Overview of Human Research Program (HRP) Sponsored Sensorimotor Research for the Human Landing System

Scott Wood

Neuroscience Laboratory, NASA JSC

Acknowledgements

Human Research Program: Human Health Countermeasures (HHC)

NASA Joint Test Panel

NASA Lunar Manual Piloting (CHIP WG)

Naval Medical Research Unit - Dayton, Ohio

Sensorimotor Risk

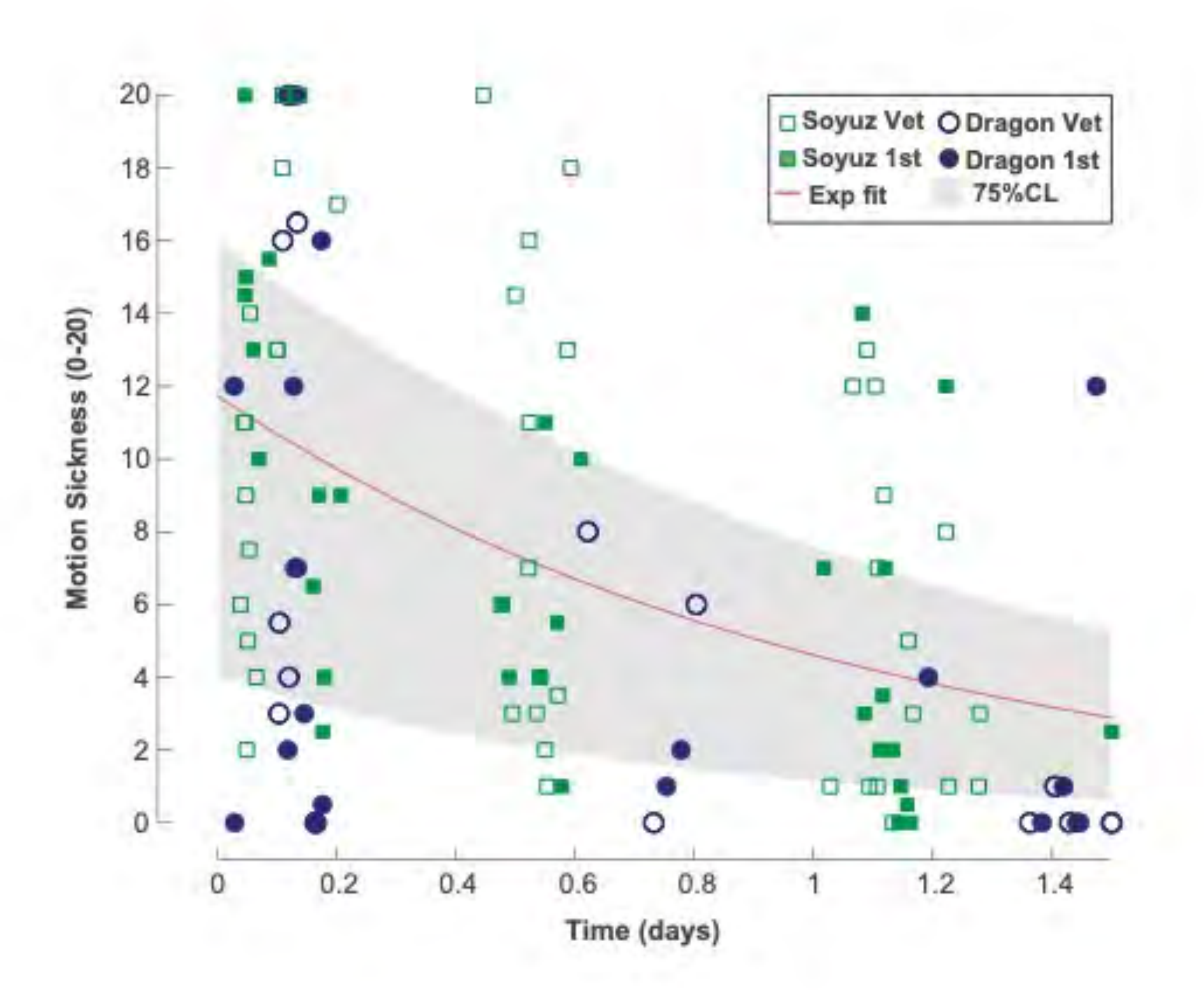
Given that altered gravity transitions lead to changes in sensorimotor / vestibular function that manifest in motion sickness, spatial disorientation, decrements in postural control and locomotion, and fine motor control deficits, there is a possibility that crew will experience performance decrements in manual / vehicle control, extravehicular activities, and egress during and following these transitions.

Manual Control

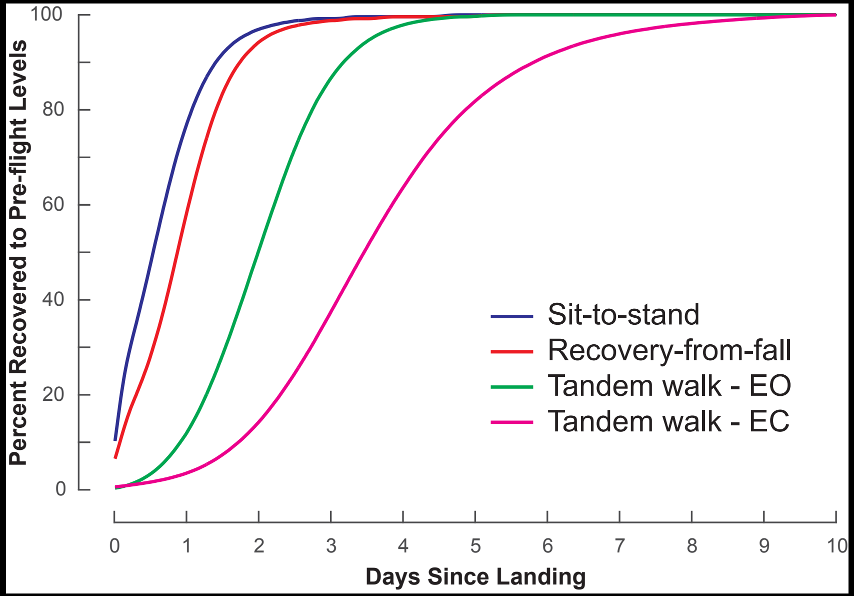
Early EVA

Crew Egress

ISS re-entry motion sickness

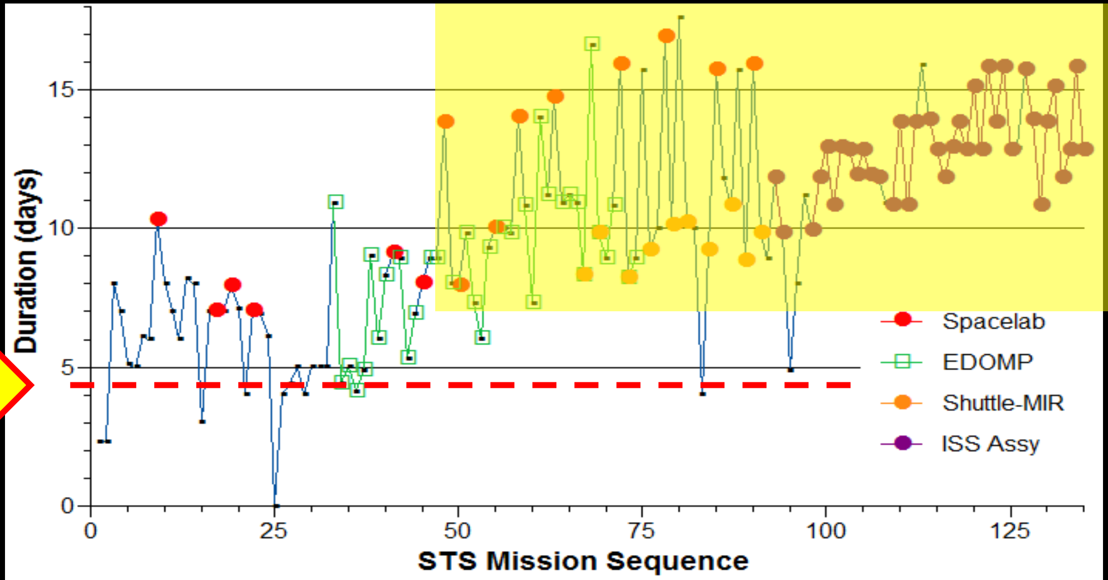


- Symptom severity highly variable across crewmembers
- Head movement wrt gravity are more provocative
- Recovery to baseline performance varies by task



Rationale for On-board "Just-in-time" trainer

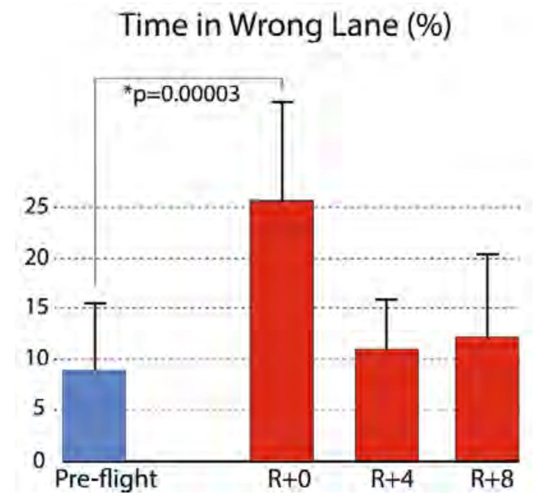
Apollo transit



Shuttle on-orbit trainer used for longer duration missions

- On-board training anecdotally effective:
  - ***CDR1:*** *helped lower cognitive workload to be able to effectively pilot through disorientation (vertigo)*
  - ***CDR2:*** *increased awareness of tendency to lag guidance, so I was able to make adjustments in approach during landing*

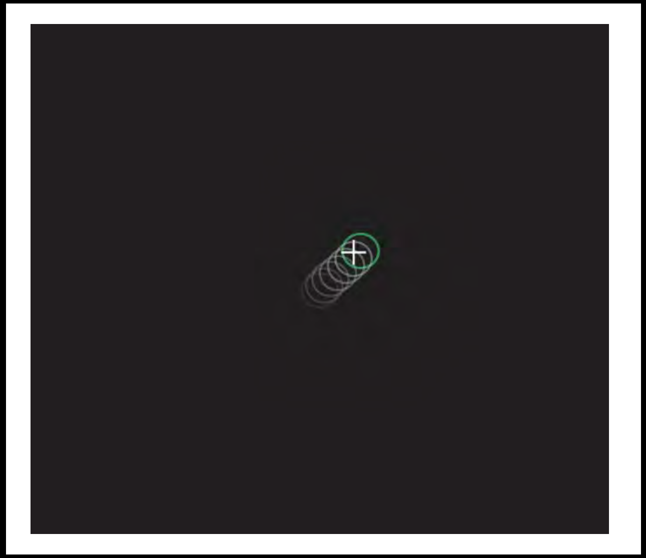
Post-ISS driving simulation

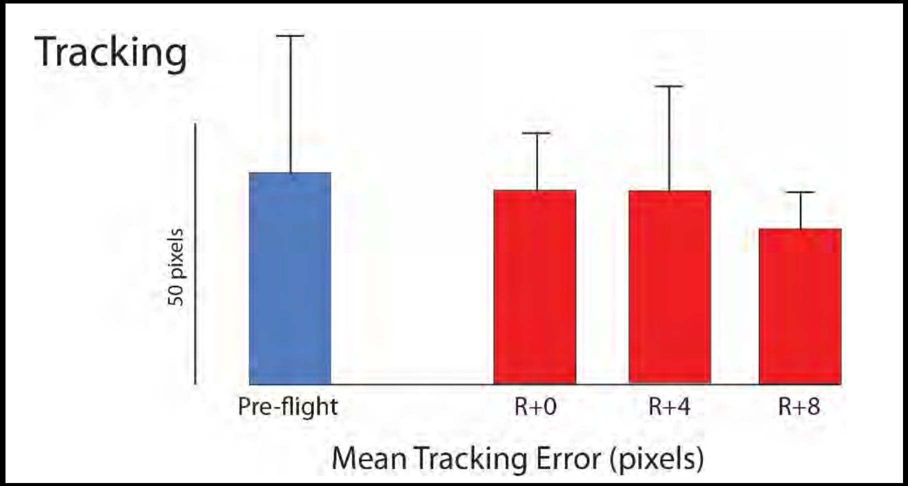


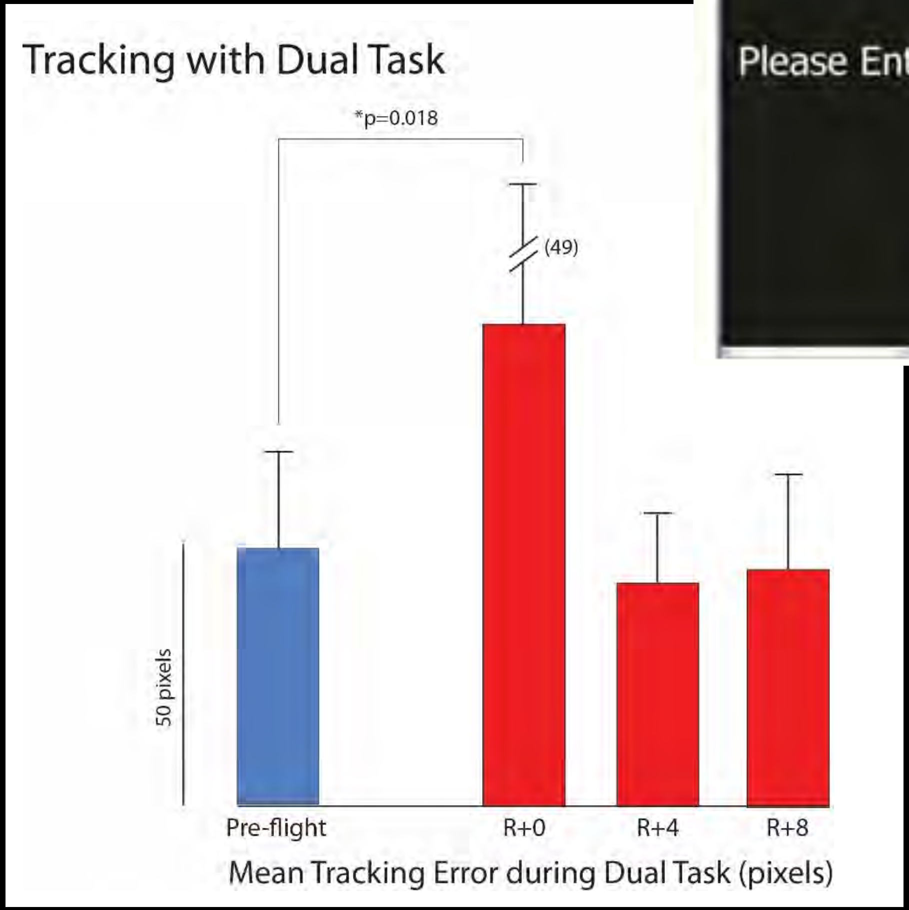
Moore et al., 2019, Sci Rep 9:2677

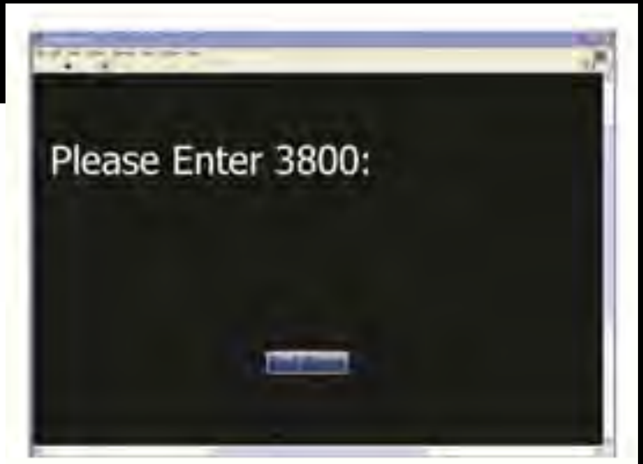
- ISS crewmembers (n=8) exhibited significant deficits on R+1d in manual dexterity (Pegboard), dual-tasking and tilt motion perception, and degradation in a driving simulation
- Similar deficits were not seen in control groups for schedule recency or following 30h sleep restriction
- Limitation: Testing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

Post-ISS dual task tracking









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Sensorimotor Research Topics

1. G-state transition (following Gx centrifugation) disorientation analog
2. Landing motion simulation – NAMRU-D Disorientation Research Device (DRD)
   - LaRC design reference vehicle
   - Motion cueing validation, SD detection – T. Clark, UC Boulder
3. ISS study: Manual Crew Override – K. Duda, Draper
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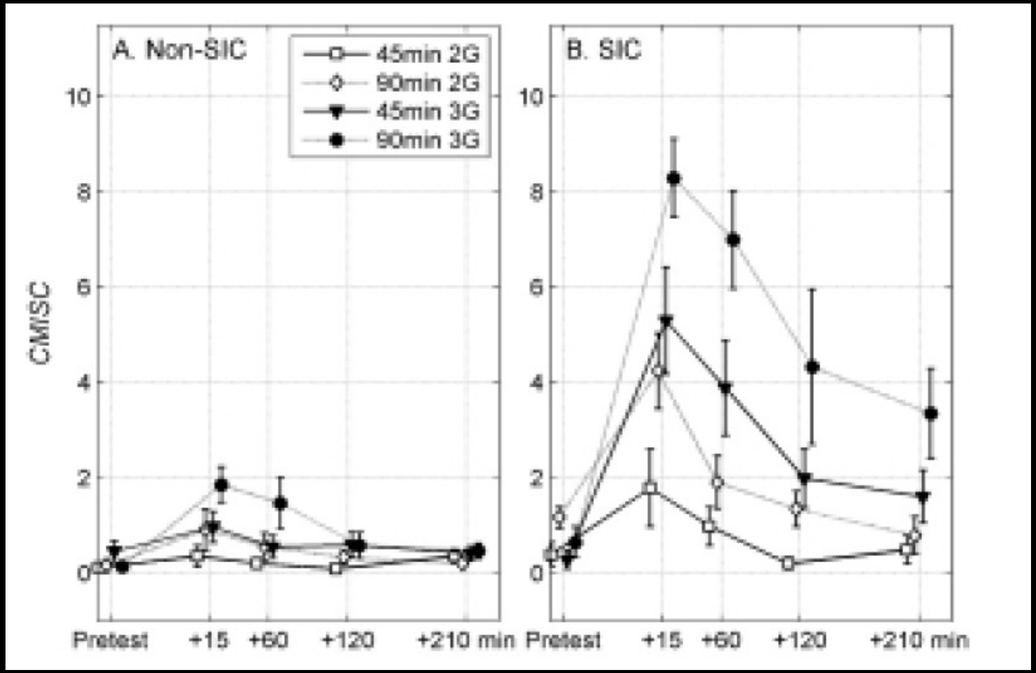
4. Landing motion simulation – post G-state transition at Brooks-KBR
   - Onboard trainer assessment – S. Moudy, JSC
5. Artemis Landing and Egress Study
6. Portable Spatial Disorientation Trainer – galvanic vestibular stimulation

G-state Transition Disorientation Analog

- Bles et al. (1989, TNO): "space adaptation syndrome" induced by a long duration +3Gx centrifuge run
- Albery & Martin (1996, WPAFB) Development of space motion sickness in a ground-based human centrifuge (90 m of +2Gz)
- Nooij & Bos (2007, TNO) Sickness induced by head movements after different centrifugal Gx-loads and durations, correlated to space motion sickness



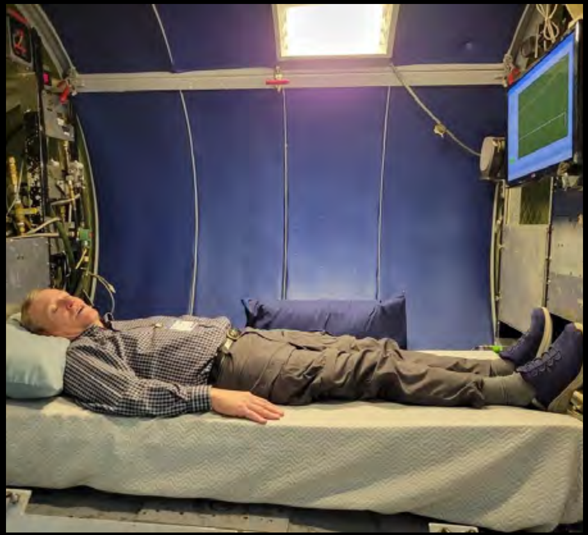
G-state Transition Disorientation Analog

NAMRU-D DRD Kraken

- 2.5Gx for 60 min (0.1 G/s)
- Precise subject positioning to mimic gimballed centrifuge, facilitate subject loading
- Seat configuration for landing sim
- IMUs to monitor head/torso accel

Brooks-KBR Centrifuge

- 3Gx for 60 min (0.2 G/s)
- Gimballed centrifuge
- Subject supine on foam, ambulate to post-Gx testing
- IMUs to monitor head/torso accel

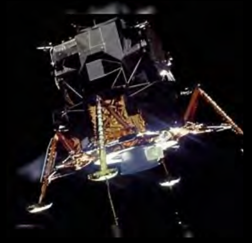


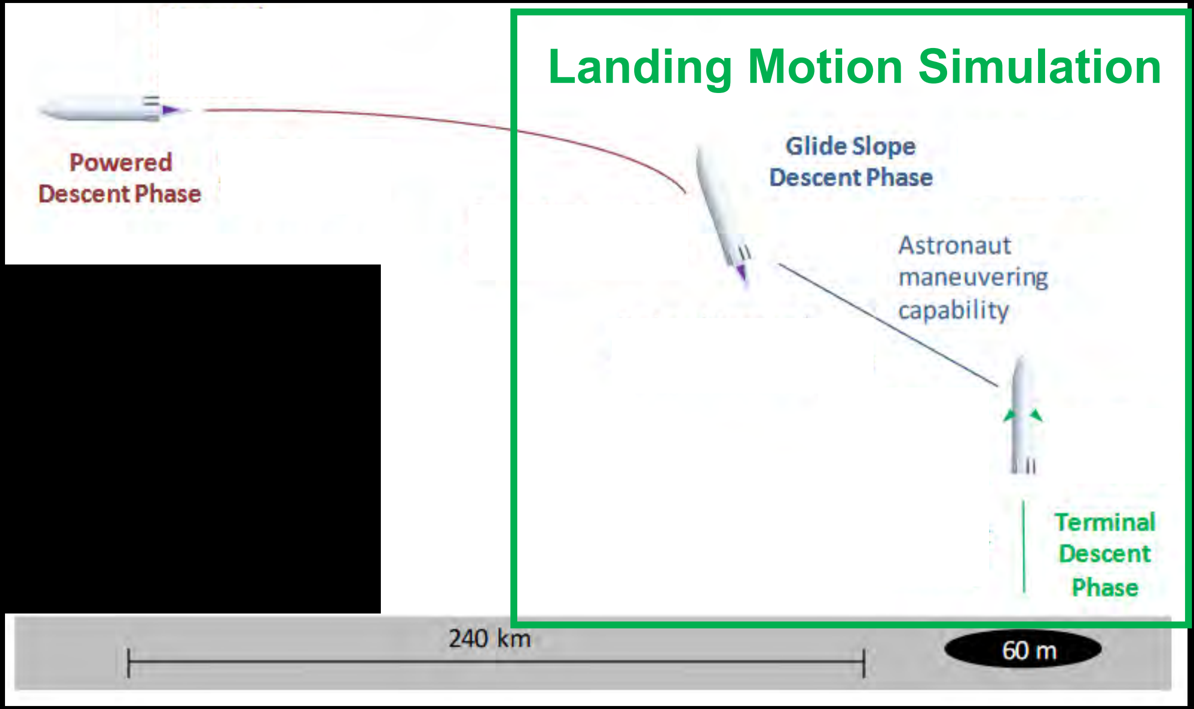
Research on Various Flight Phases with DRD

Onboard Trainer Assess-ments

Kraken G-state Transition Analog

G-transition induced disruption





EVA assessments
Self-administered Rehab

Return to Earth

Capsule Wave Simulation Motion Sickness CMs

DRD lunar simulation

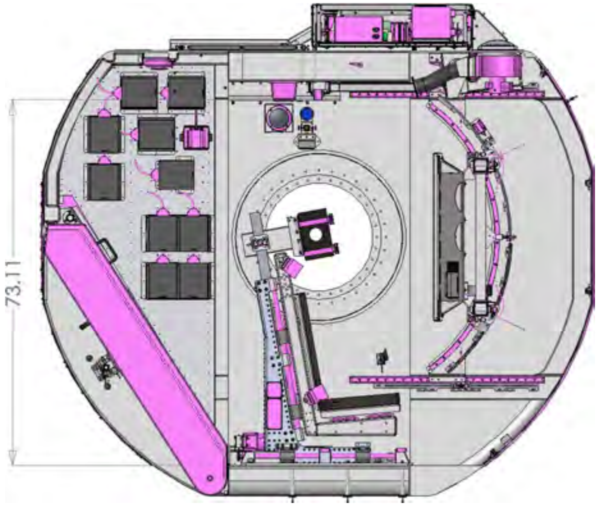
- LaRC provided host sim computer to run HLS Gov't Reference Model (GRM) vehicle
- Completed initial automated landing – no controls, observation only to begin motion cueing development
- Implementing auto and manual flight modes with different control laws and trajectories
- Using ER7-Orion hand-controllers
- Starting with single seat and existing DRD cabin layout, will refine for crew override assessment
- Potential to enhance for 2-seat cabin and implement provider specific properties

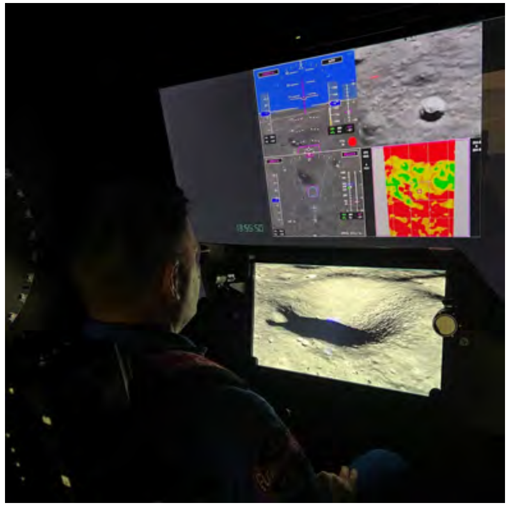
DRD Overview

Axis	Motion Range	Position Accuracy	Velocity	Velocity Accuracy	Acceleration	Acceleration Accuracy	Dynamic Bandwidth
Planetary	360 º	± 0.4 º	± 150 º/s	± 0.7 º/s	30 º/s^2	± 1.0 º/s^2	0.5 Hz
Roll	360 º	± 0.4 º	± 180 º/s	± 0.7 º/s	± 200 º/s^2	± 1.0 º/s^2	1.0 Hz
Yaw	360 º	± 0.4 º	± 180 º/s	± 0.7 º/s	± 200 º/s^2	± 1.0 º/s^2	1.0 Hz
Pitch	360 º	± 0.4 º	± 180 º/s	± 0.7 º/s	± 200 º/s^2	± 1.0 º/s^2	1.0 Hz
Vertical	± 3 ft	± 0.45 in	± 6.6 ft/s	± 1.5 in/s	± 16 ft/s^2	± 2.3 in/s^2	0.5 Hz
Horizontal	± 16.5 ft	± 0.45 in	± 11 ft/s	± 1.5 in/s	± 16 ft/s^2	± 2.3 in/s^2	0.5 Hz

DRD Capsule

- Configurable payload space (680 lbs, 32 cubic ft)
- Existing OEM single seat installed
- Existing visual displays for head down displays and out-the-window visuals
- Closed-circuit television (CCTV) camera
- Hands-free communications system
- Air vents, adjustable lighting
- Interface with a Data Acquisition System

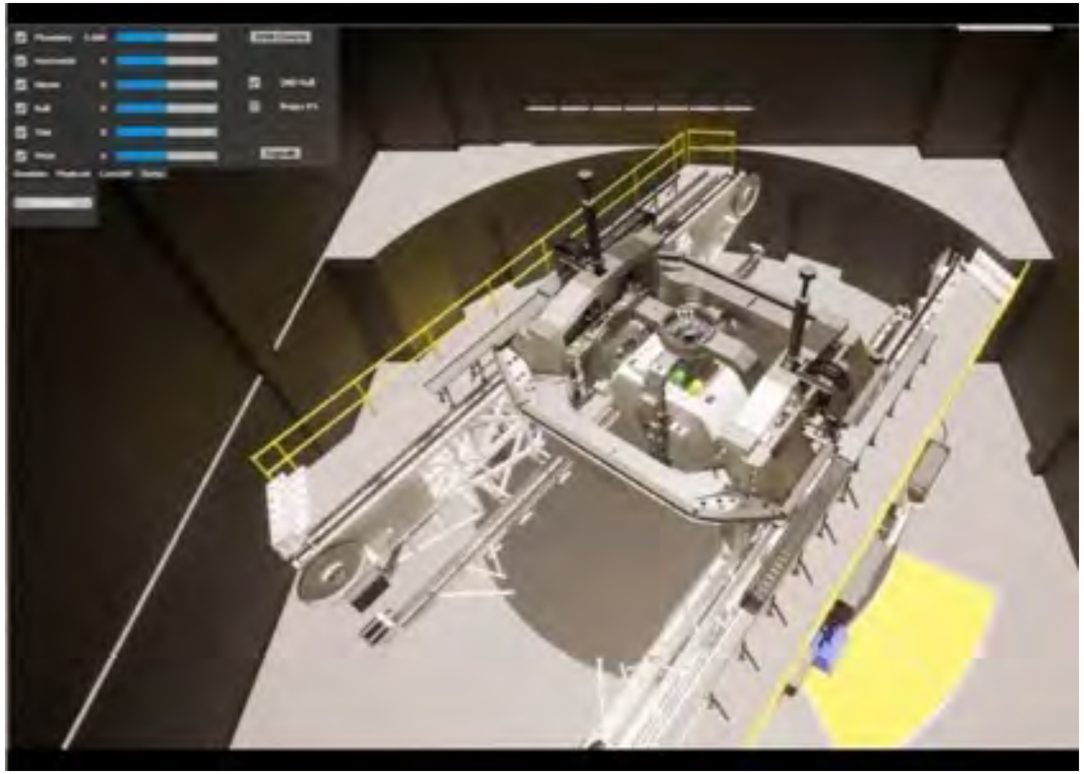




DRD Control Room

- Motion Control Computer and Safety Control Computer monitor 450 interlocks
- Research Operating Station (ROS) collects data from NASA-Sim and send scenario control commands to NASA-Sim (start, pause, trim, etc.)
- CCTV System in the control room monitors capsule, device hall and pit
- Emergency Power Off (EPO) with fail-safe braking that closes linear and gimbal brakes with power disconnect (halt device <6 sec from max speed)
- Uninterruptible Power Supply (UPS) provides capsule homing with power loss
- Stopping options: (1) Normal: nominal return of device to the load position; (2) Medical: fastest return of capsule to the load position for medical or facility emergency; (3) E-Stop: generated automatically or by operator, removes device power and requires drive reset or brake release to home capsule

Build Lab and Motion Visualizer



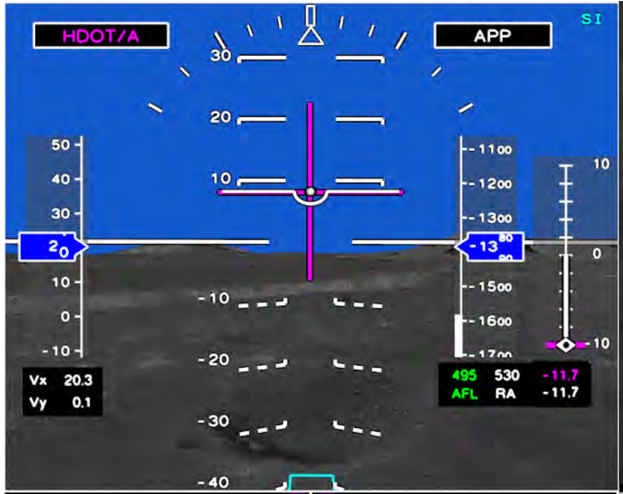
- Build Lab components: NASA-Sim, HLS Graphics, Sound Generator, Unreal Lunar Surface, ROS, ER7 Driver, Motion Model PC and DRD Visualizer tool
- DRD Visualizer receives commands from Motion Model PC which receives motion data from NASA-Sim to display the motion that would be commanded

Government Reference Model (GRM) Simulation

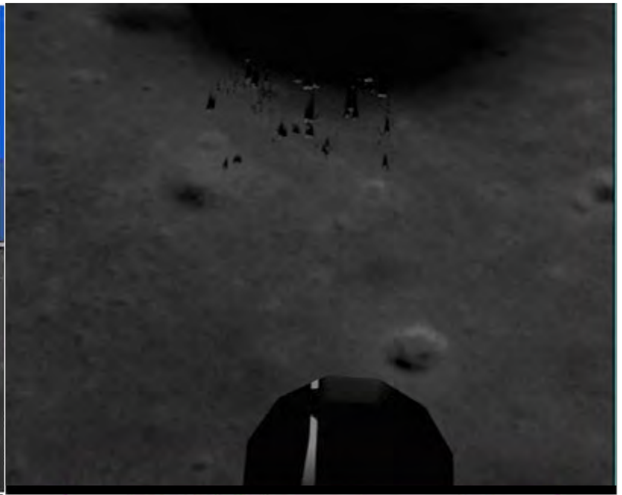
LaRC providing:

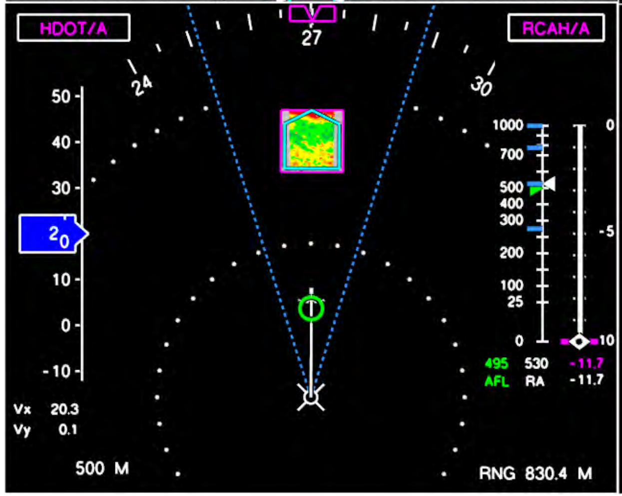
- GRM Simulation Software
- LIDAR modeling
- Heads-down displays
- OTW Lunar South-Pole Visuals
- Sound generation software
- ER7 Controller software
- Integration with
  - DRD motion system
  - Research Operator Station (ROS) control software
- On-site integration, execution support

Primary Flight Display

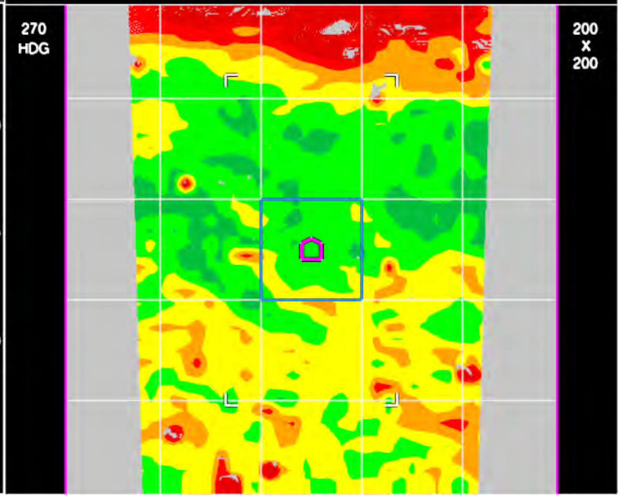


Camera View





Navigation Display



Hazard Map Display

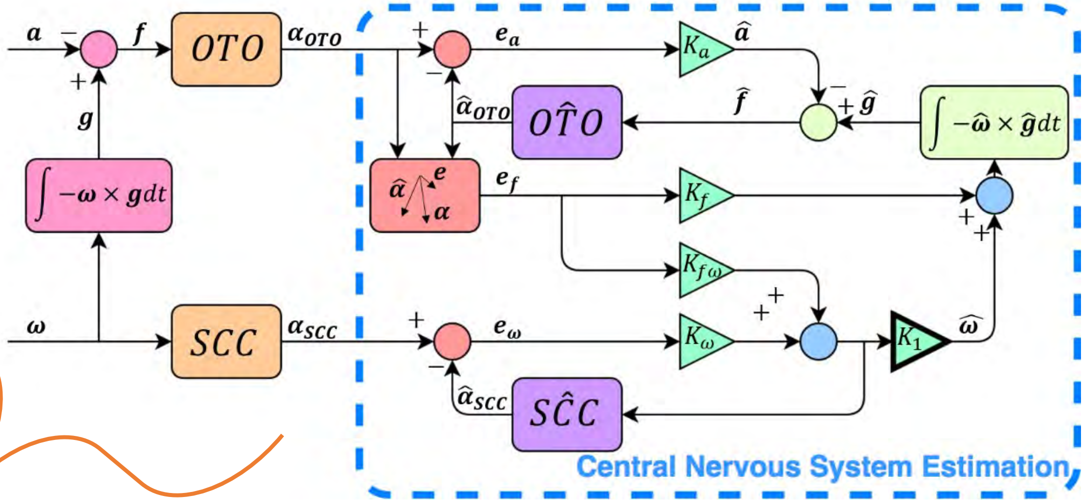
Validating Motion Algorithm using a Model for Spatial Orientation Perception, Torin K. Clark, PhD, University of Colorado-Boulder

(Merfeld, Shelhamer, et al. 1993, Clark et al. 2015, 2019)

Current approach: subject matter expert (e.g. pilots) experience motion algorithm on simulator and provide subjective feedback

Limitations: lack of pilot experience landing on the moon (plus SME/pilot feedback is qualitative, may not be actionable, different between individuals, time consuming, and expensive)

Alternative: model for spatial orientation simulated with vehicle flight profile and DRD motions and compare predicted perceptions



Vehicle State
(flight profile)

Transform vehicle state to vestibular stimuli

$\vec{\omega}_{veh}, \vec{a}_{veh}$
$\vec{g}_{veh}$

Orientation Perception Model (vestibular)

Perceived Motion and Orientation
$\hat{\vec{\omega}}, \hat{\vec{a}}, \hat{\vec{g}}$

DRD commanded state
planetary spin
horizontal position
heave position
roll, yaw, pitch gimbals

Transform DRD state to vestibular stimuli

$\vec{\omega}_{DRD}$
$\vec{a}_{DRD}$
$\vec{g}_{DRD}$

Orientation Perception Model (vestibular)

Perceived Motion and Orientation
$\hat{\vec{\omega}}_{DRD}, \hat{\vec{a}}_{DRD}, \hat{\vec{g}}_{DRD}$

+ / –

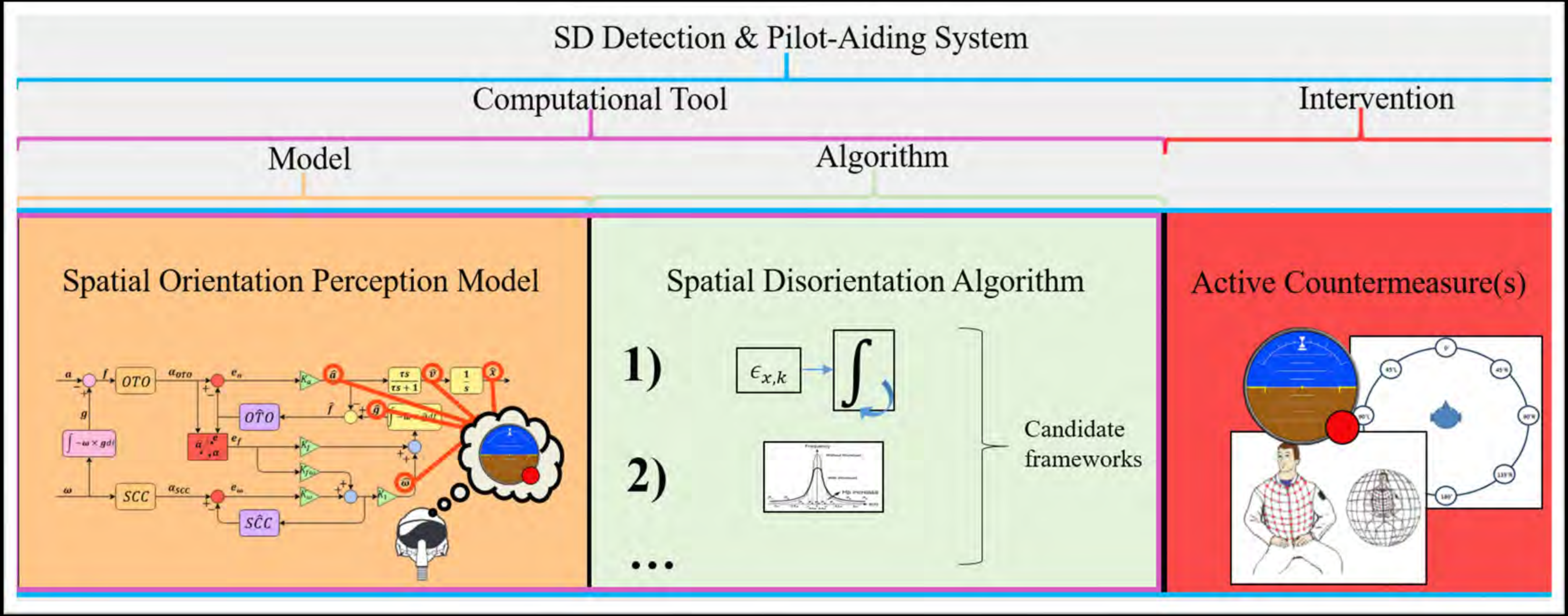
Goal: minimize

Validate perceived motion and orientation are similar

(Dixon, Etgan, Horning, Clark, Folga, 2019)

T. Clark: SD Detection during DRD simulations

Aims: (1) Validate the computational model's predictions of pilot spatial disorientation, specifically for lunar landing, (2) characterize manual control decrements following G-state transition analog, and (3) evaluate triggering an active countermeasure in real-time using the computational model to predict spatial disorientation (SD).



DESDEMONA FACILITY

- DESDEMONA = most advanced motion simulator (6-DOF) in the world
- Operational since 2007, owned by TNO, operated by Desdemona BV
- Simulation of complex, motion critical situations during flight, driving, sailing ..
- Motion simulator, disorientation trainer & advanced research lab, all in one
- Technicalities
  - Centrifuge up to 3.3G (sustained), 8 meters linear track, 2 meters vertical heave
  - Unlimited pitch, yaw & roll
  - 3D rotations: Range >360º, Velocity 180º/s, Acceleration 300º/s²
- Cabin with modular layout, mounted on fully gimbaled system
  - Reconfigurable cockpit: Fighter, Helicopter, Transport aircraft, Spacecraft, …

www.desdemona.eu

Mountain flying training course in DESDEMONA for Chinook CH-47 pilots

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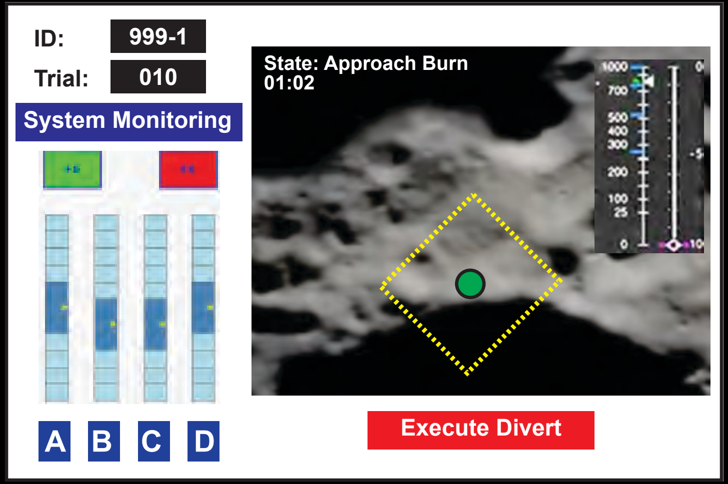
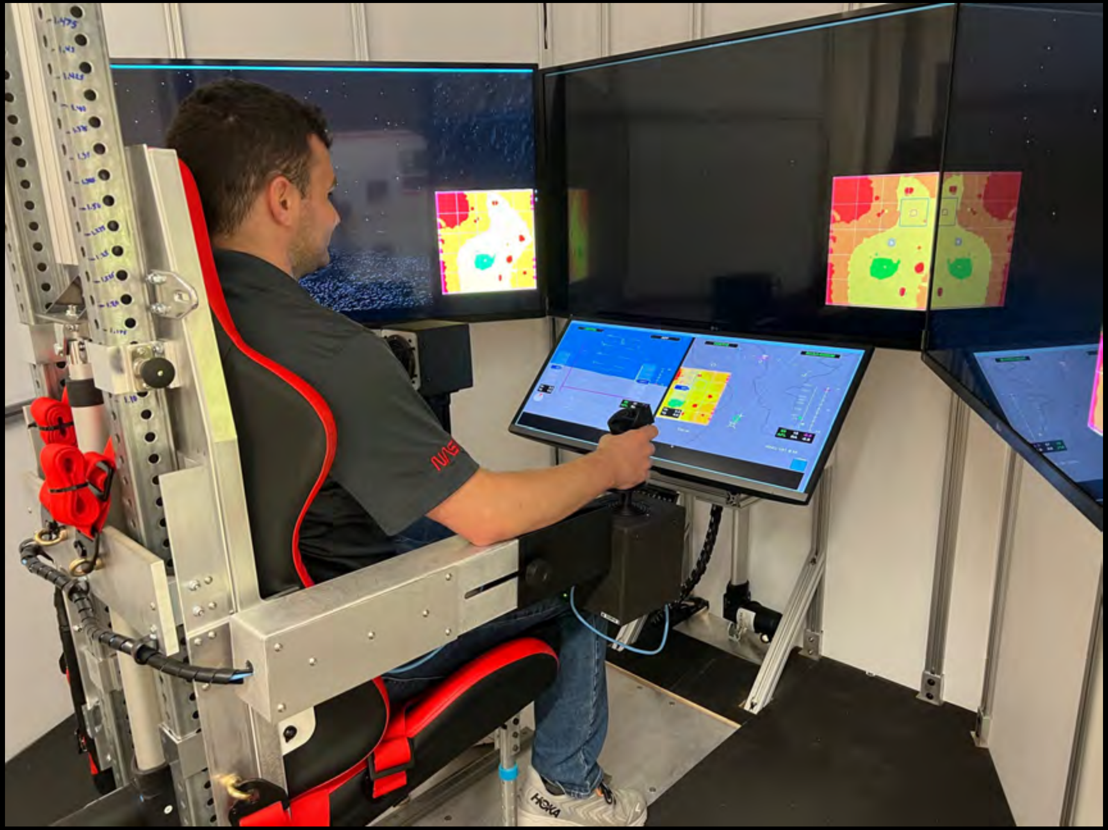
ISS Manual Crew Override

- Aim 1: Characterize the impact of spaceflight on crew capability to perform manual crew override tasks using both fixed and 6DOF motion base
  - Includes HLS-relevant supervisory landing tablet task involving execute divert decision
- Aim 2: Examine how measurements in vestibular and cognitive function relate to proficiency during supervisory manual control and crew override
- Aim 3: Compare performance during “just-in-time” training on the lunar landing tasks conducted late in-flight with post-flight crew performance
  - Utilize existing ROBoT-r platform, including the same hand controllers in 6DOF system



ISS Motion Base Cabin

- Postflight ISS measures will use seated configuration: portable fixed base at rally airport and motion base at JSC
- Cabin can be reconfigured for standing position



ISS study motion base (CKAS)

Configuration	Modified Stewart Type 6 DOF System
Independent Axes	Heave, Surge, Sway, Pitch, Roll, Yaw
Maximum Independent travels	Heave, Surge, Sway: ±150 mm Pitch, Roll, Yaw: ±24 deg
Maximum Acceleration	0.5 g
Maximum Payload	650 kg
Maximum MOI	270 $kg.m^2$
Nominal Voltage	220 - 240 Volts AC Single Phase (50 – 60 Hz)

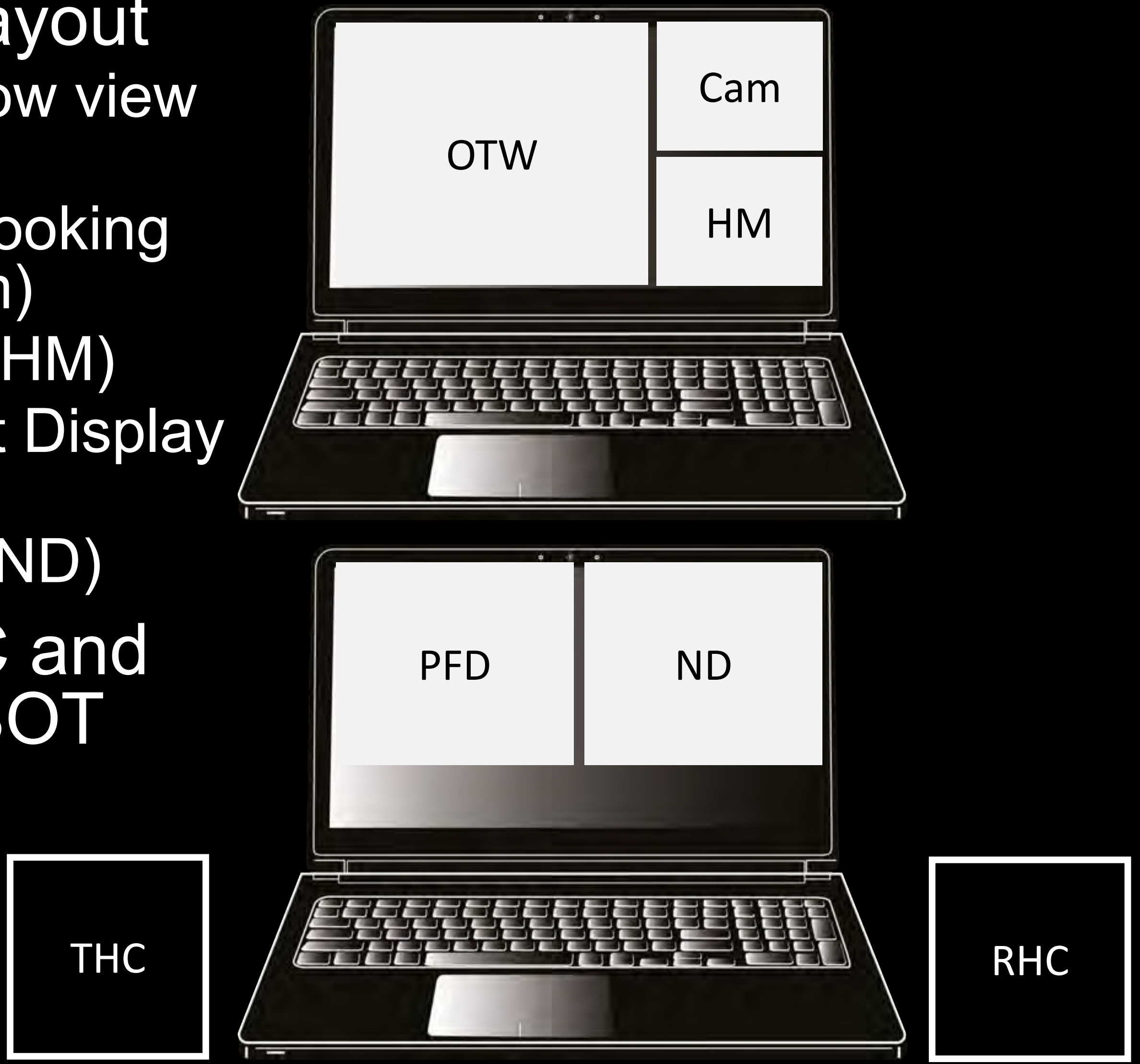
- Man-rated for previous (manual control) and ongoing (wave motion) NASA studies
- Generic UDP high speed interface (includes Washout algorithms) for direct drive of platform
- 2nd system available to be deployed to alternate sites (e.g., KSC for PAM testing)
- POC: Austin Bollinger (NASA global)

ISS simulation parameters

- Flight Control Modes (2)
  - All sims expect to start in Automatic flight, then transition to manual
  - Rate Control Attitude Hold (RCAH) all the way to the surface
  - RCAH to “low” altitude, then Incremental Position Command (IPC)
- Attitude Maneuver Control Power (2)
  - 1.1 deg/sec2 (low) – Altair LDAC-2
    - Designed to push as pilot “lead” and preventing PIOs
  - 1.6 deg/sec2 (okay) – Altair LDAD-1

ISS Displays & Eye Tracking During Sim

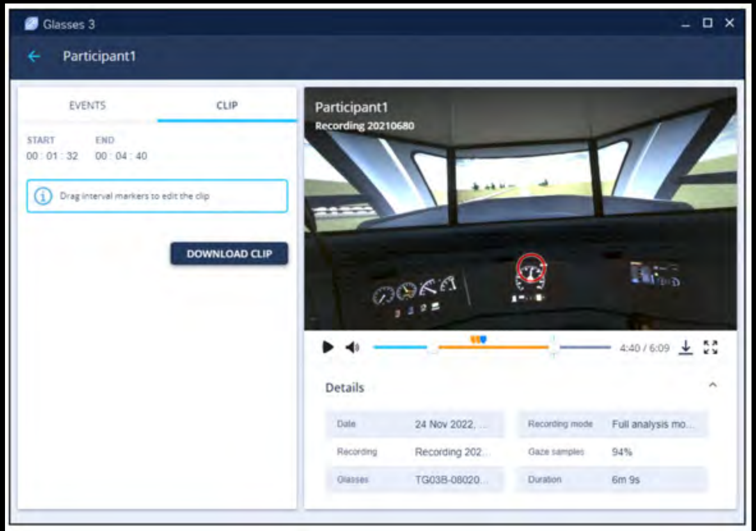
- Sim displays layout
  - Out-the-window view (OTW)
  - "Downward" looking Camera (Cam)
  - Hazard Map (HM)
  - Primary Flight Display (PFD)
  - Nav Display (ND)
- Leverage RHC and THC from RoBOT workstation



Audio cueing of system events and flight control settings

Tobii Pro3 Point-of-Regard Gaze Tracking

- Lightweight, wearable eye tracker
- Binocular pupil tracking, 0.6 º accuracy
- Scene camera FOV: 95º x 63º
- Head tracking: Gyroscope, Accelerometer (100 Hz), Magnetometer (10 Hz)
- Built-in mic for ambient recording
- Export video for session playback



S. Moudy, JSC: DRD On-board Task Assessments

"On-board" laptop assessment prior to 3Gx + Lunar Landing Simulation

Sustained G-state Transition Analog

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Artemis: Lunar Landing & Egress

Aim 1: Preflight and On-Board Training Assessments for Lunar Landings

(a) Utilize crew feedback following landings to refine a spatial orientation modeling approach to inform preflight simulation training, and (b) utilize inflight on-board training assessments of landing point redesignation and workload

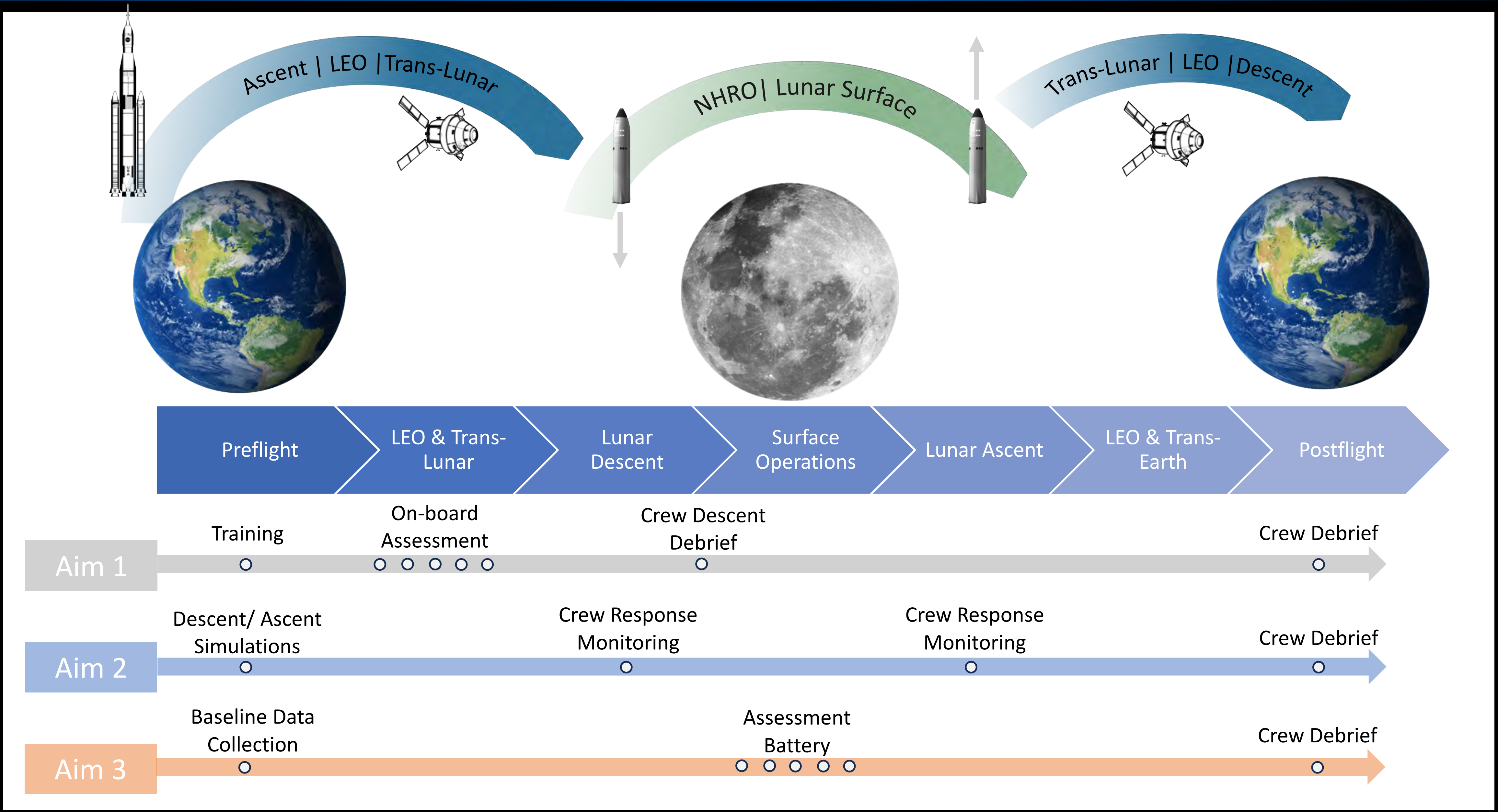
Aim 2: Characterizing Responses during Lunar Descent and Ascent

Capture crew perceptual responses and physiological parameters during lunar descent and ascent to characterize individual and landing trajectory factors that may impact landing, fine-tune perceptual modeling

Aim 3: Post-Landing Lunar Surface Assessment Battery

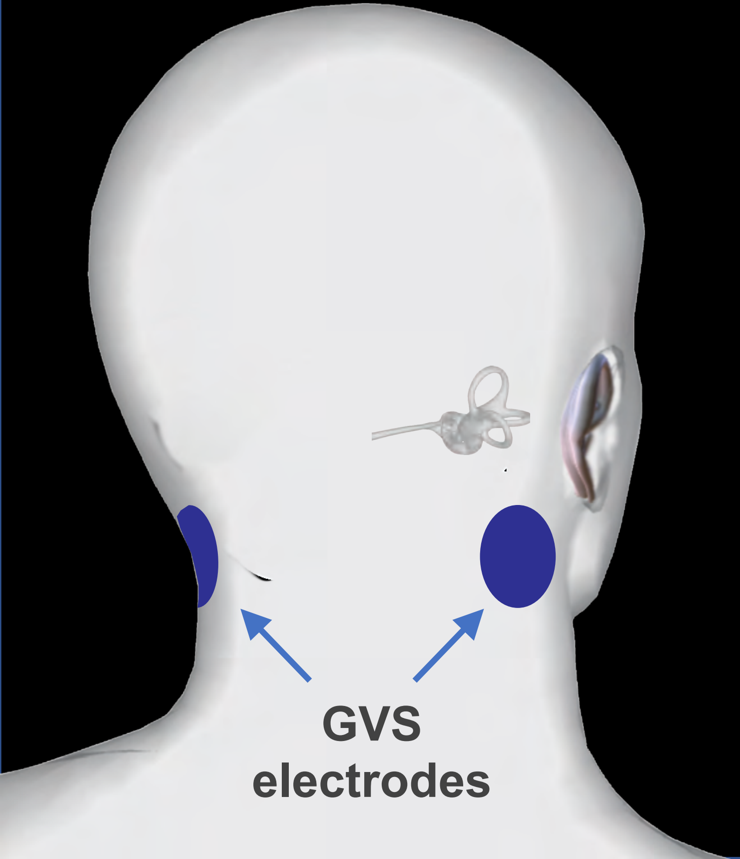
Characterize adaptive responses in crewmembers on the lunar surface using a post-landing lunar surface assessment battery

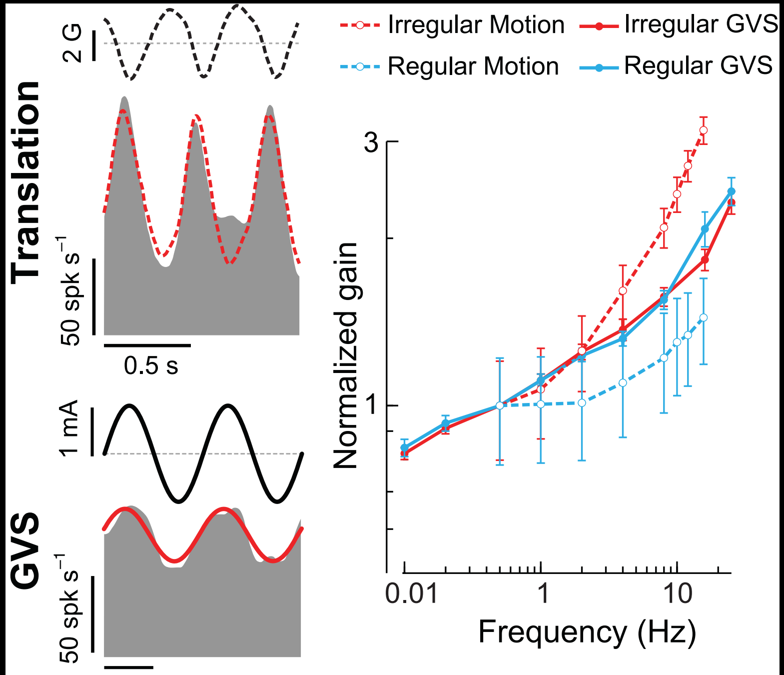
Artemis Study Timeline



Portable Spatial Disorientation Trainer

- Galvanic current stimulation (applied using surface electrodes on mastoid) can excite, inhibit, or sensitize neurons thus altering vestibular neural activity
- Subjective feedback from previously flown astronauts suggests GVS replicated ≥ 50% of postflight sensorimotor disruption

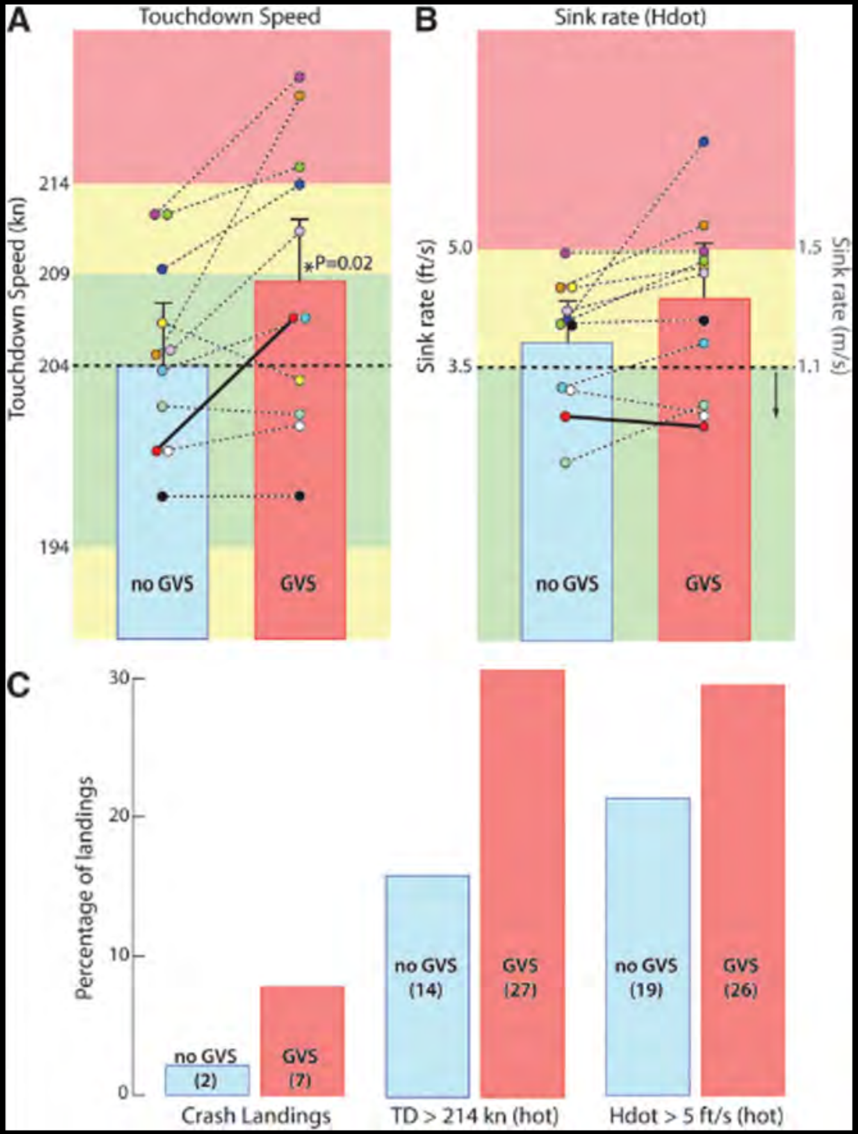




(from Kwam et al., Nat Comm, 2019)

Moudy et al. (2023) HRP Investigators Workshop

GVS during simulated Shuttle landings



- Moore et al (2011) demonstrated that GVS was an effective analogue of decrements in postflight Shuttle pilot performance
- Shuttle landing simulations were conducted at the Ames Vertical Motion Simulator with and without GVS (sum-of-sines 0.16-0.61 Hz up to ±5mA)
- GVS increased the percentage of unsuccessful (crash) landings and the number of landings with touchdown speed and sink rate in the ‘ red ’ (unacceptable) range

Moore et al. (2011) Aviat Space Environ Med 82:535-542

NASA HRP Artemis Sensorimotor Ground Research

- NASA-Navy Interagency Agreement has been established to use the Disorientation Research Device (DRD, aka Kraken) at Wright-Patterson Air Force Base in Dayton, including:
  - Sustained +3Gx runs as a sensorimotor analog to G-state transitions
  - Lunar landing simulation using design reference vehicles
  - HRP is partnering with Flight Operations Division to evaluate this platform to augment crew training on landing skills
- HRP is supporting advanced spatial orientation modeling as a means of validating how well the DRD motion simulations provide the motion cueing anticipated for the design reference vehicle trajectories, and to inform manual control countermeasures

Proposed ESA Collaboration on Artemis Research

- Navy DRD/Kraken was patterned after the TNO Desdemona
  - Operational since 2007, owned by TNO, operated by Desdemona BV
  - Both devices have similar degrees of freedom and motion capabilities
  - Desdemona personnel has specific expertise using this device for advanced disorientation research & training that could be translated to lunar landing motion simulations
  - TNO personnel also pioneered the use of sustained +3Gx as a sensorimotor analog
- TNO has specific expertise in motion perception modelling, including the prediction of motion sickness and spatial disorientation similar to NASA HRP interests
  - Current collaboration with Torin Clark from University of Colorado-Boulder comparing predictions with his Observer model

Recommended path forward

- Propose joint research plan to (1) develop lunar landing simulation on complex motion bases (DRD-Kraken and Desdemona), and (2) utilize spatial orientation modeling to validate motion simulations compared to design reference vehicle lunar trajectories
- Technical Interchange Meeting with TNO and NASA Insight, Research and Operations group involved in developing lunar landing motion base simulation
  - TIM would allow TNO to demonstrate Desdemona and spatial orientation modeling capabilities
  - Initial TIM could be conducted virtually or hybrid to enable scheduling
  - Virtual-hybrid TIM could be followed with NASA and ESA flight crew visit to experience hands-on demonstration of the Desdemona using their current training simulations (e.g., Mountain flying training course in DESDEMONA for Chinook CH-47 pilots)
- TNO and Navy also developing a Technical Planning Document (TPD) to collaborate on spatial disorientation training and research
  - TPD includes objectives to jointly improve the performance of Kraken and Desdemona
  - HRP-Navy IAA work could be used as framework for some of the TPD tasks

EXPLORE MOON to MARS

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