30% after 1-2 week missions, greater after longer duration flights (100% after 6 mo based on recent field tests)



Re-entry motion sickness



(Pilot and Full Field Tests, Reschke & Kozlovskaya, n=38)

Post-flight STS neuro exam

Rank Order	Neurological Function Test	% with positive signs on Landing Day
1	Tandem/Heel to Toe Walk (eyes open)	57.0%
2	Gaze/Ocular Movements	55.0%
3	Dynamic Equilibrium	47.2%
4	Leg lift-Hop	39.6%
5	Standing/ Romberg	22.2%
6	Finger to Nose	19.4%
7	Dizziness/Faintness	16.5%
8	Rising from Chair	13.8%
9	Vertigo/Spinning	11.9%
10	Drift	10.2%
11	Headache	7.5%



Clark JB. J Vestib Res (2002)
11:321-322

Sensory Organization Tests

Altered Vision

Eyes Open

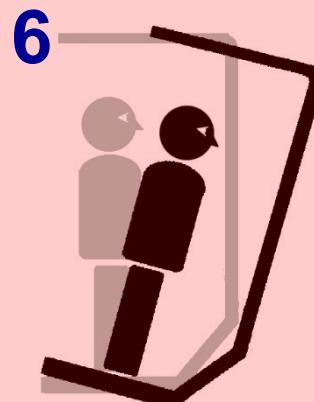
Eyes Closed

Head-Fixed Surround

Fixed Support



Unstable Support



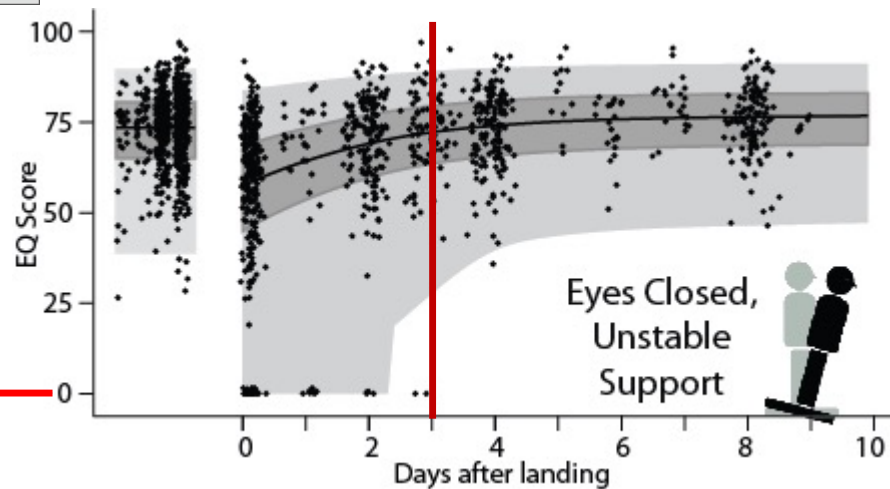
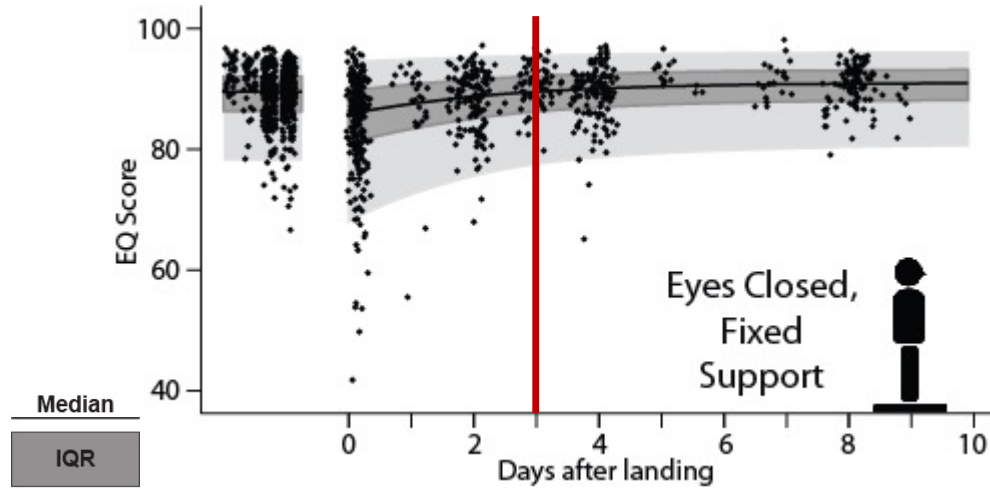
Altered Somatosensory



Nashner et al., J Neurosci
(1982) 2:536-544

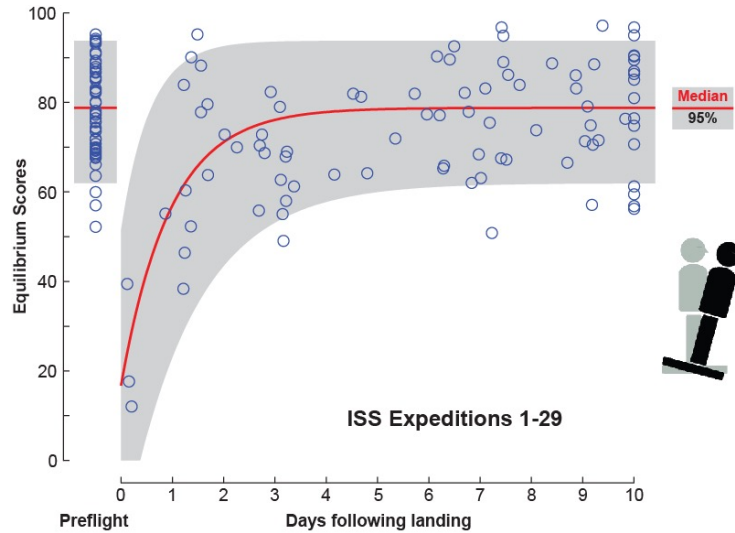
Supplement to Post-Shuttle Neuro Exam

← Less stable
Fall



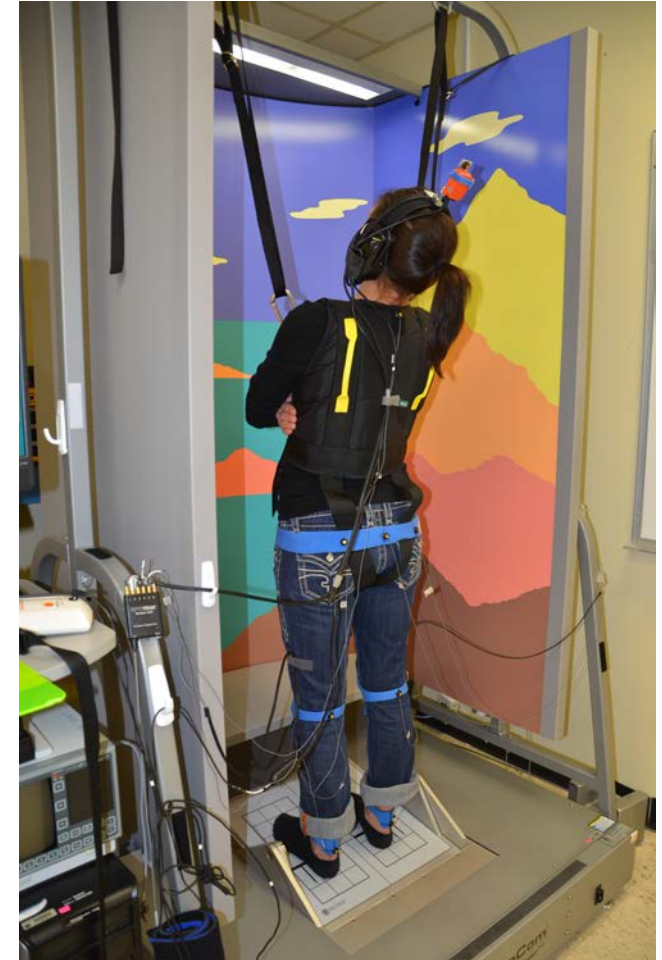
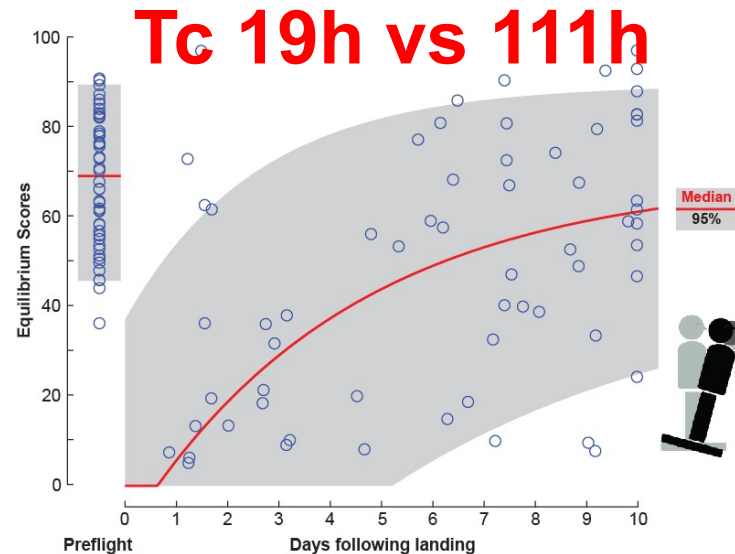
Sharpen tests with head tilts

Head Erect



Head Moving

**Pitch
0.33 Hz
 $\pm 20^\circ$**

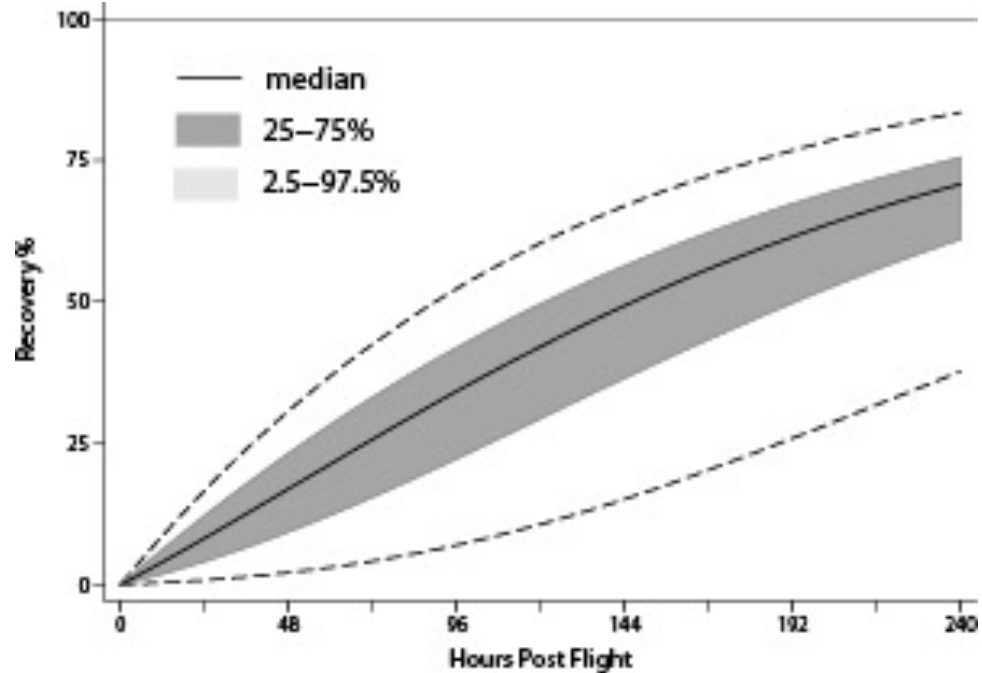
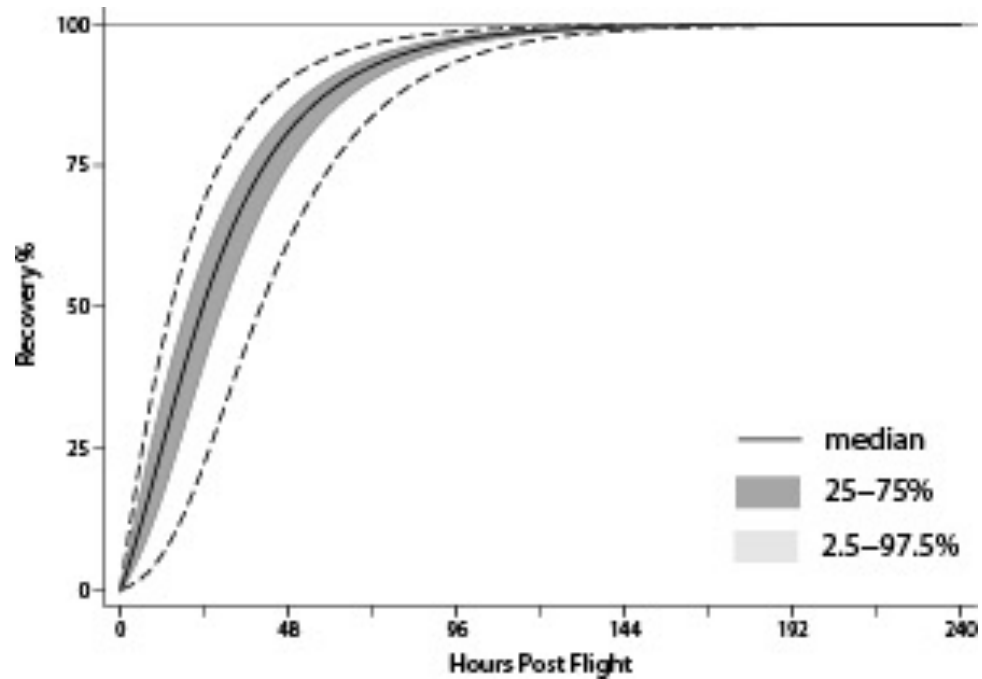


Short



SOT-5M
Eyes Closed,
Unstable support,
Head moving

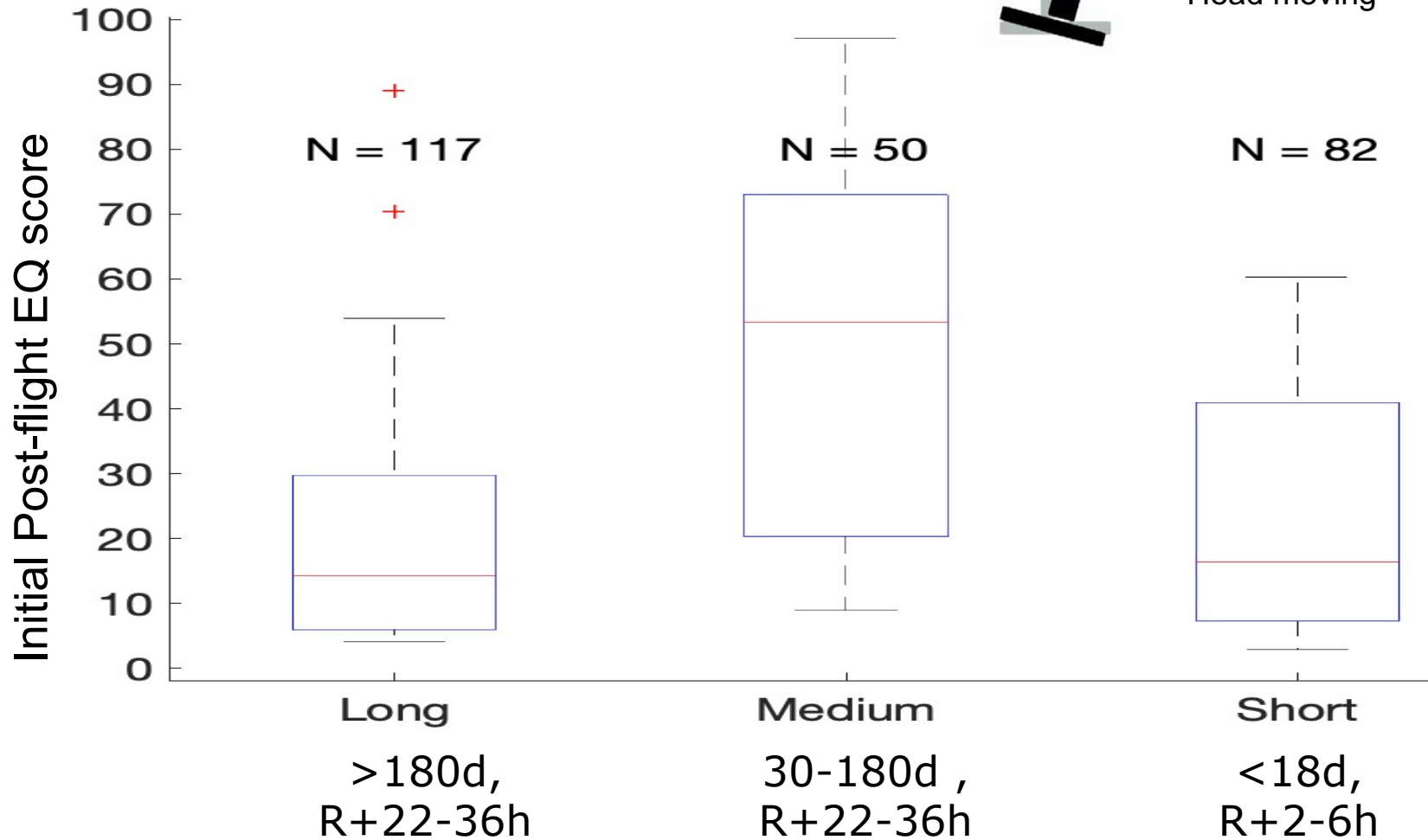
Long



Effect of duration



SOT-5M
Eyes Closed,
Unstable support,
Head moving



Functional Task Test

Functional Performance

Seat Egress and Walk

Ladder Climb

Recovery from Fall/Stand

Rock Translation

Construction Activity

Torque Generation

Jump Down

Physiological Measures

Muscle

- Strength
- Power
- Control
- Neuromuscular Drive



Sensorimotor

- Balance
- Gait
- Dynamic Visual Acuity
- Fine Motor Control

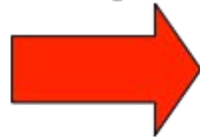


Cardiovascular

- Plasma Volume
- Heart Rate
- Blood Pressure

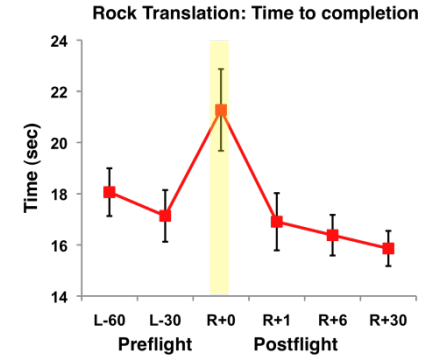
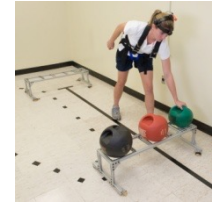
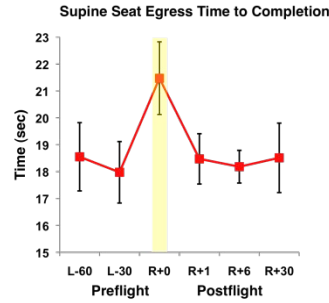
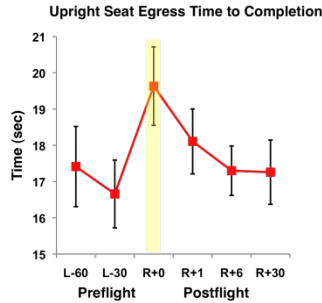
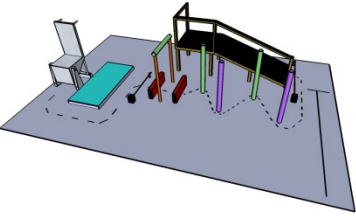


Map



Interdisciplinary testing regimen maps postflight functional performance to related physiological changes.

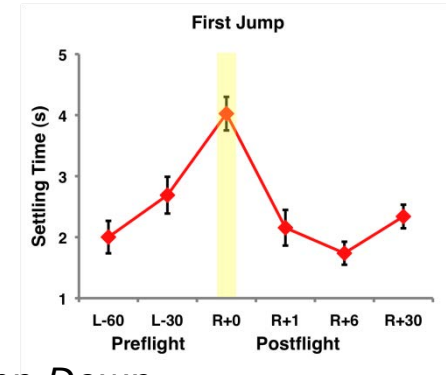
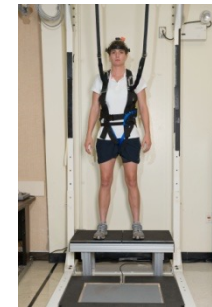
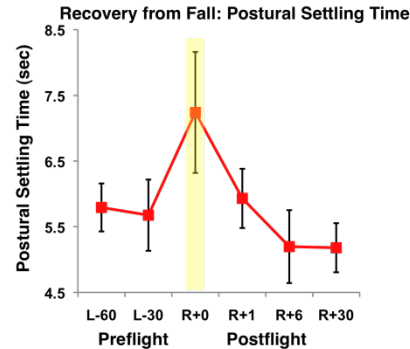
Functional task tests



Shuttle n = 7

Seat Egress and Walk

Rock Translation



Recovery from Fall/Stand

Jump Down

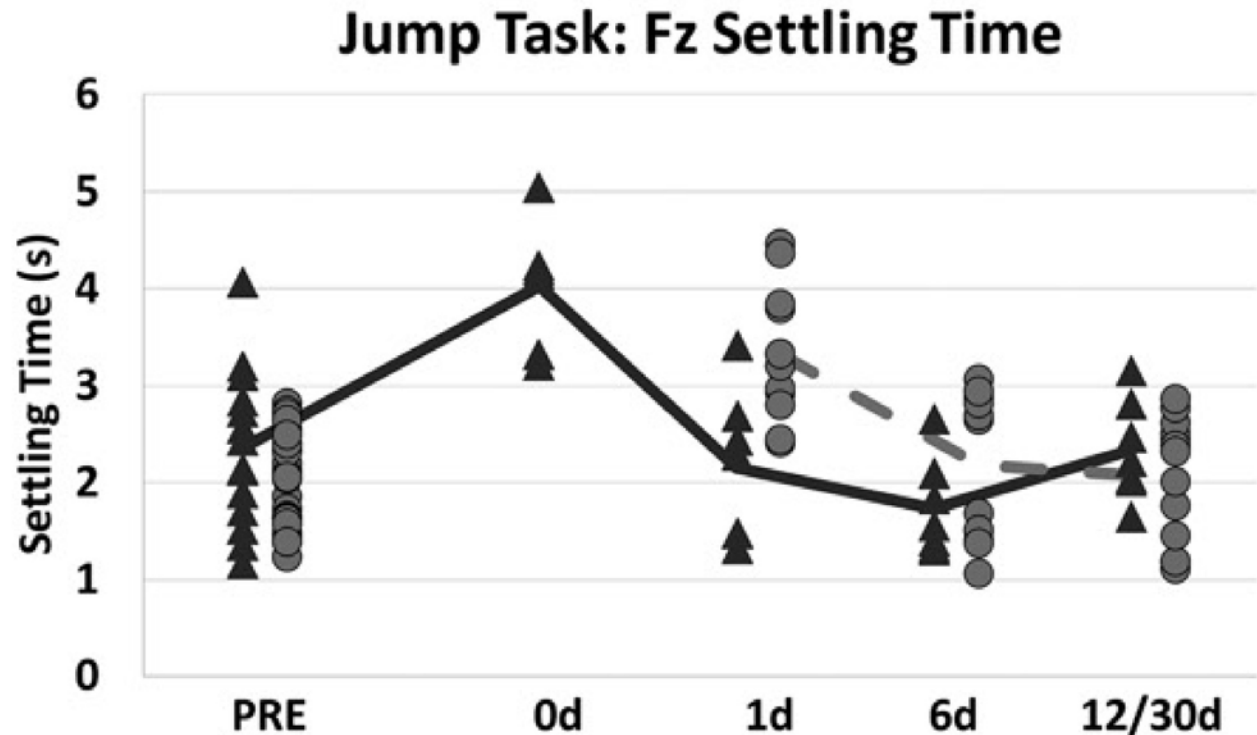
Functional tasks with a postural equilibrium challenge show the greatest change shortly after Shuttle landings (Bloomberg et al, 2012)

Functional task tests

—▲— Short-duration Flight

··●·· Long-duration Flight

*Jump
Down*

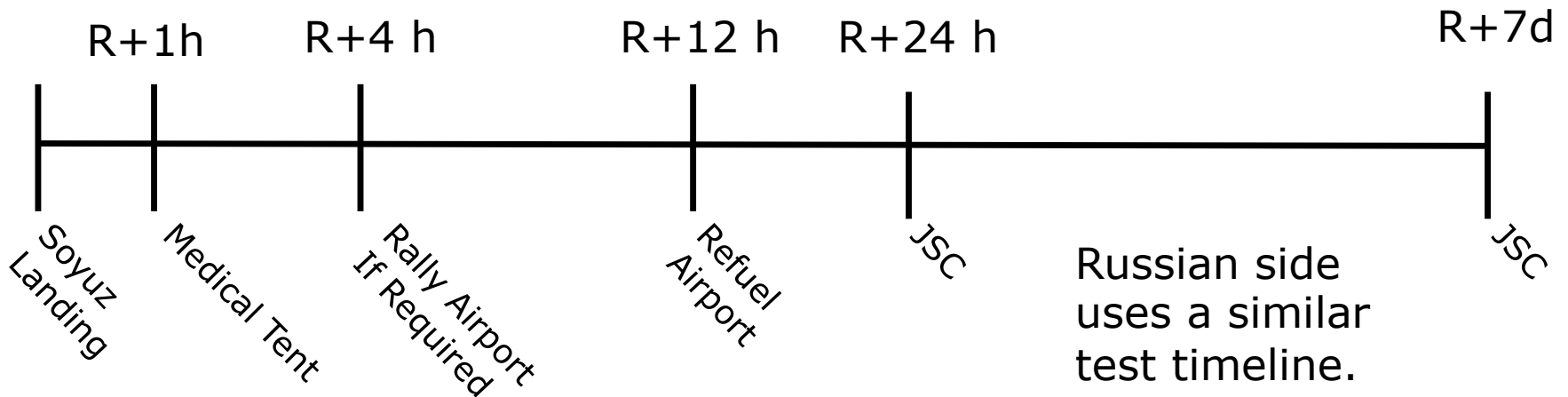


- Performance more impaired following longer duration ISS missions on R+1 compared to short-duration STS missions (Miller et al, 2018)

Field Test: Early Postflight Testing

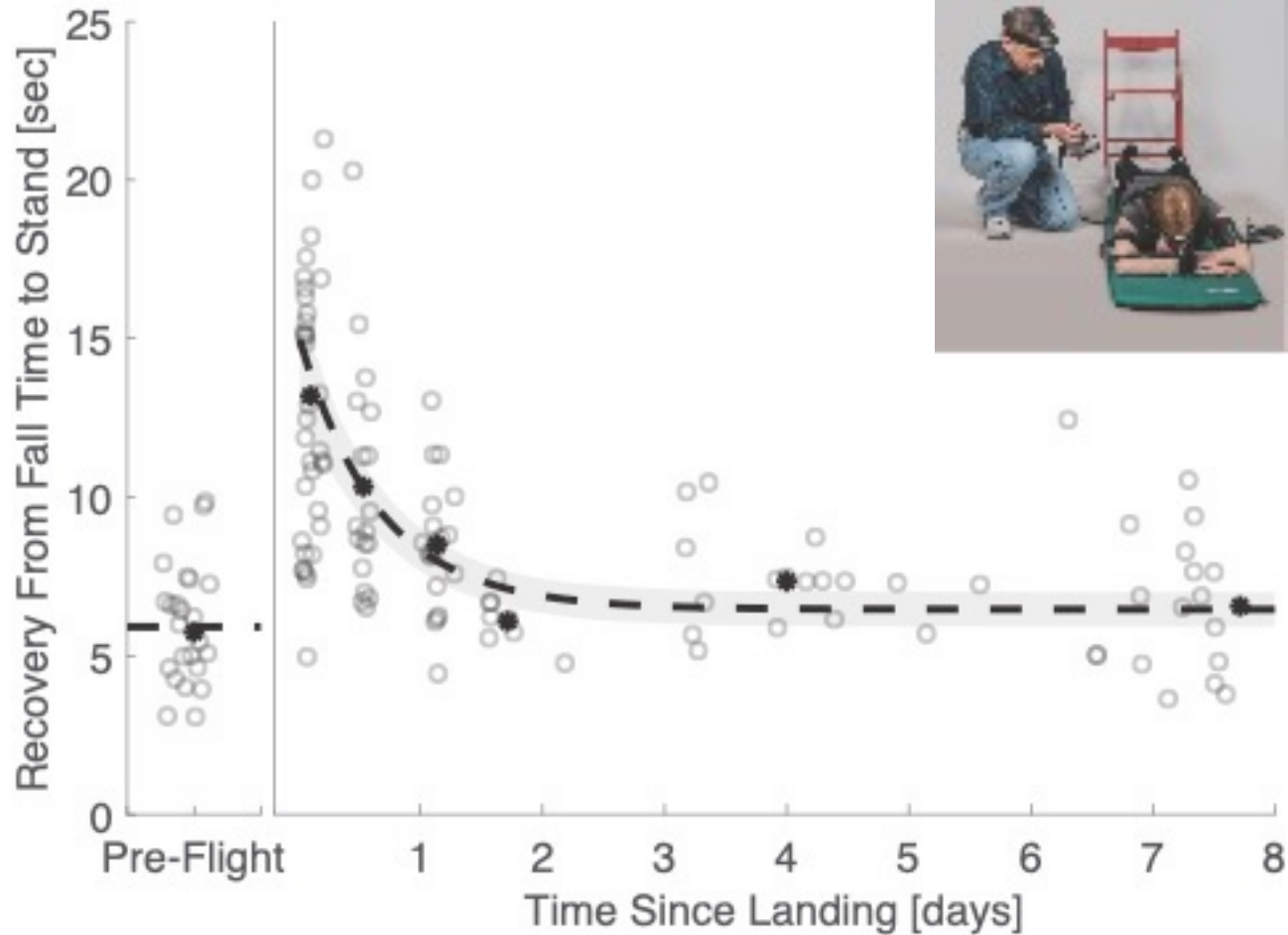


Field Test: Early Postflight Testing



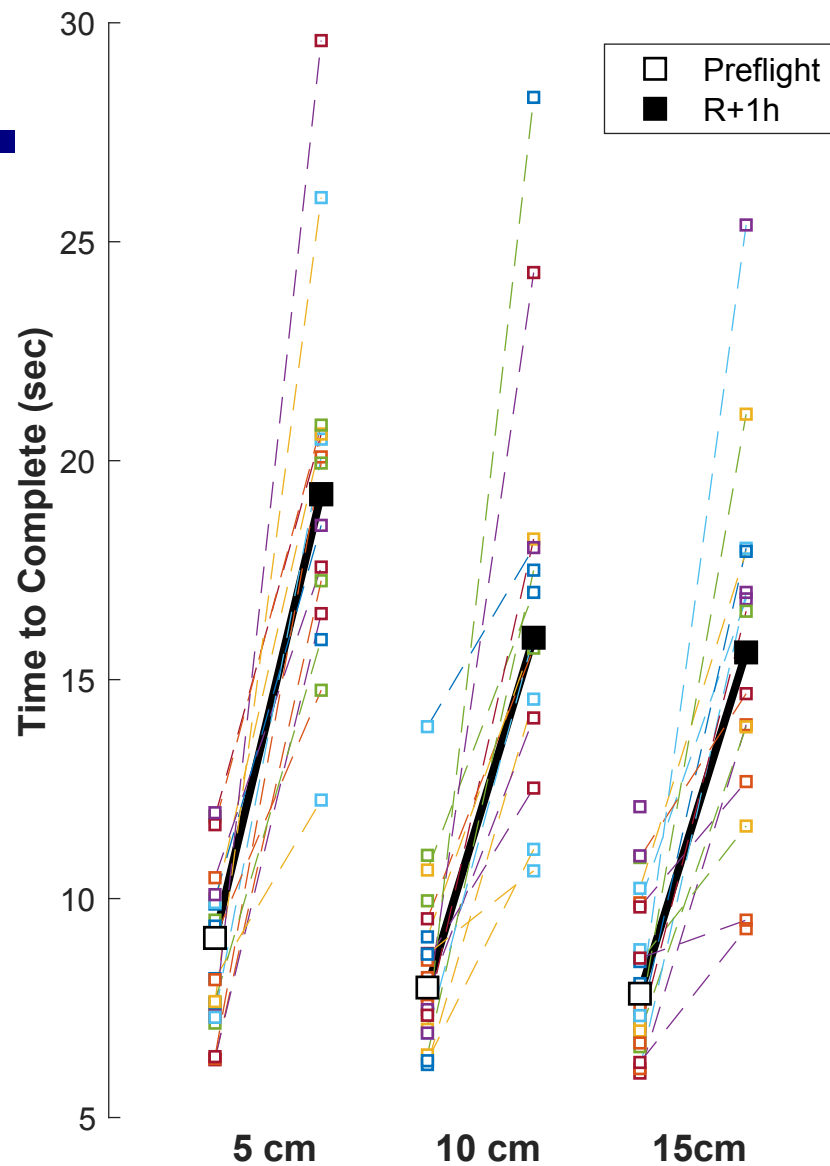
PIs: M. Reschke, I. Kozlovskaya

Recovery from fall



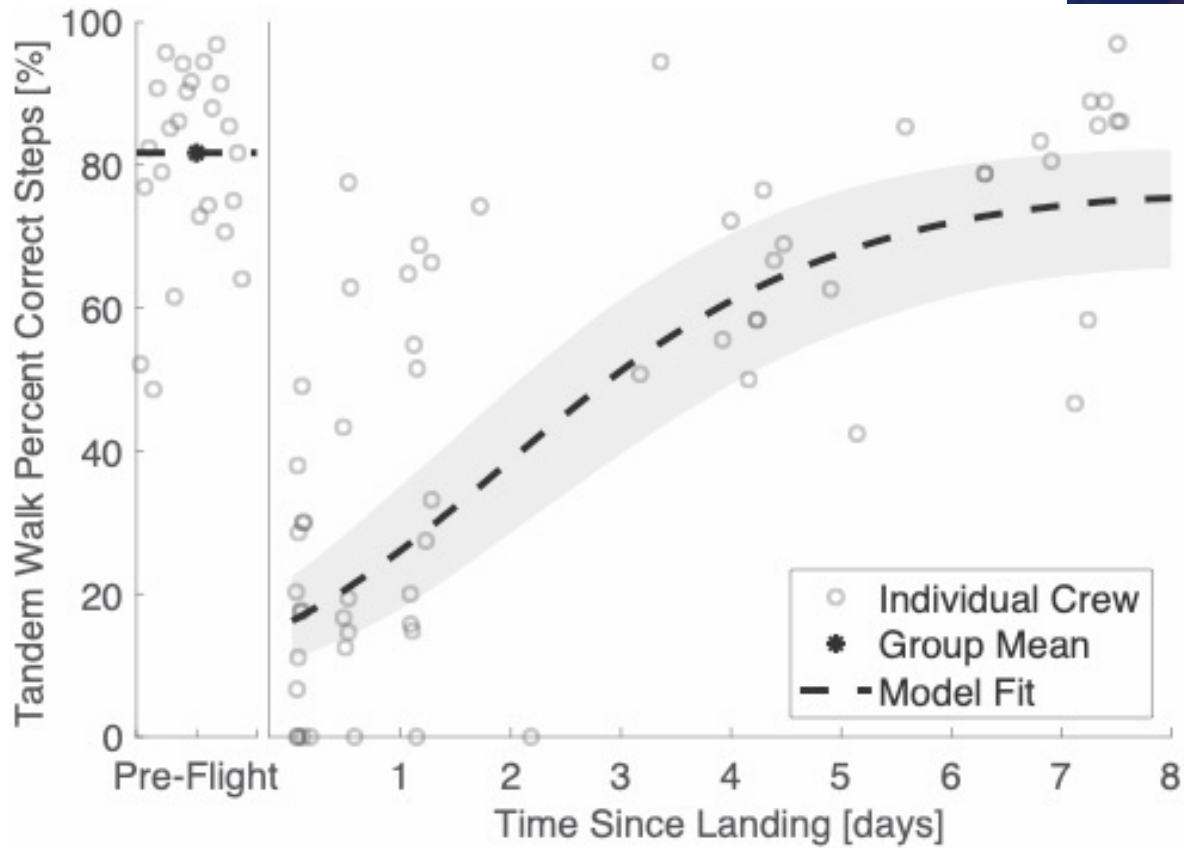
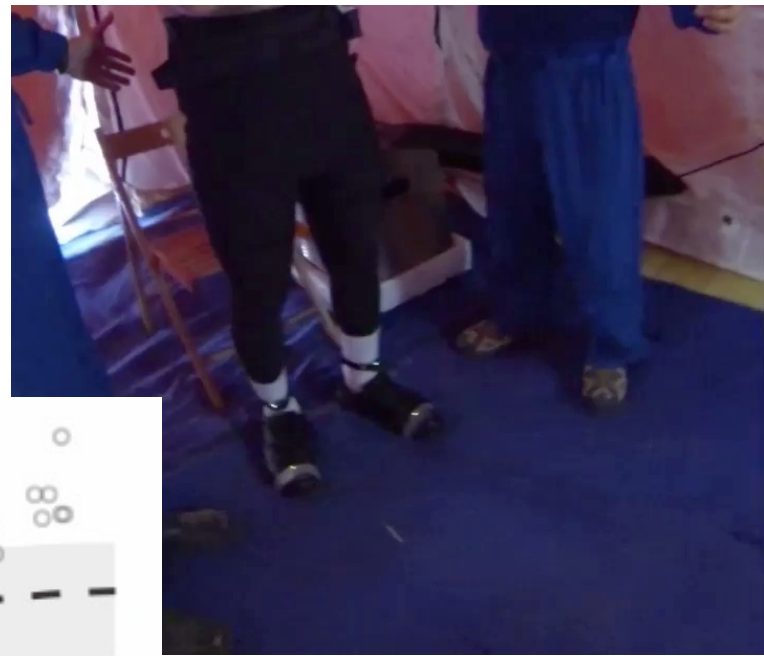
- Individual Crew
- Group Mean
- - Model Fit

Obstacle Walk

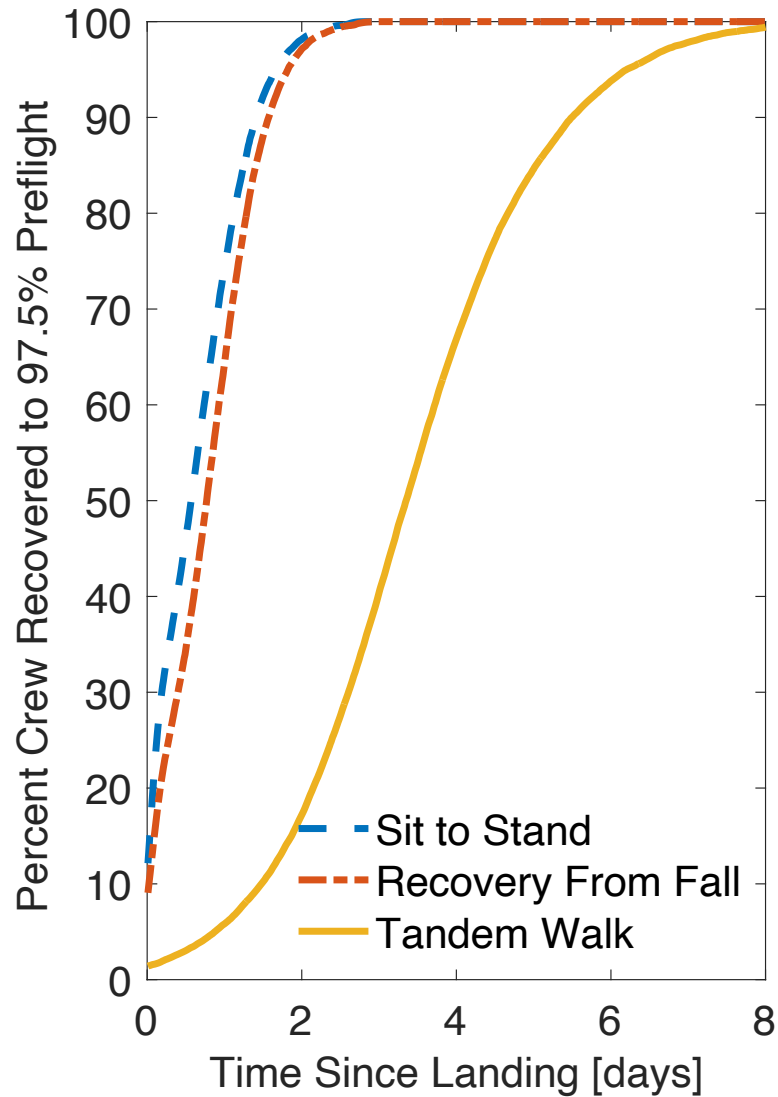


(Reschke et al., 2020)

Tandem walk



Recovery curves



Sit-to-stand



Recovery from Fall

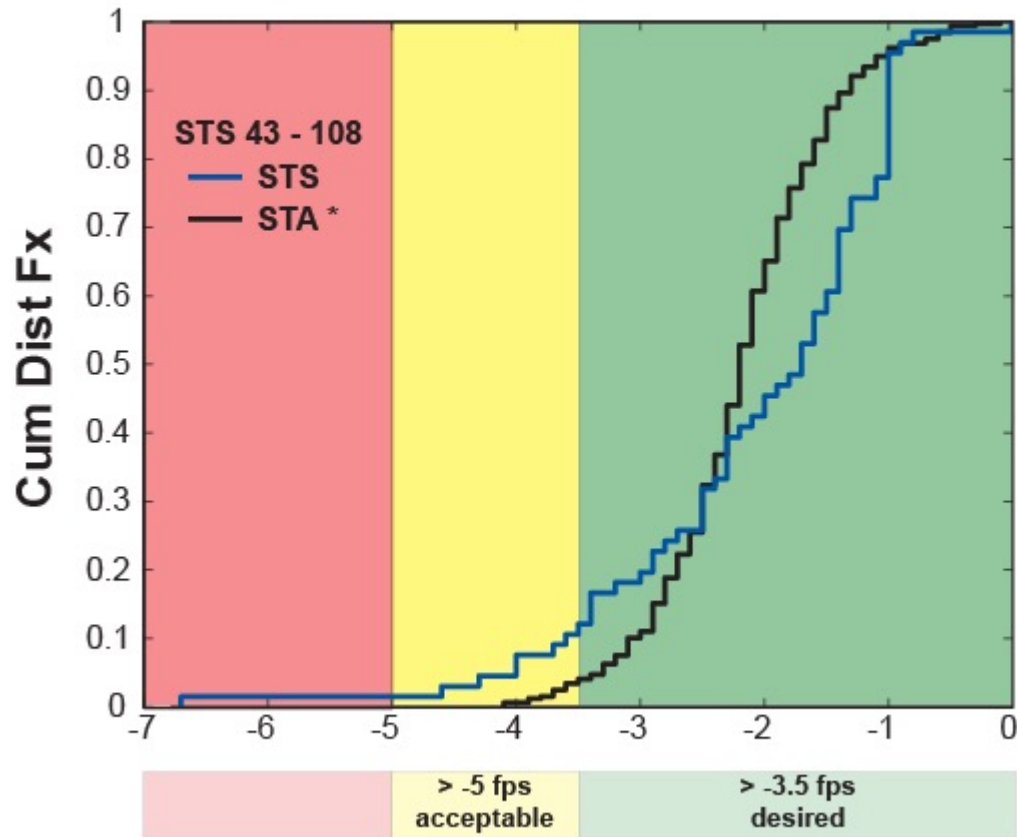


Tandem Walk



Manual control

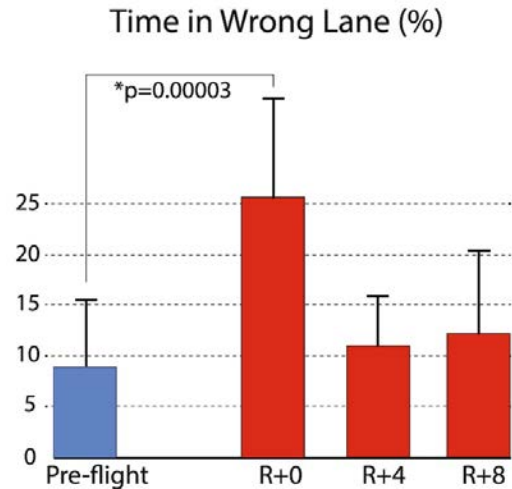
Vertical Velocity at Touchdown
STS Landing versus STA



* Note: STA data from same CDRs within 1 month of launch



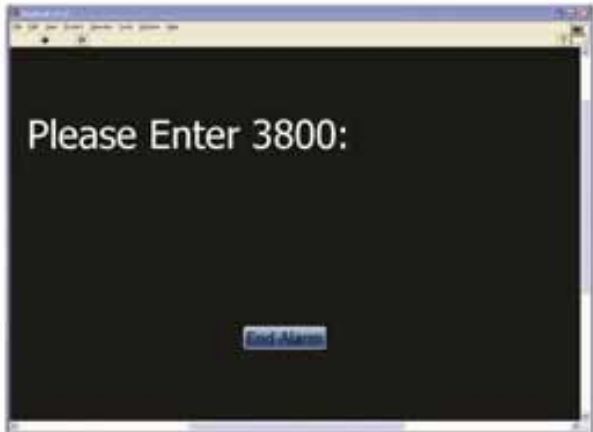
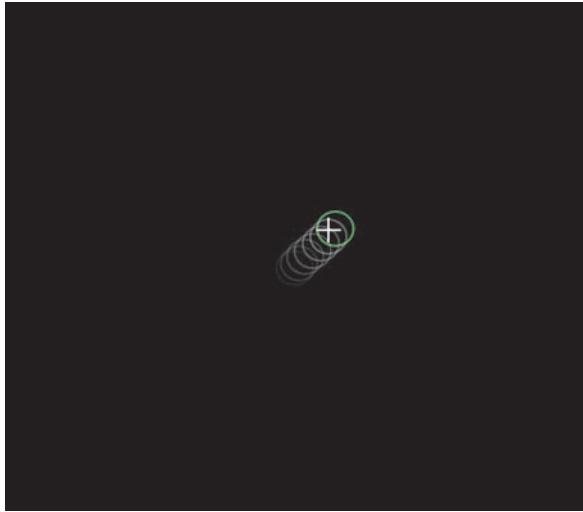
Manual Control



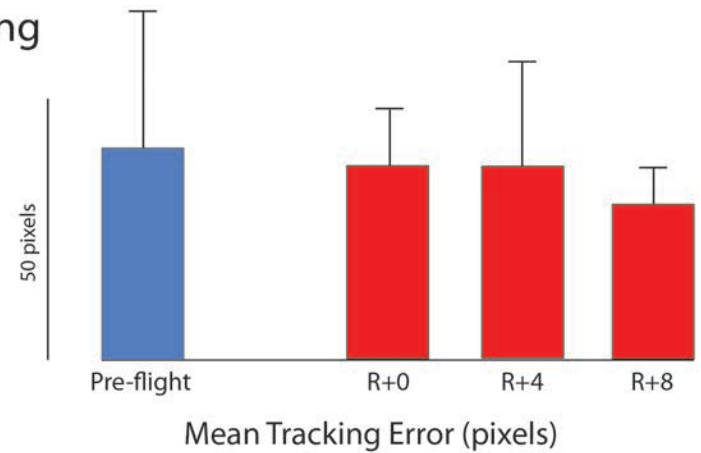
Moore et al., 2019, Sci Rep 9:2677

- ISS crewmembers (n=8) exhibited significant deficits on R+1d in manual dexterity (Pegboard), dual-tasking and tilt motion perception, and a striking degradation in the ability to operate a vehicle
- Similar deficits were not seen in control groups for schedule recency or following 30h sleep restriction
- Limitation: Testing conducted following return to JSC (>R+24 hrs)

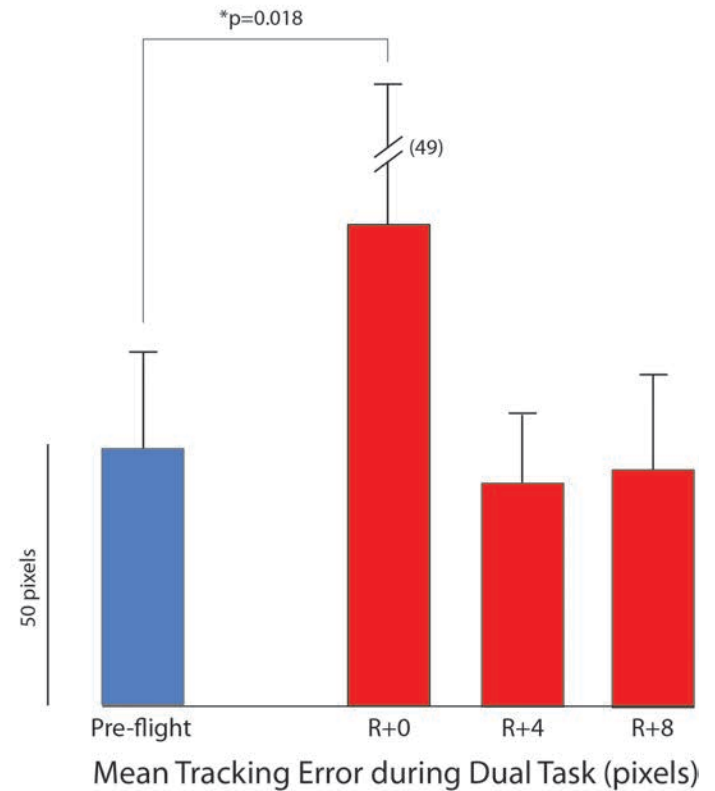
Dual task



Tracking



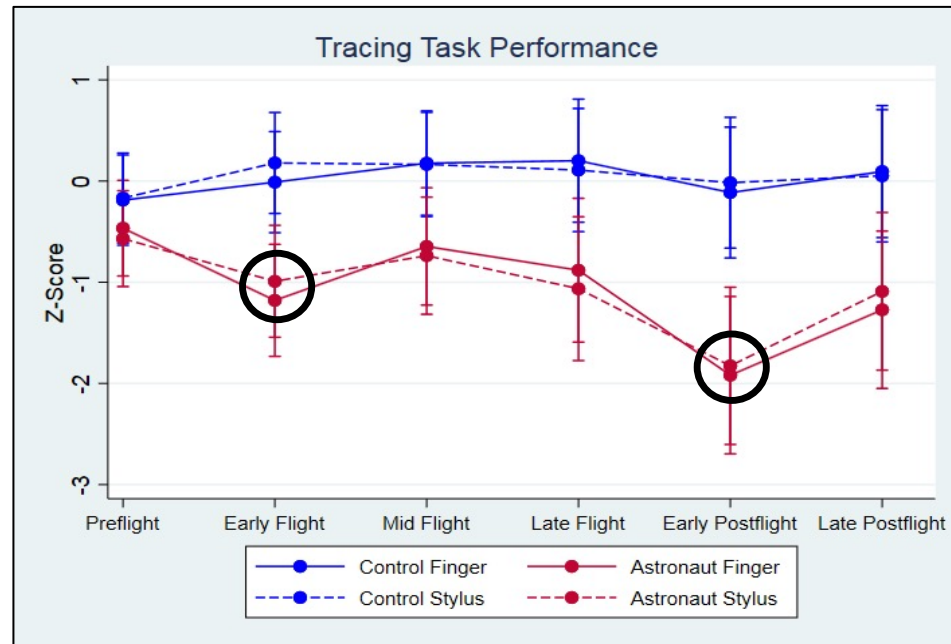
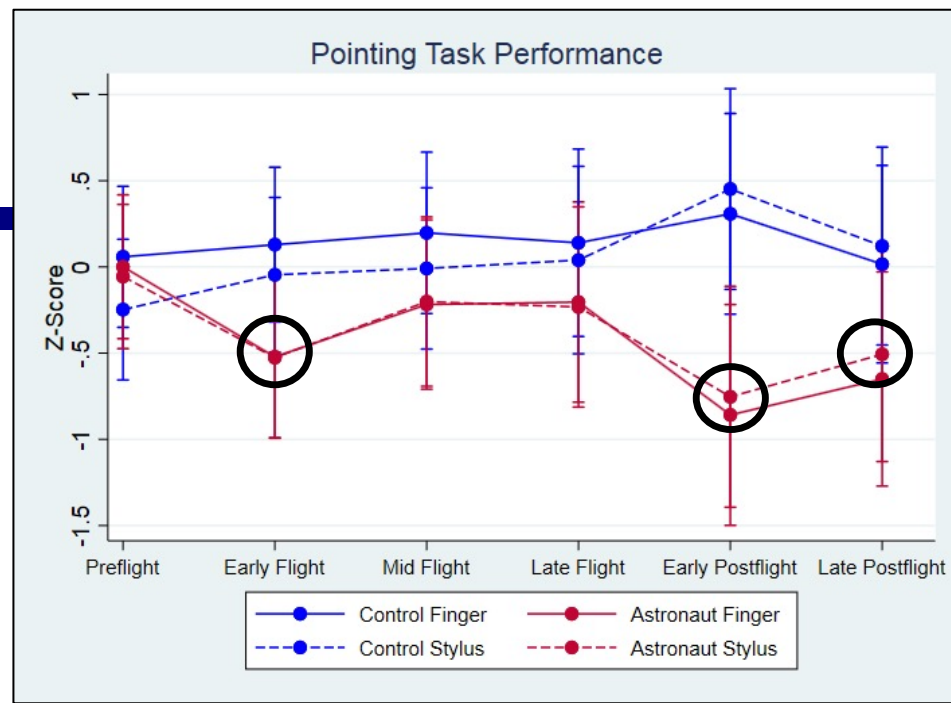
Tracking with Dual Task



Fine motor control

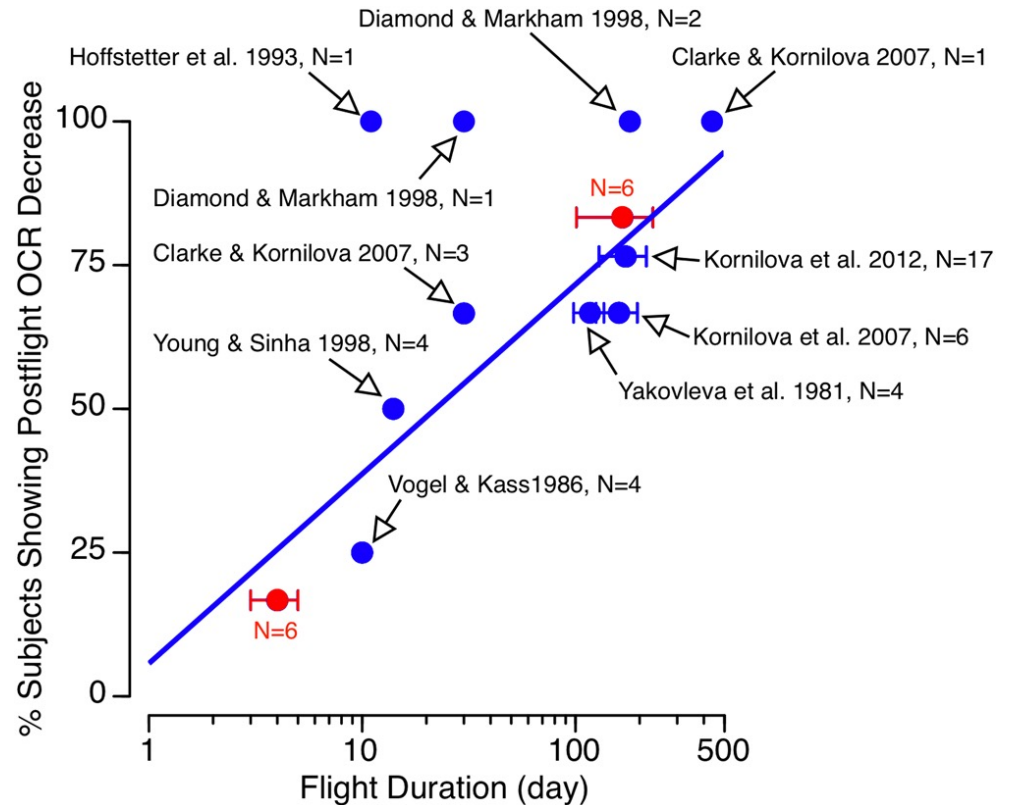
Small but reliable decrements in fine motor control observed during g-transitions (PI: Holden)

- Specifically seen in pointing tasks, dragging tasks, and shape tracing tasks.
- Decrements were observed while transitioning from 1G to microgravity as well as upon return to Earth



Vestibulo-ocular reflex

- Clark et al. (2000) reported changes in up/down asymmetry of vertical VOR gain and reductions in torsional VOR gain during active head movements on ISS flights, with some recovery in the later phase
- Reschke et al (2019) reported decreases in post-flight ocular-counterrolling that were dependent on mission duration

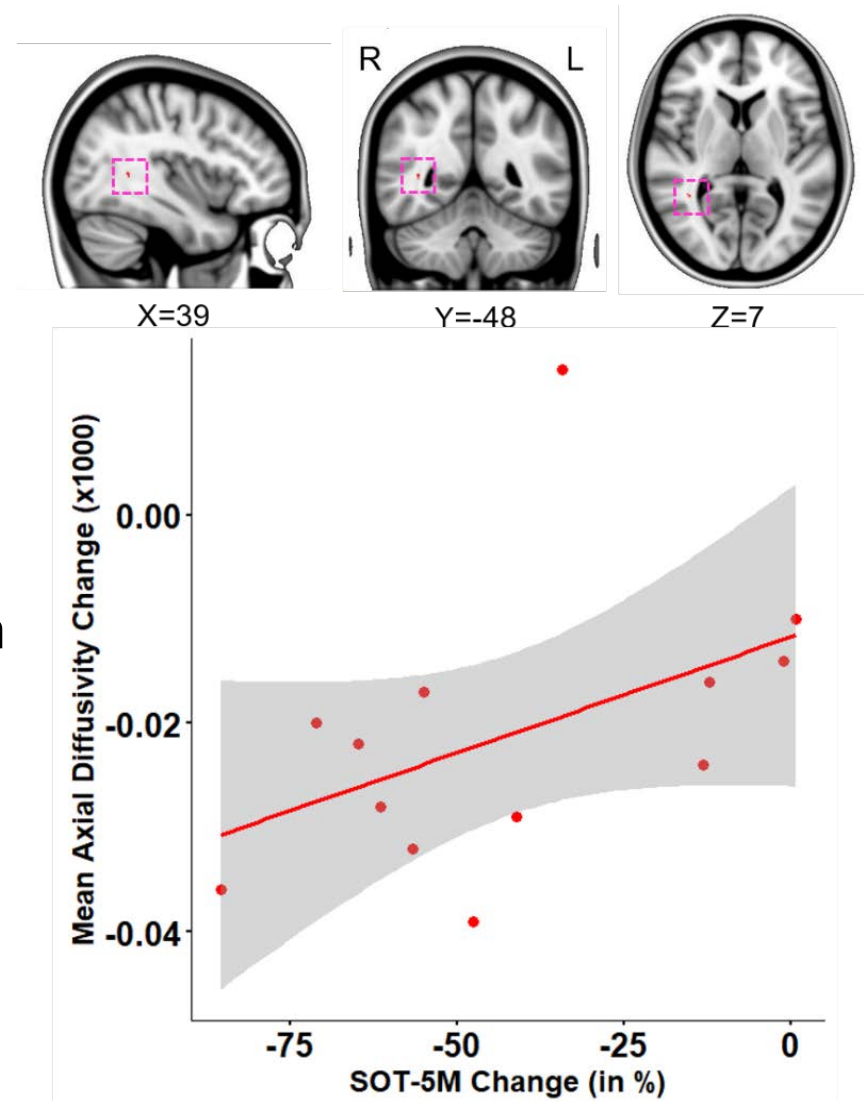


(Reschke et al. 2018, *Sci Report*)

Neuroimaging

- Spaceflight is associated with redistribution of brain extracellular fluids; white matter changes occur throughout the brain and, in some cases, are significantly associated with mission duration and post-flight declines in balance.
- Greater declines in the white matter underlying the vestibular cortex from pre to post flight are associated with larger declines in balance.

PI R. Seidler, Neuromapping



(Lee et al. 2019, *JAMA Neurology*)

Objectives

- Sensorimotor adaptation
 - G-transitional nature of risk
 - Clinical assessments
 - Research findings
- Countermeasures
 - Landing & egress
 - Reconditioning
- Lessons learned

Motion sickness

- Medications – research with intranasal scopolamine
- Titrate head movements, especially change in orientation relative to gravity
- Strobe glasses – may need to be done prior to landing
- Training / Desensitization – challenge is lack of ground-based analog
- Vestibular “white noise” (galvanic or vibration)



Sensory supplementation

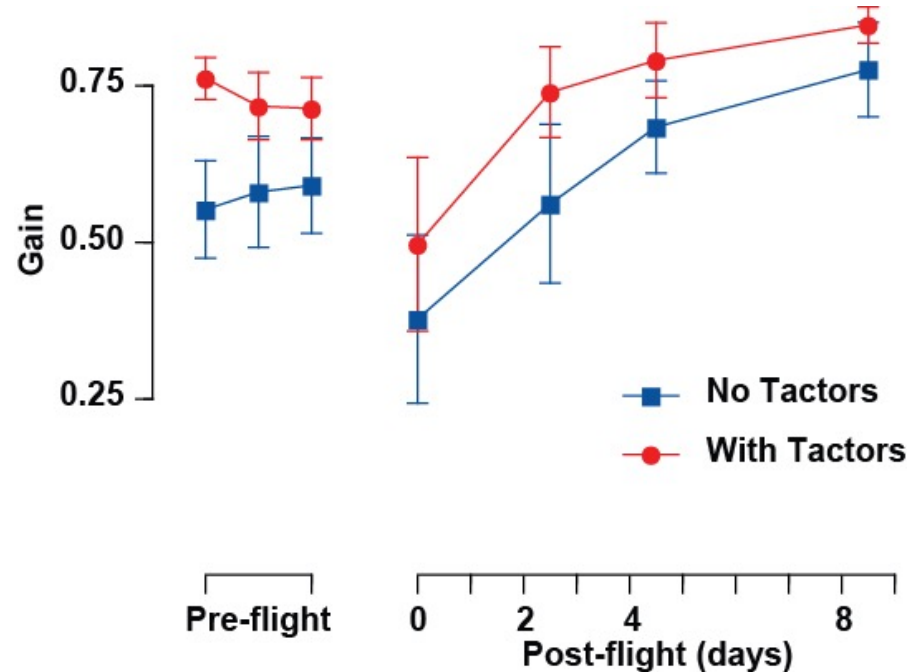
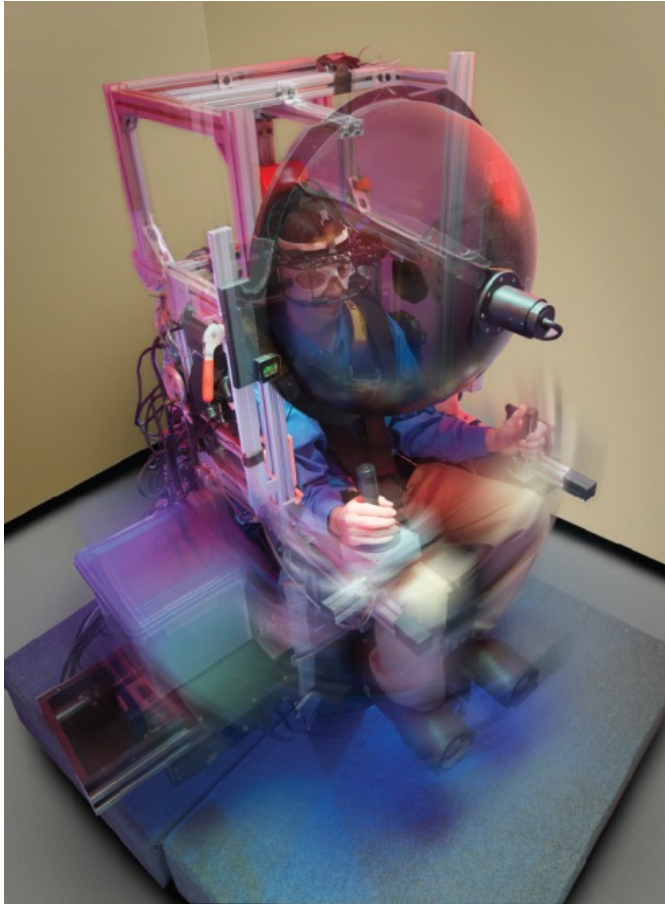
- Using natural senses (touch, sight, hearing) to display information intuitively from physical sensor
- Focus is on reinforcement of accurate sensory information rather than enhancing signals (stochastic resonance) or substitution (prosthesis)



Tactile Situation Awareness System

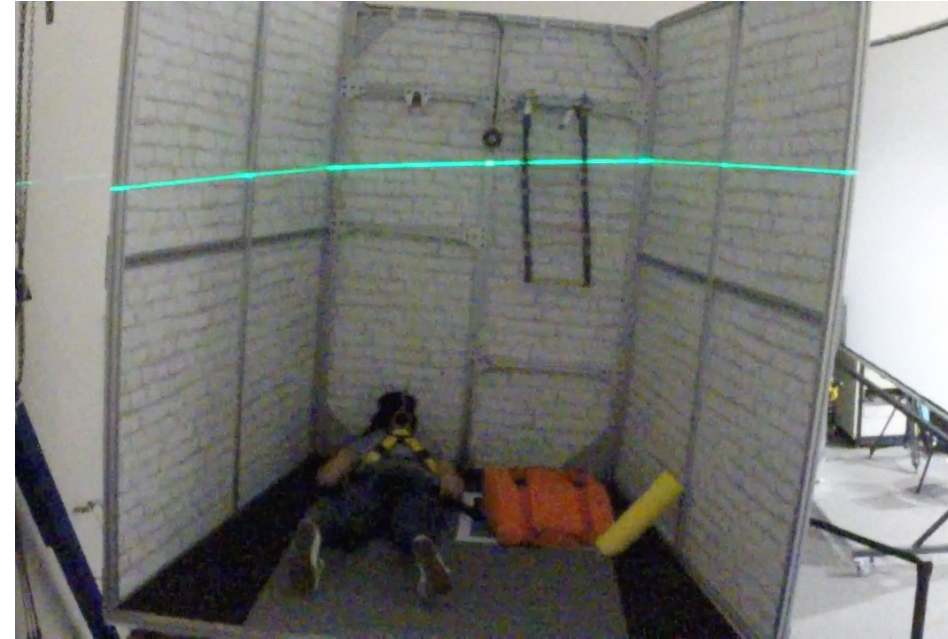


Shuttle ZAG experiment – Clément



- **Performance improved with tactors**
- **R+0 with tactors similar to preflight without**

Artificial horizon

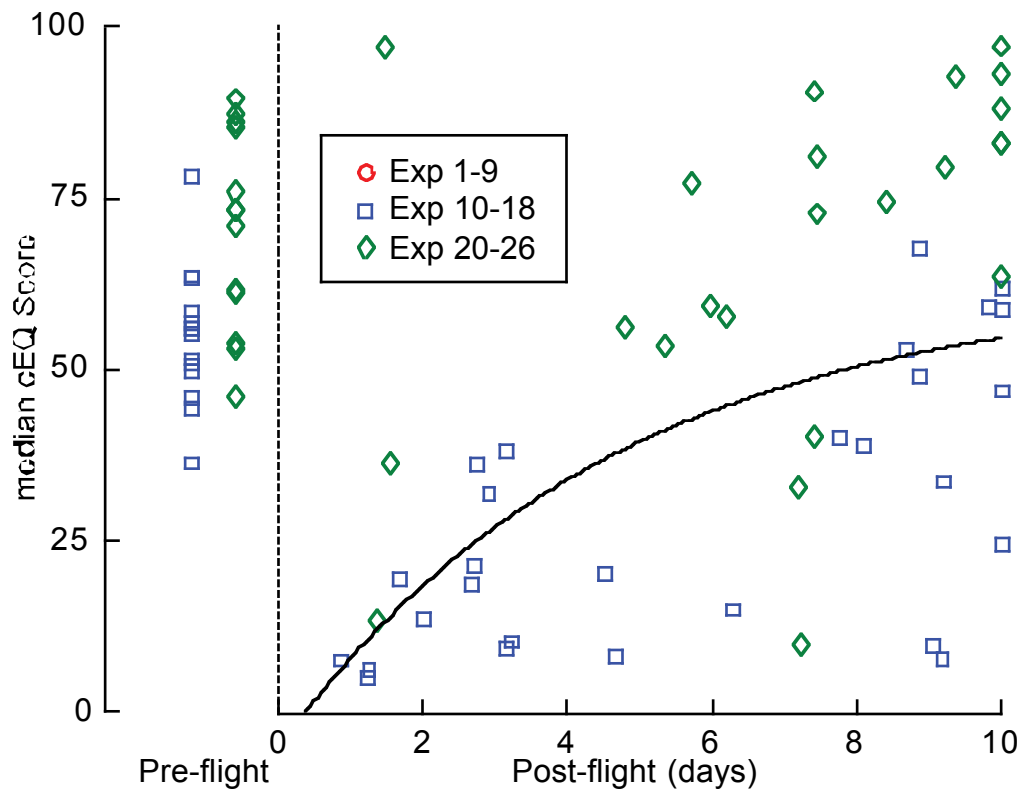


Water landings create “worst case” for egress:

- Vestibular hypersensitivity – head movements provocative
- Support not stable – exacerbate motion sickness
- Deprived of stable Earth visual reference
- Ability to control movement is compromised

ISS Countermeasures

Head Moving, Eyes Closed, Unstable Support



Interim Resistive Exercise Device

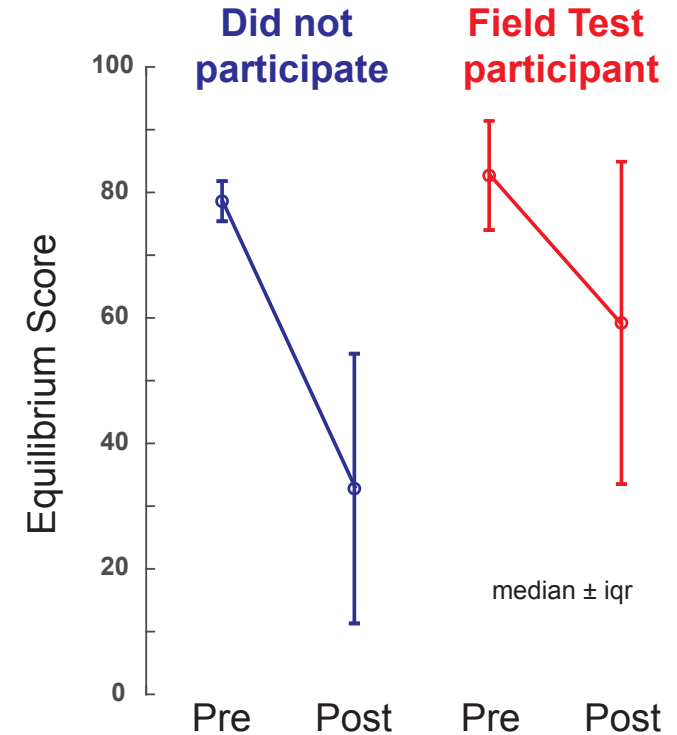


Advanced Resistive Exercise Device



Incremental rehabilitation

- Anecdotal reports suggested field test participation may accelerate recovery
- Incremental head movements used successfully by some STS crews
- *Incremental rehabilitation* approach: maintain active head movement above a lower “therapeutic” threshold to enhance adaptation while restricting movements below an upper “aversive” threshold to minimize motion sickness and aversive conditioning



Post-flight Reconditioning Program

Exercise

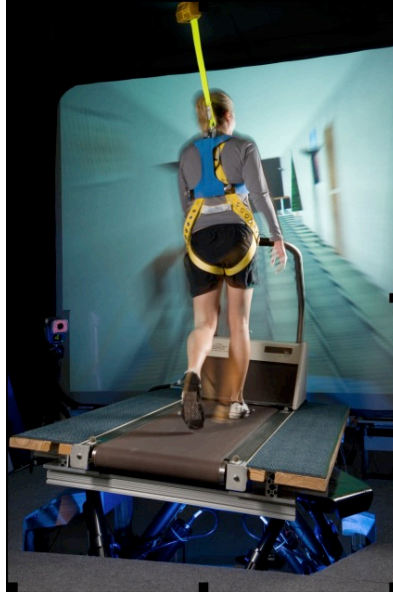
- 1 Dynamic Stretch & Warm-up
- 2 Aerobic Conditioning
- 3 Resistance Exercise
- 4 Mobility, Balance & Proprioception Drills
- 5 Medicine Ball Drills
- 6 Cone and Agility Ladder Drills
- 7 Jumping Drills
- 8 Core Exercise
- 9 Static Stretching

Schedule

- Every day: R+1-45
- Every day: R+1-45
- Every other day: R+1-45
- Every other day: R+1-45
- Every other day, R+1-45
- Every other day: R+6-45
- Every other day: R+21-45
- Every day: R+1-45
- Every day: R+1-45

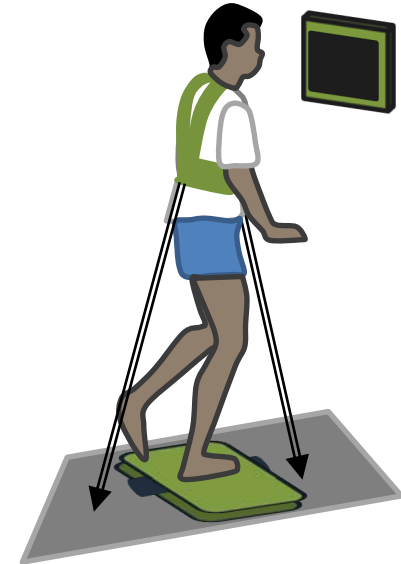
Wood, Loehr & Guilliams, NeuroRehab (2011) 29:185-95

Preflight Sensorimotor Training Spatial Disorientation Trainer



- Vestibular disruption (using galvanic vestibular stimulation) – trains subject to ignore inaccurate vestibular input
- Support surface motion – provides a balance challenge during walking

Inflight Balance Training



Keeps the proprioceptive system tuned to respond to upright balance challenges

Lessons learned ...

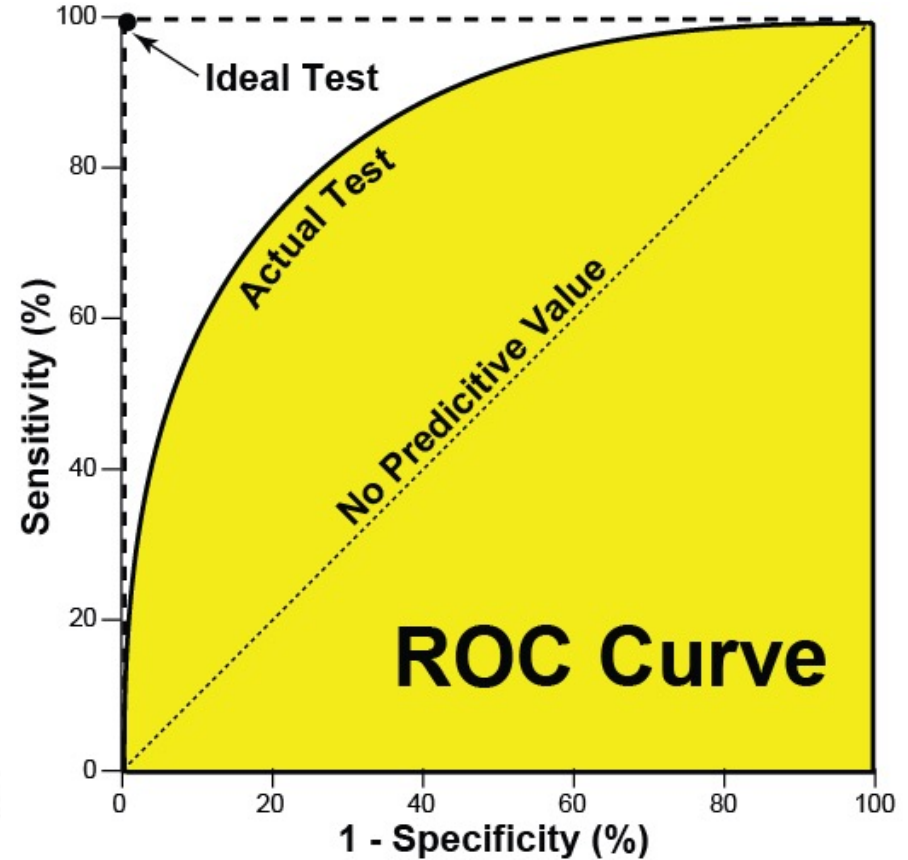
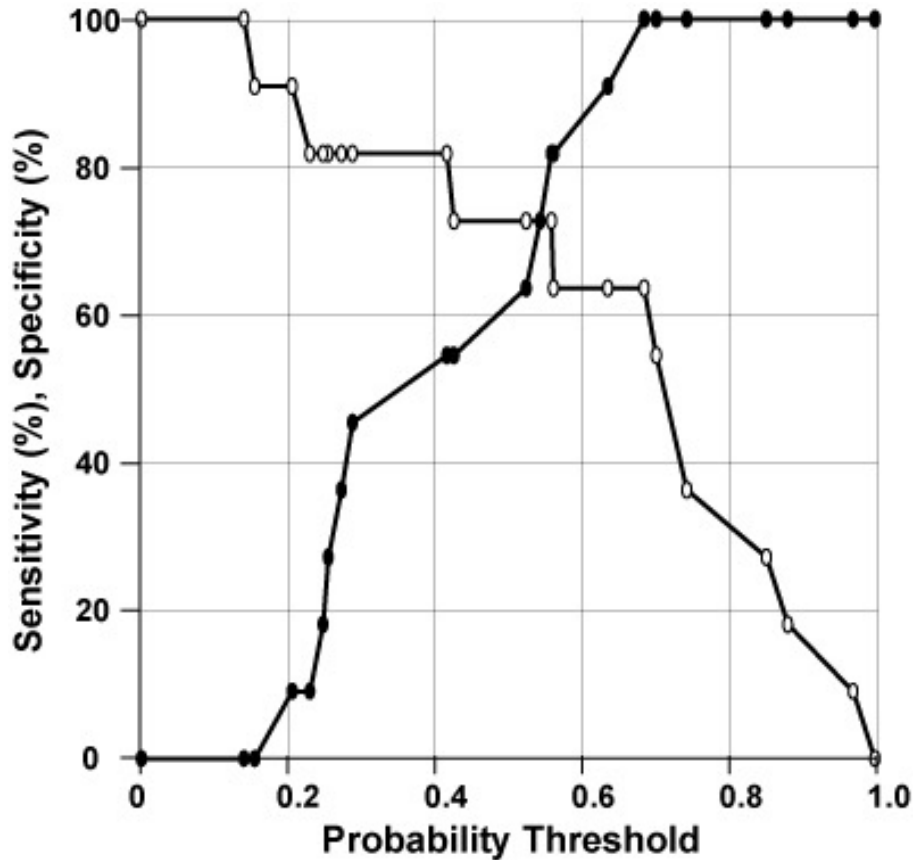
- Returning crewmembers exhibit vestibular/cerebellar and sensorimotor decrements following G-transitions that reflect adaptive responses in central neural pathways
- Large inter-subject variability, also influenced by current countermeasures and amount of active movement
- There is a greater incidence and severity of sensorimotor deficits with increasing flight duration
- Time course of recovery for a given metric depends on flight duration and task complexity
- Ongoing work to map changes in neuroimaging studies with behavioral consequences, long term health consequences (e.g., fall risks) unknown

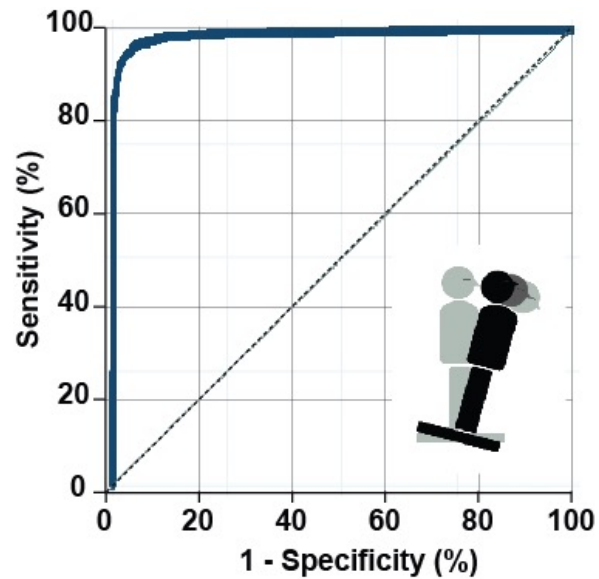
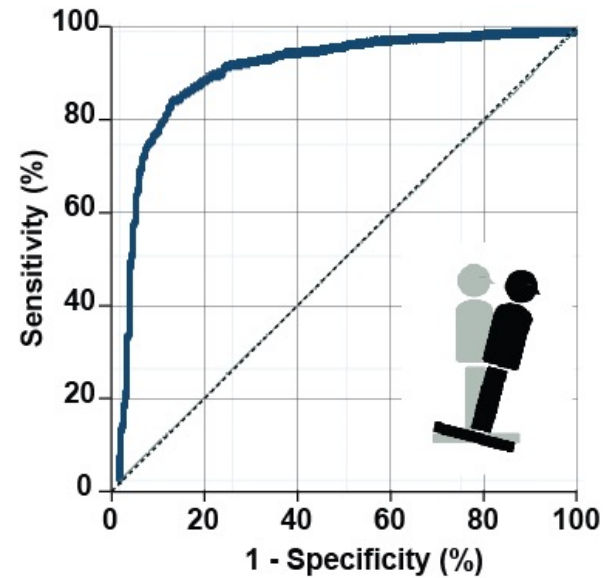
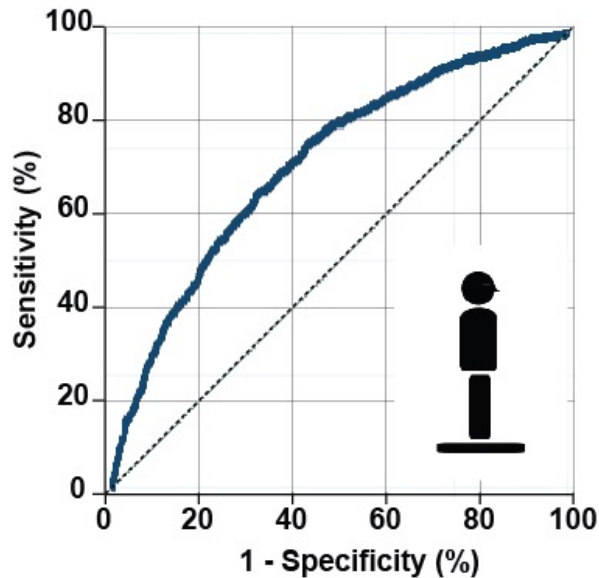
EXPLORE

MOON *to* MARS



Receiver Operator Characteristic





Fixed support, head erect

ROC area = 0.718

Unstable support, head erect

ROC area = 0.923

Unstable support, dynamic pitch tilt

ROC area = 0.991

(Jain et al, 2010)