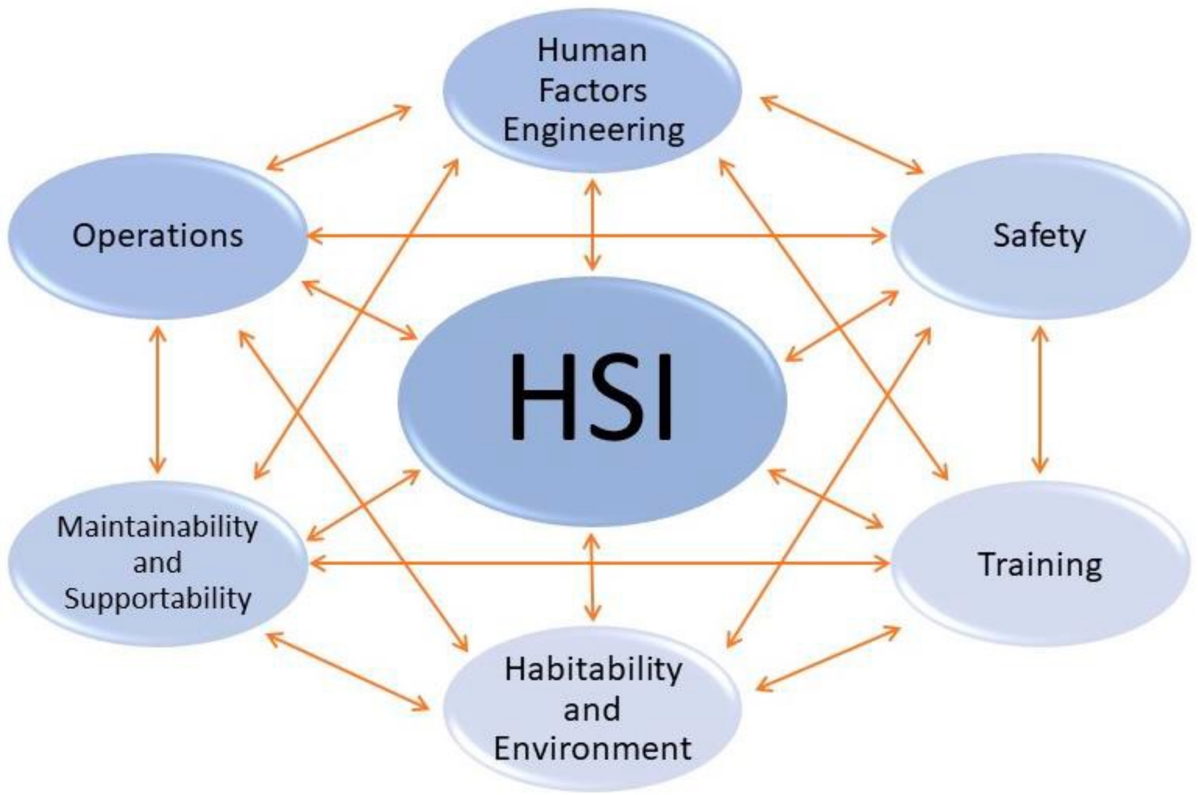
Taking Measure of Human Systems Integration: A View from NASA



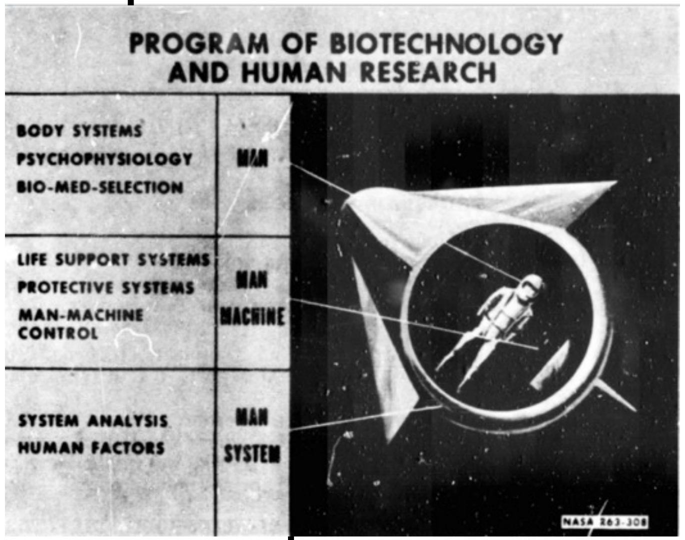
Dr. Cynthia H. Null, Technical Fellow
NASA Engineering and Safety Center

INCOSE HSI 2024 /IEA 2024
Jeju, S. Korea

28 August 2024

A Brief History of HSI at NASA

"This program is designed not only to do human research and development of adequate life support and protective systems for man's survival in the aerospace environment, but to adequately determine man-machine relationships, and integrate them properly into the advanced aerospace systems."



MSFC—STD—512
(1974) Man/System Design Criteria for Manned Orbiting Payloads

NASA—STD—3000
(1987) Man-System Integration Standards

1964 — 1984 — 2004 — Today

NASA—STD—3001
Human Spaceflight Standards

https://www.nasa.gov/ochmo/human-spaceflight-and-aviation-standards/

HSI Today

NPR-7123.1D

NASA program/project technical team shall develop and document an approach to Human Systems Integration. In developing and documenting this approach, the technical team ensures that aspects for all humans interfacing with the system (e.g., crew, operators, users, maintainers, assemblers, and ground support personnel) are considered in life-cycle and technical reviews throughout the project life cycle.

HSI Handbook v2.0 092121_FINAL COPY.pdf

A key HSI challenge

Challenge: Designing to enable resilient behavior

- Understanding routine operations and characterize resilience
- Emphasizing design for human performance and resilience
- Analyzing designs and operations

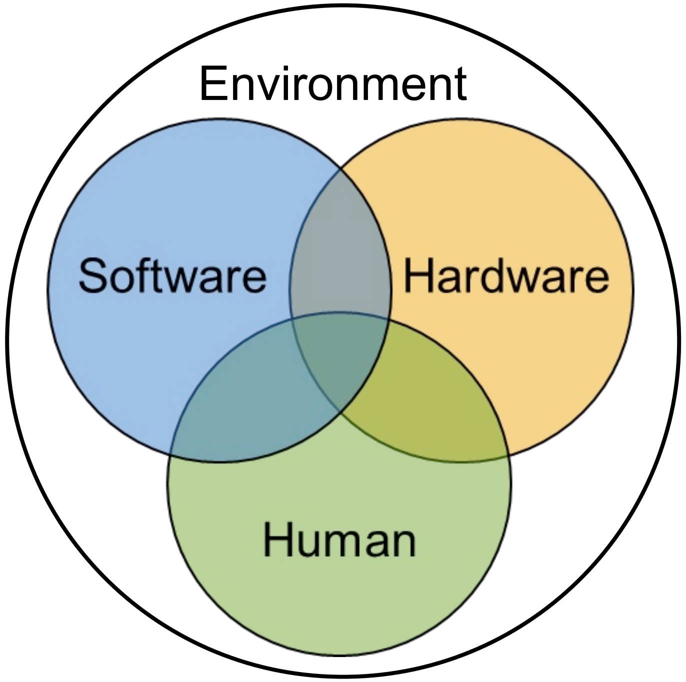
Concerns:

- ***Designing new systems without acknowledging the role of human resilient performance through the life cycle***
- ***Designing new systems without understanding human capabilities***
- ***Designing new systems without enhancing HSI methods, models, and measurement***

Human resilient performance through the life cycle

System failures are “predictably unavoidable”*

- Designing for failure prevention can reduce failures but doesn’t make systems failure-proof
  - All system elements are potential sources of failure
- Designs must also enable preparing for and recovering from both expected and unexpected failures
  - Humans are the primary source of failure preparation and recovery



* van der Schaaf & Kanse (1999)

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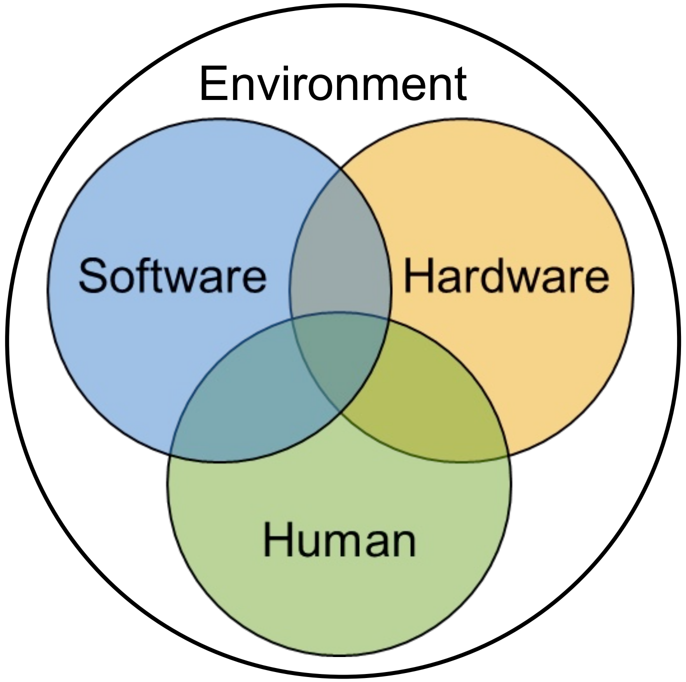
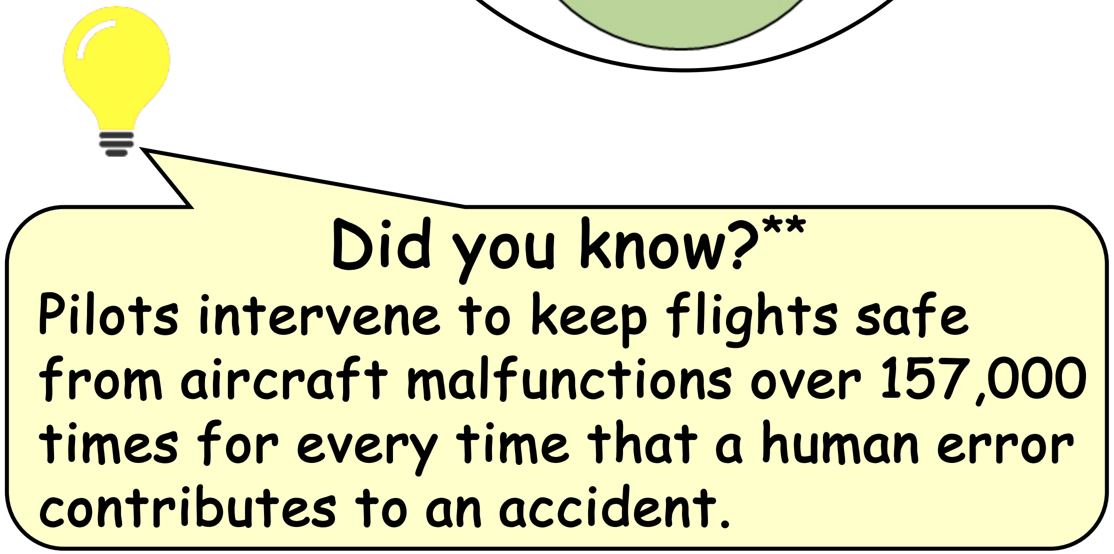
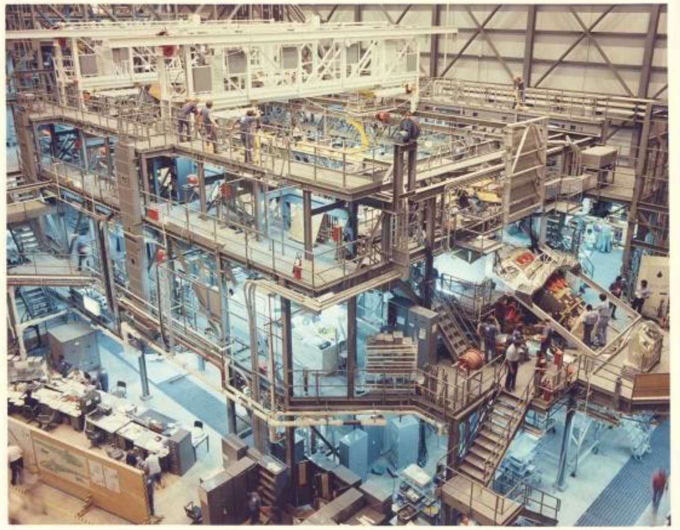




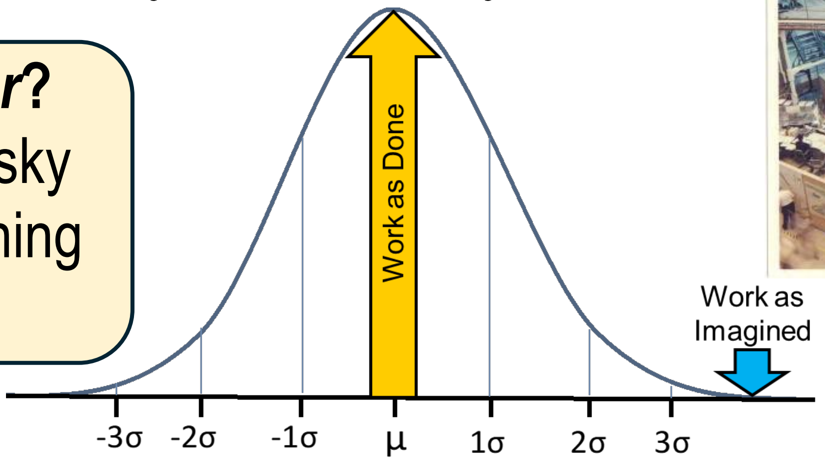
* van der Schaaf & Kanse (1999); ** Holbrook (2021)

Design for "nominal" system performance

- ***Nominal*** describes performance according to plan or design
- Because the human's role in preventing failures is rarely acknowledged, it is often assumed that "nominal" system performance is free of failure and free of human intervention
- Even in ultra-safe, well-studied systems, failures and the need to deal with them are *routine*
  - Airline pilots intervene to deal with system malfunctions on 1 in 5 "normal" flights
  - These systems are carefully designed, rigorously tested, & fully certified



What are we planning and designing *for*?
When 'nominal' is characterized as a blue-sky "everything works" condition, we risk designing for a state that rarely if ever occurs.



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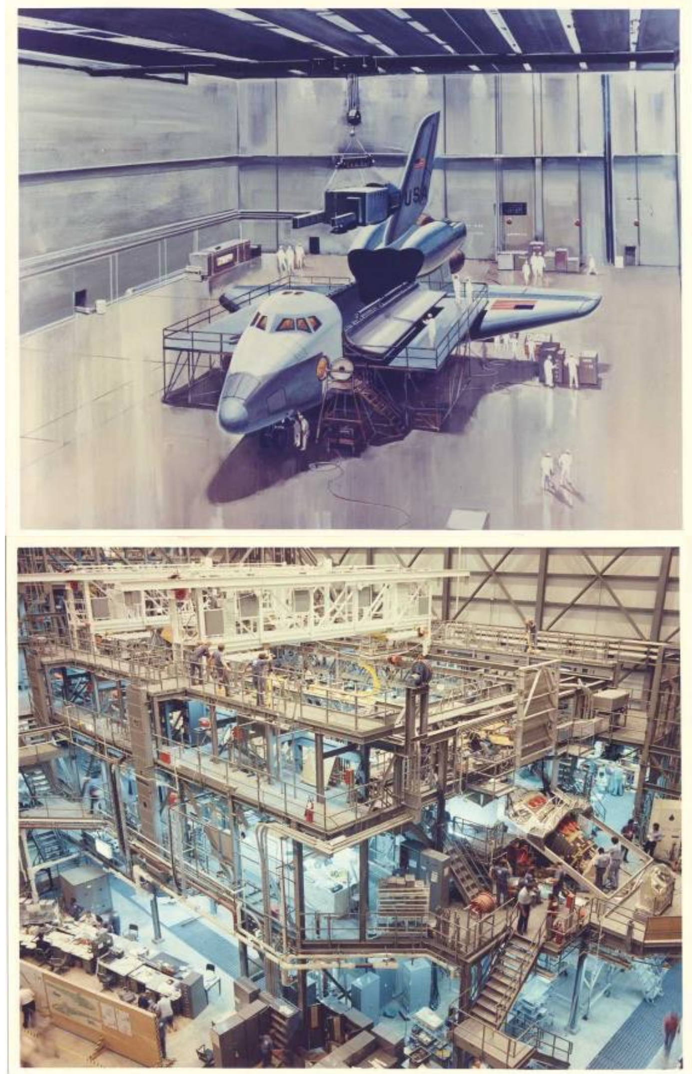

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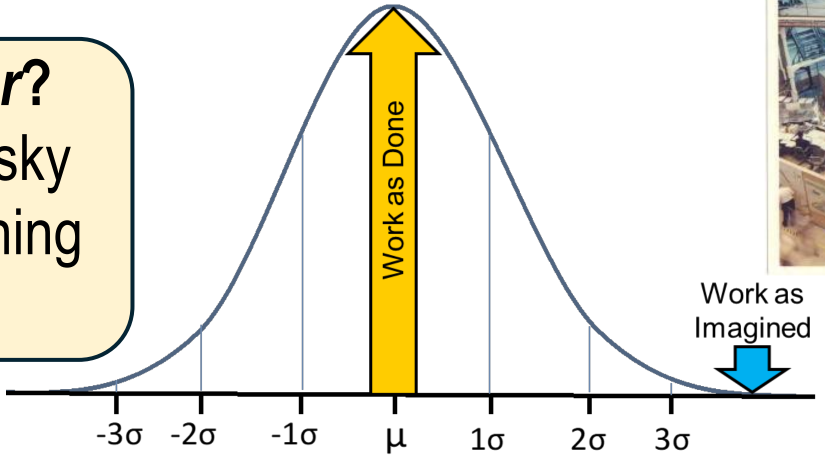


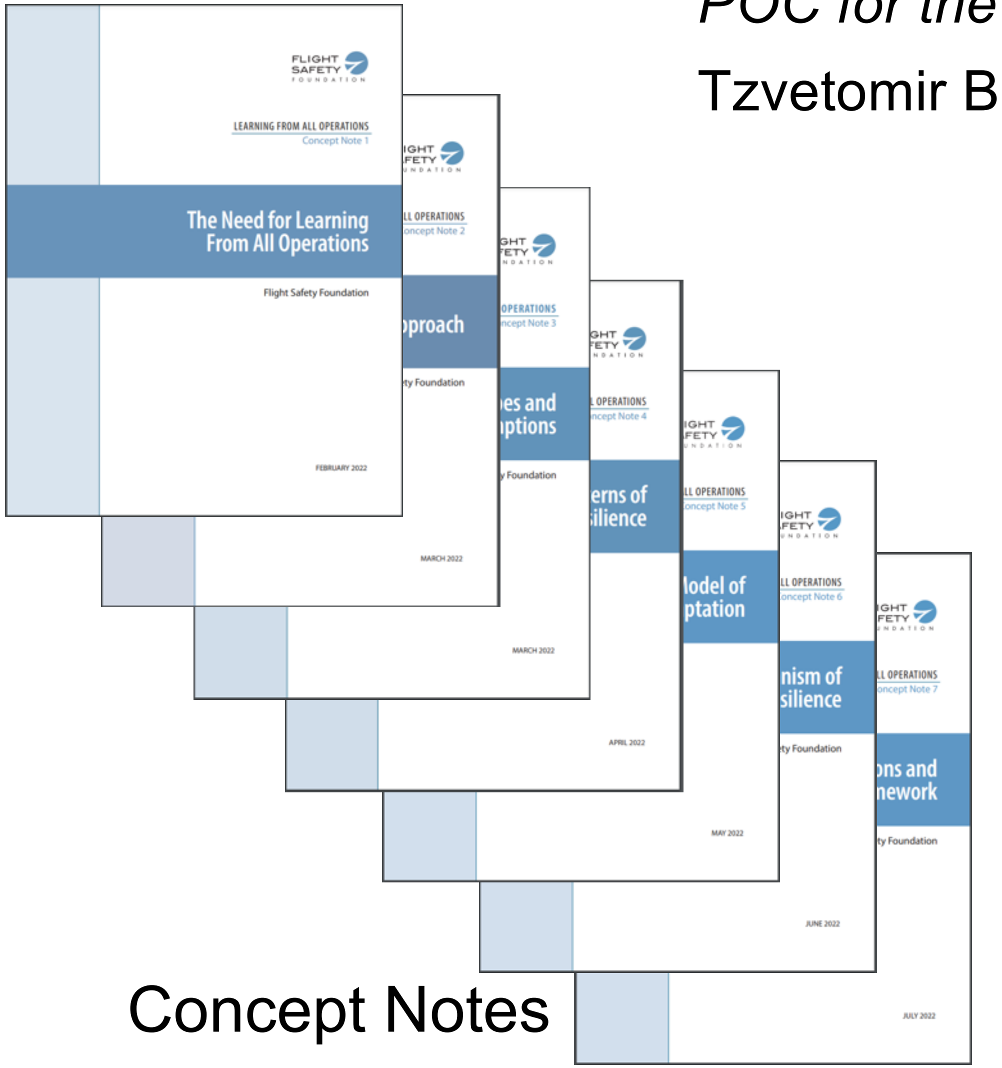
Learning from All Operations

POC for the FSF LAO initiative:

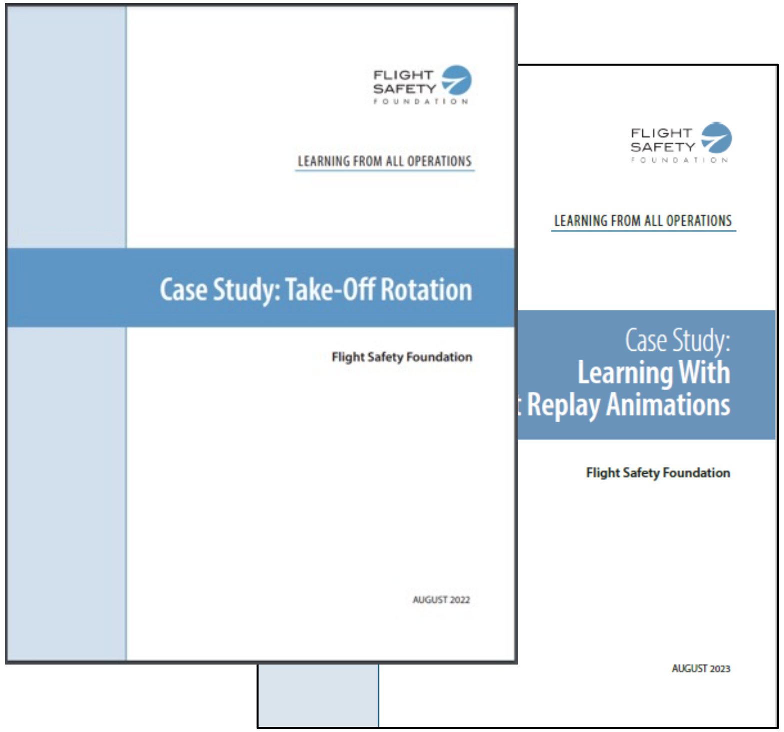
Tzvetomir Blajev (blajev@flightsafety.org)

FLIGHT SAFETY FOUNDATION

White paper



Concept Notes



Case Study

https://flightsafety.org/toolkits-resources/learning-from-all-operations/

System Complexity

Complexity arises in any system in which many agents interact and adapt to one another and their environments --Santa Fe Institute

(Some) Characteristics:

- A number of strongly coupled components or nested systems of systems, or networks
- Sudden transitions or tipping-points
- Emergent behavior
- Limited predictability
- Large events or Cascading Failures
- Self-organization
- Nonlinearity
- Dynamic Complexity
- Interfaces can hide complexity

Leads to:

- Routine operations that include unexpected events with antecedents in unrecognized faults that have
  - existed in the systems from design,
  - emerged, or
  - been added over the lifecycle

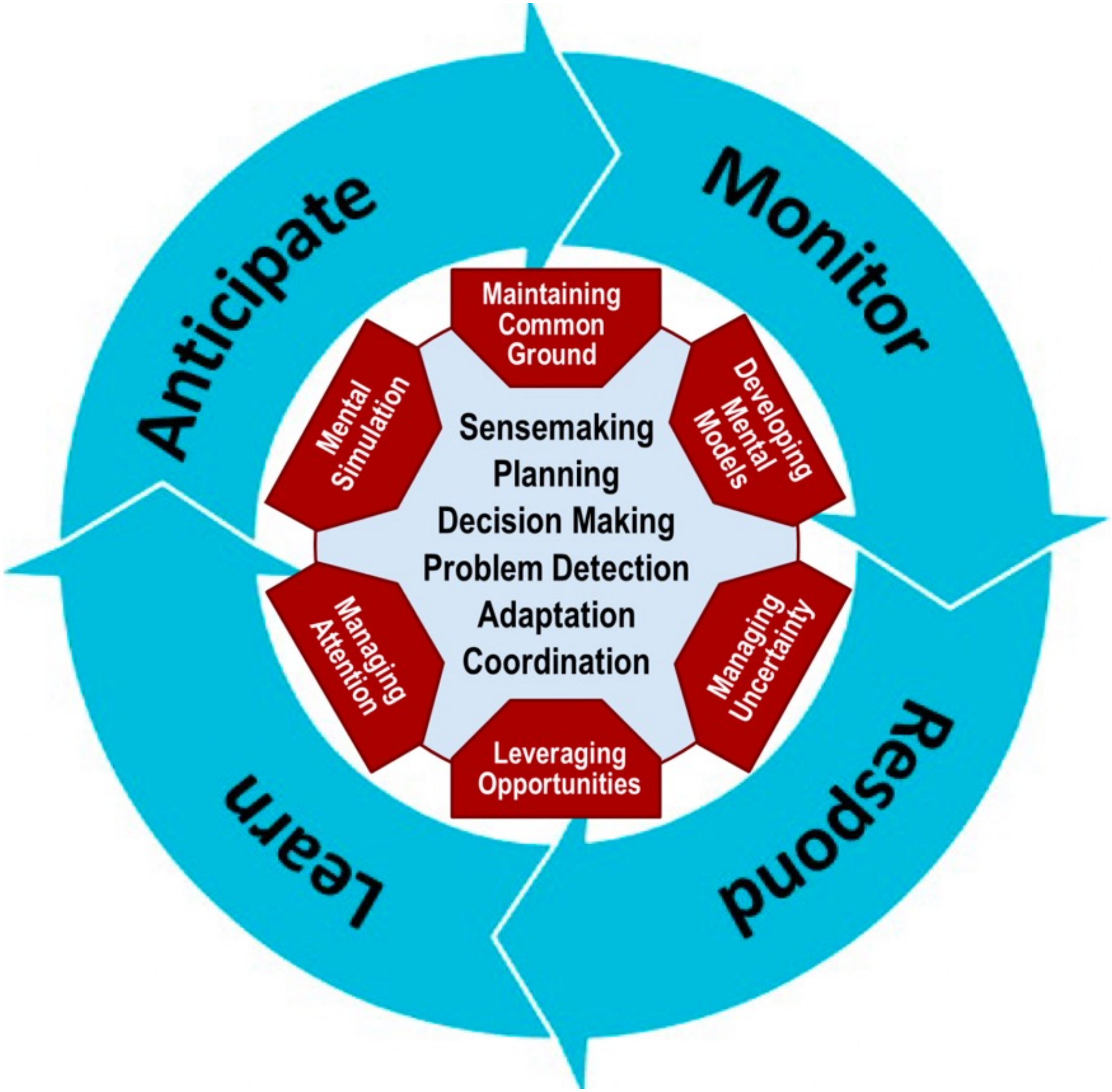
People in complex systems create safety

- People make it their job to anticipate pathways to failure
- People negotiate between safety and other operational pressures
- People invest in their own resilience
  - by tailoring tasks,
  - by inserting buffers, routines, and memory aids
- …. to increase safety

How humans succeed, and sometimes fail, may only differ in the outcome

Resilient Human Performance

- Resilient performance[1] comprises the capabilities to:
  - **Anticipate**–consider what might happen in the future
  - **Monitor**–know what is happening and where to look for change
  - **Respond**–know what to do and have the opportunity to do it
  - **Learn**–know what has happened and why
- Resilient performance enables macro-cognitive functions[2] (i.e., “goals”)



Outer circle adapted from Hollnagel (2015)[1]; Inner circle adapted from Klein et al. (2003)[2] by J. Holbrook

Managing system failures by designing for humans

- The mind is a successful adaptive system
  - Natural selection produced cognitive systems that solve problems reliably, quickly, and efficiently, but those systems are *functionally specialized* (Cosmides & Tooby, 2013)
- Including expertise on how humans work is critical to successful system design
  - Often-cited examples of what humans are "bad at" may actually reflect highly adaptive, evolutionarily successful cognitive processes at odds with a technological design

Work environments that are poorly aligned with what our cognitive systems evolved to do limit human capabilities for failure management

Premise for complex safety critical systems

- Humans are key to every mission (crewed or uncrewed)
- Everything at every phase in mission development has the potential to influence humans or be influenced by humans
- All human roles across the mission life-cycle must be considered
- Designs and operations need to be compatible with human capabilities and meet human needs
- To be successful, mission must take advantage of the unique ability of humans to be flexible, creative, adaptable, resilient, and to solve problems

Understanding human capabilities

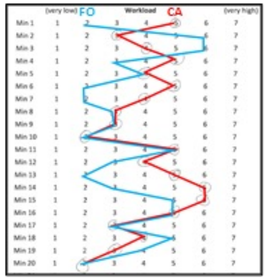
We don’t think like we think

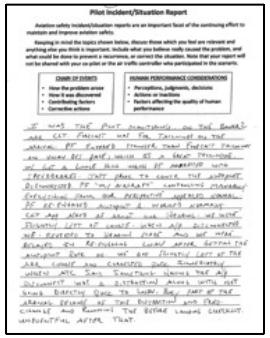
- Why everyone isn’t an expert on how humans think just because they’re human
    - People do not have reliable introspective access to their own cognition (Nisbett & Wilson, 1977)
    - It doesn’t *feel* like our introspections are unreliable, so people overestimate their ability to do so (Dunning & Kruger, 1999)
    - We employ scientific methods to understand how people think
    - We employ human performance experts to understand the science

Mental models affect system design

	Unaligned **with how human cognition works**	***Aligned*** **with how human cognition works**
HABA-MABA	Humans are bad at monitoring, decision making, planning, probabilistic reasoning, but good at adapting and improvising.	The human mind is a successful adaptive system that is functionally specialized. Environments and tools that are poorly aligned with what our cognitive systems evolved to do drive our cognitive successes and failures.
Nominal perfor-mance	The system mostly functions successfully as-designed – when there aren't accidents or near-misses, "nothing is happening".	All complex sociotechnical systems are in a constant state of decay and must be actively maintained. System failures are predictably unavoidable. There will always be surprises – we can never fully understand everything about how a dynamic unbounded system works.
SOPs	Desired behaviors are a nice to have, but mostly entail following SOPs – little to no recognition of how safety is actively and routinely created and maintained.	Desired behaviors are routinely sustaining the safe operation of the system, and without those behaviors, the system would rapidly decay. SOPs are an invaluable tool, but must be interpreted, followed, and sometimes deviated from to sustain safety.
Human as a hazard	The most direct path to improving safety is replace, restrict, or isolate the primary source of error. We can do this by assigning tasks that people are bad at to automation and leave the human to adapt and improvise on the rare occasions when that is necessary.	The most direct path to improving safety is ensuring that our systems and work environments (including procedures, training, workstations, etc.) are aligned with what we know about how our cognitive systems actually work.
Human error	Undesired behaviors can lead to accidents. Indeed human error is implicated in 80% of accidents. "To err is human" -- infers that human error is unavoidable, inevitable, invariant -- something that "just happens".	Undesired behaviors can lead to accidents – the likelihood and impact of human errors can be impacted by system design (i.e., we can set operators up for success or for failure).

Using simulations to systematically explore insights



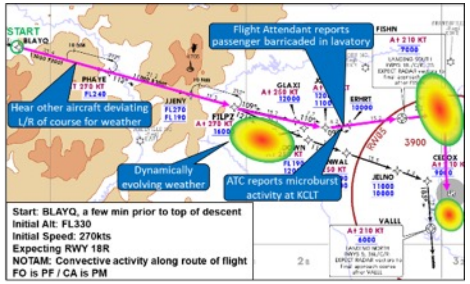


Motivation and Objectives

- Test concept assumptions
- Validate insights from behavioral field observation
- Identify systematic, repeatable measures generalizable to many safety-critical domains

Approach

- 12 B737 flight crews took part in a 1.5-day study, using a high-fidelity B737 motion-base simulator
- Participating flight crews flew a series of eight 20-minute scenarios based on arrivals into Charlotte Airport.
- Each scenario was designed to contain at least 2 manageable "pressures"



All images, credit: NASA

Outcome

- Data testbed for identifying approaches for measuring the actions and strategies that operators use to successfully anticipate, monitor for, respond to, and learn from events in their environment
  - **Observer data** (including "over the shoulder video recordings to support post-hoc observation)
  - **Self-report data** (e.g., surveys, questionnaires, subjective ratings, event narratives, cued retrospective think-aloud)
  - **System data** (e.g., simulated flight data, psychophysiological data)

Impact

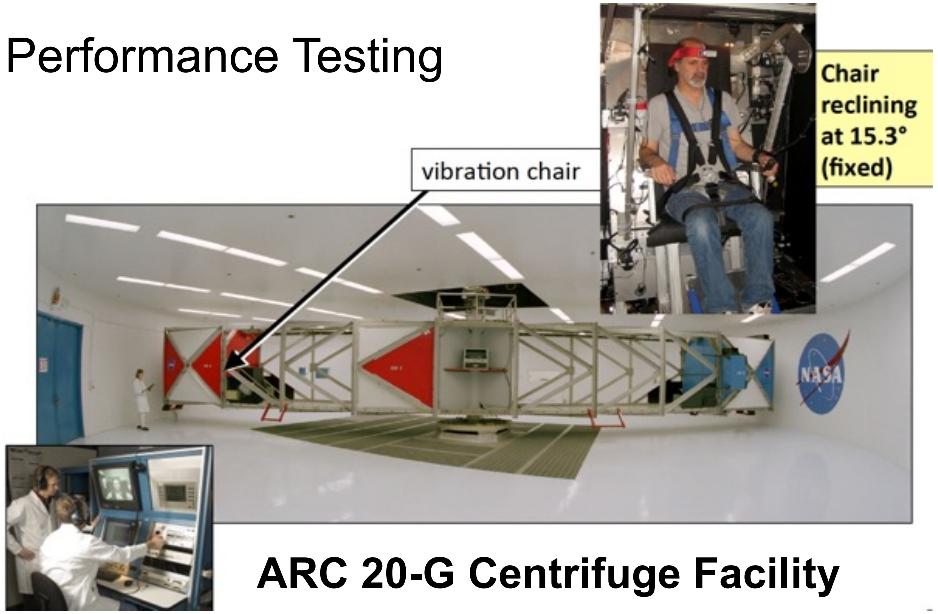
- Assess methods for learning from what *happens*, not just from what *fails*
- Potential to massively expand the pool of safety-relevant data, which can
  - Enhance timeliness of safety learning
  - Reduce risk of sampling bias
  - Inform system design

For more information: Jon Holbrook, PhD
jon.holbrook@nasa.gov

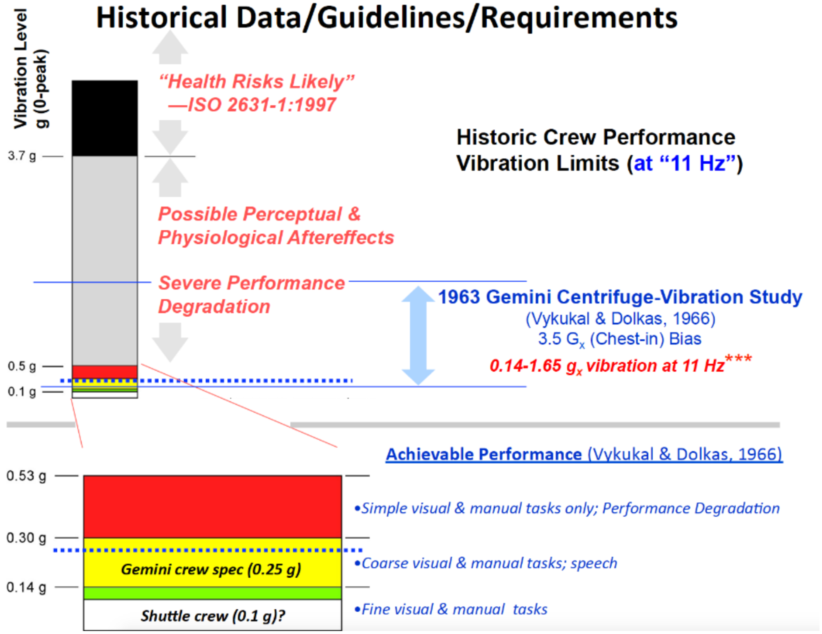
Human Factors solution to Ares vibration challenge

- Background
  - Ares program accepted requirements identified by SMEs for limitation on vibration environment for health
  - After Ares development began, it was realized that the induced environment from thrust oscillation exceeded requirement and interfered with task performance (e.g., ability to read displays)
  - Workshop conducted bringing together external expertise
  - No outside organization could offer a solution

- Human Performance Testing



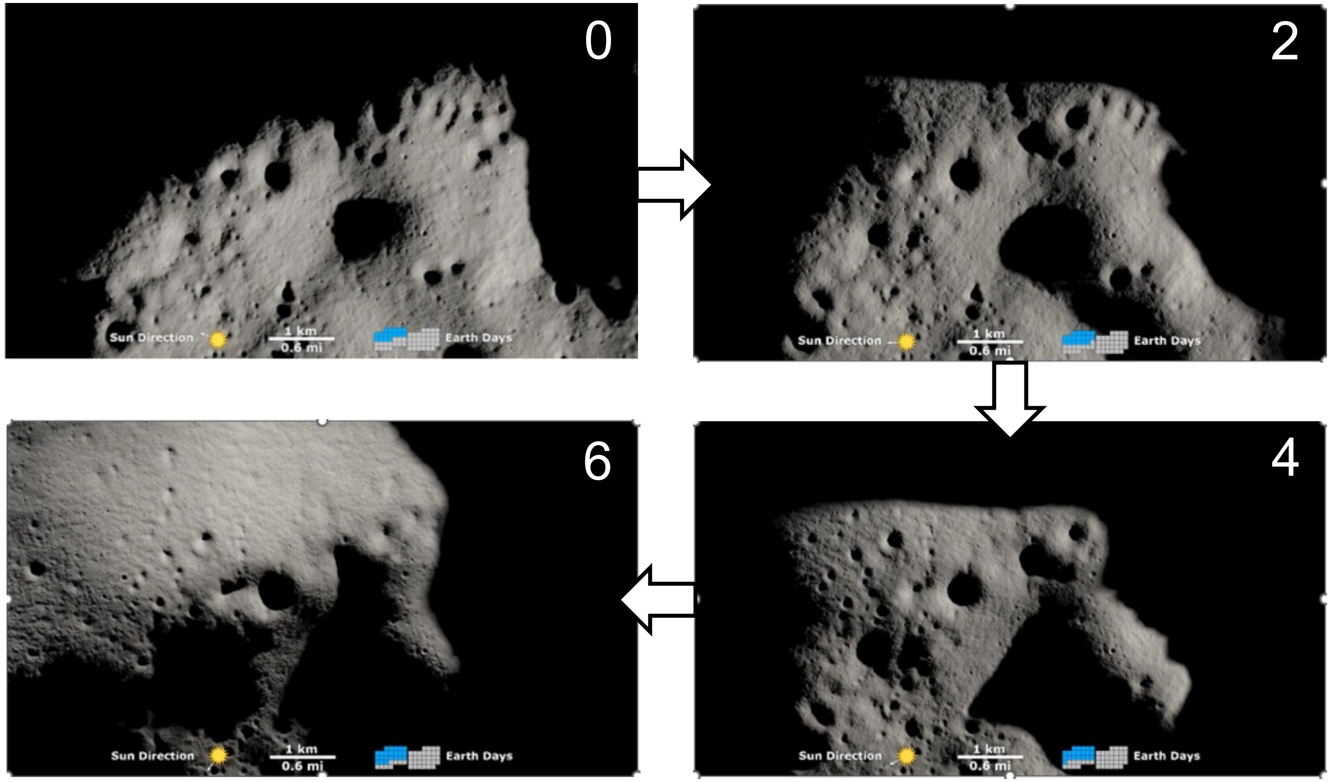
ARC 20-G Centrifuge Facility

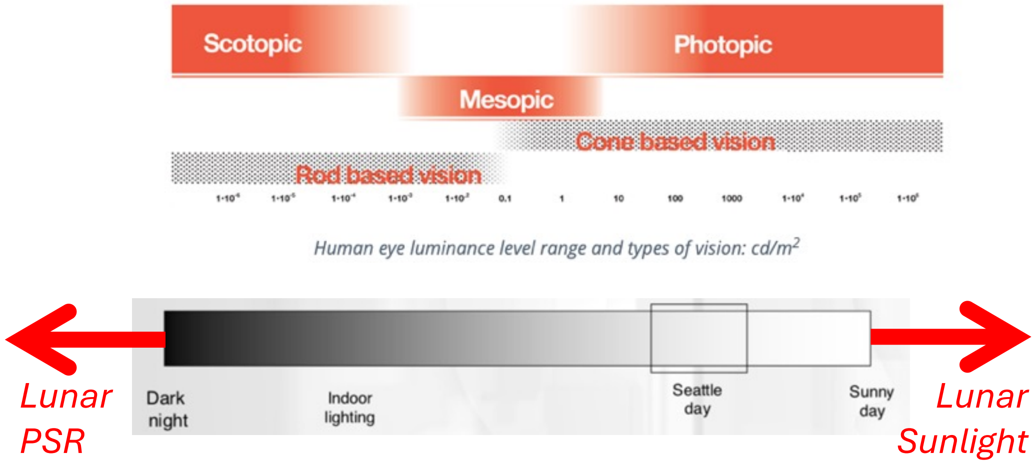


- Conclusion
  - Initial analysis provided human performance requirement, but did not help the rocket
  - Insights from human performance provided an ingenious mitigation (US Patent **#8,711,462)**
  - The vibration performance requirements developed for Ares-1 was inherited by Orion for which it together with SLS must now comply.
  - Subsequent crew-occupied flight and extraterrestrial surface vehicles have vibration/acceleration limits for human performance as well as health based on data.

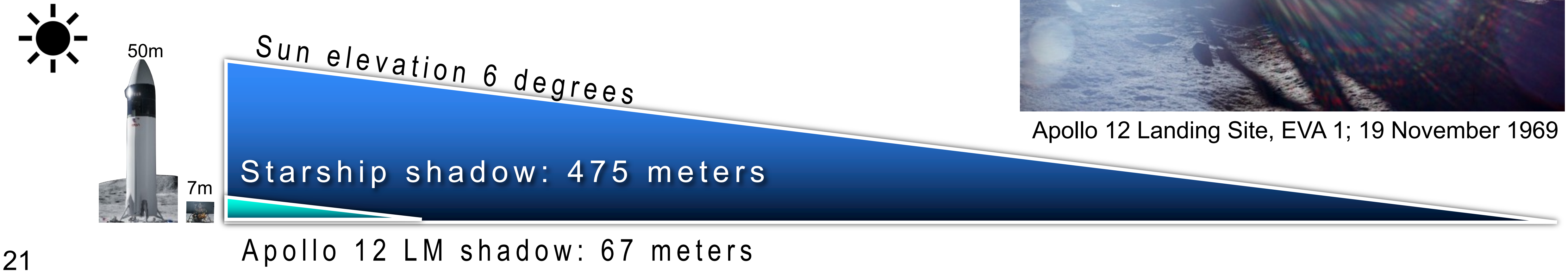
Integrated solution to support functional vision for exploring the lunar south pole

Progression shows lighting change over 6 earth days





Apollo 12 Landing Site, EVA 1; 19 November 1969



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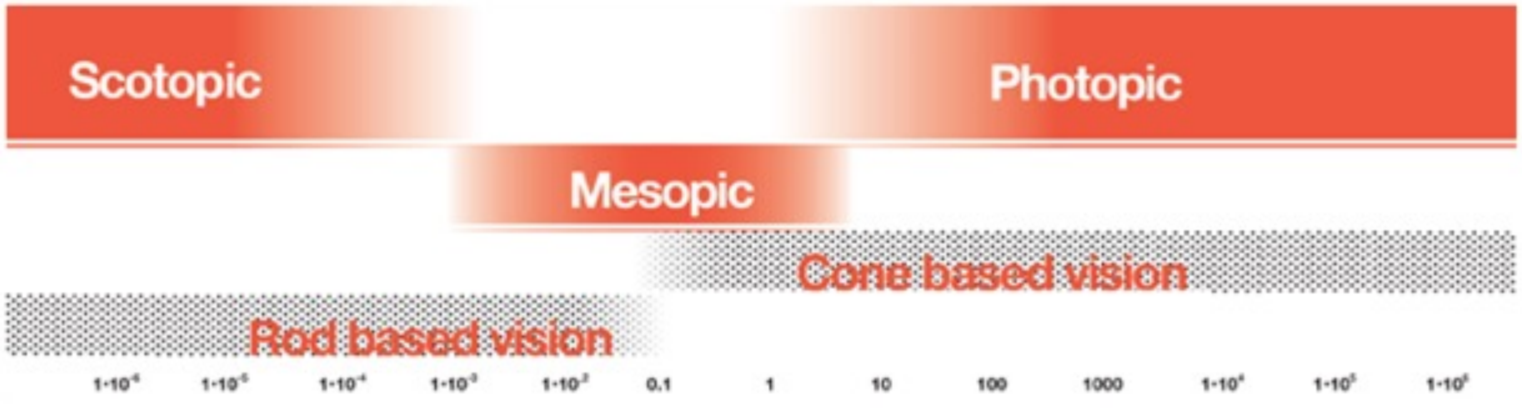
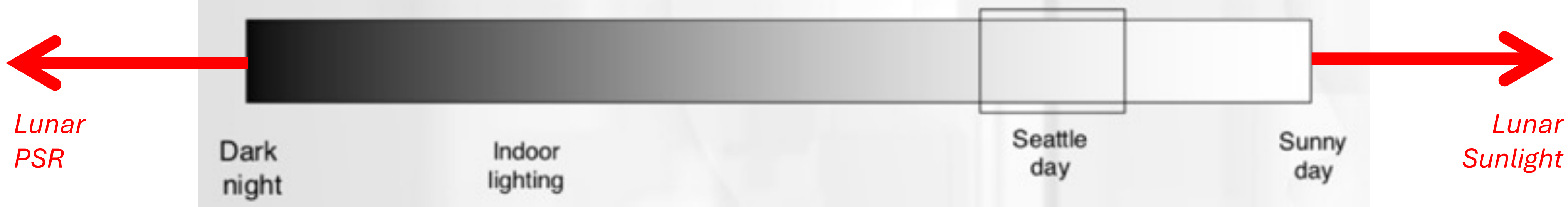


Human eye luminance level range and types of vision: cd/m²



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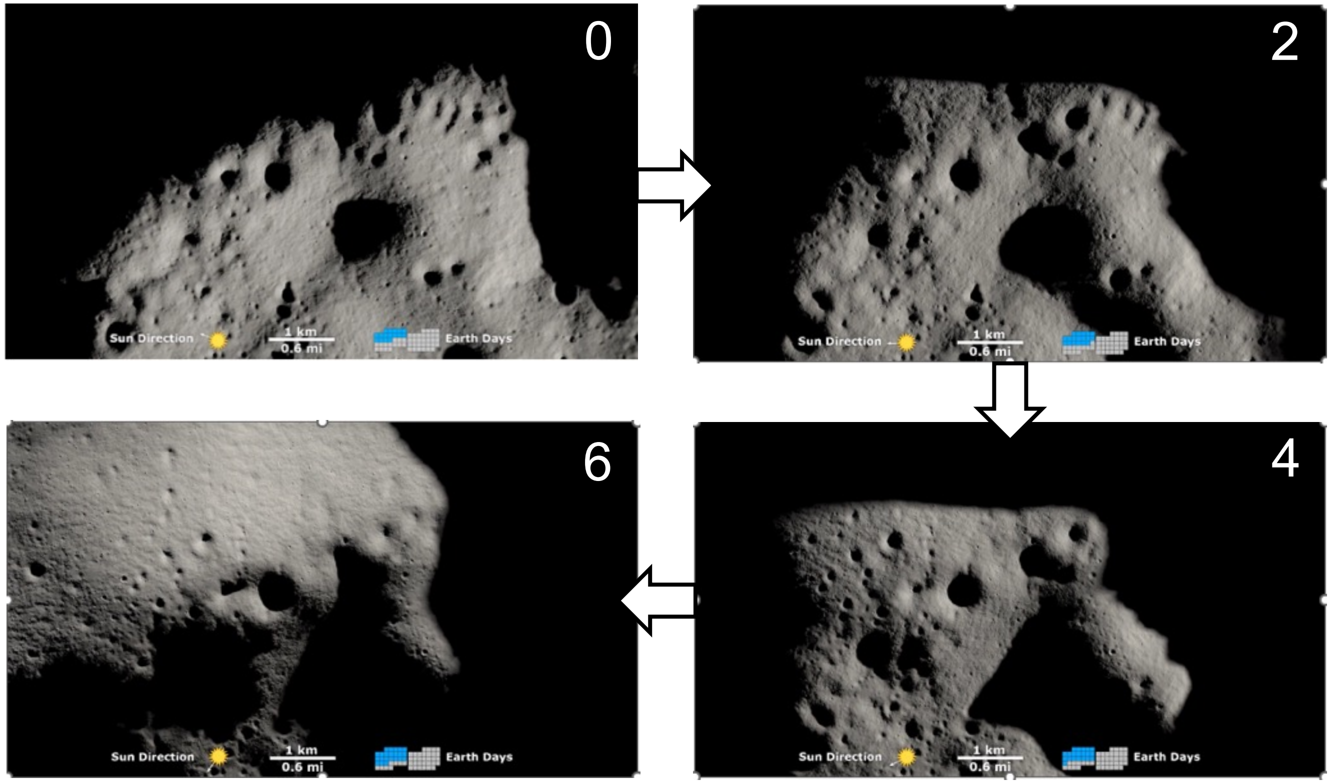

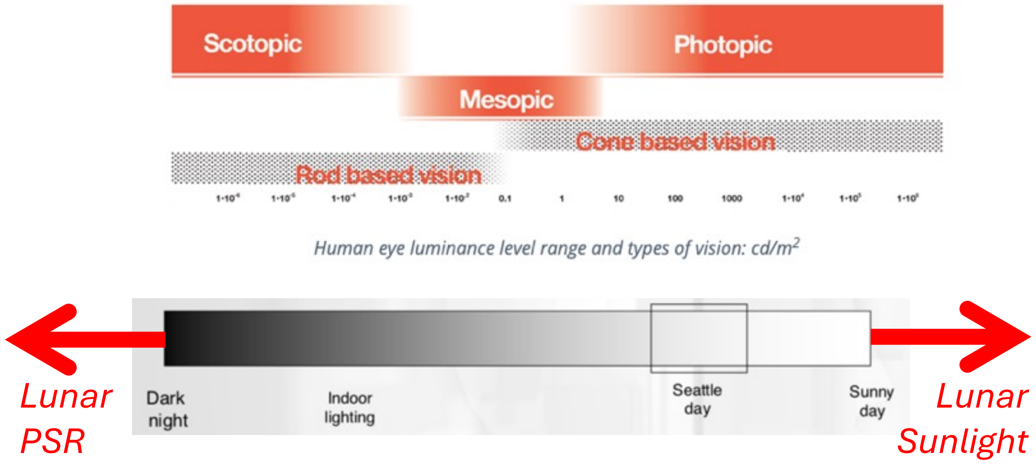

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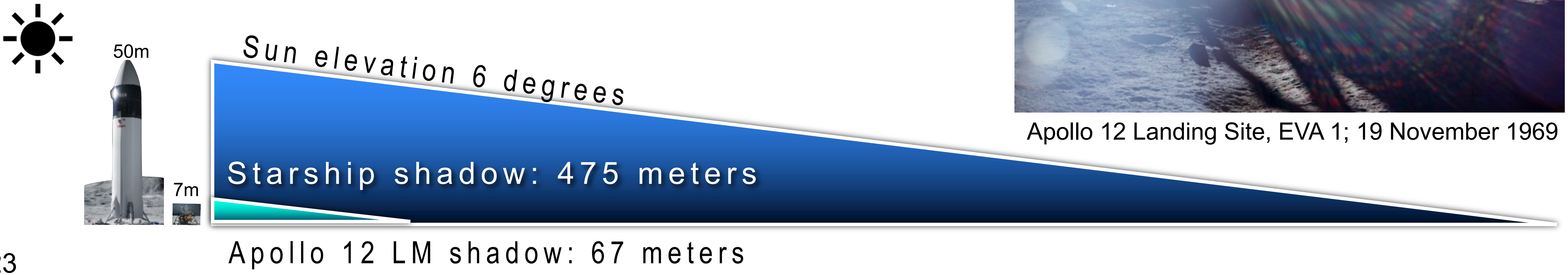

Enhancing HSI methods, models, and measurement

Comprehensive Oculomotor Behavioral Response Assessment (COBRA)

Step 1: VALIDATING PERFORMANCE MEASUREMENT TOOLS

- One example of an emerging new tool is Oculometrics
- Eye movements have long been known to provide insight into human sensorimotor brain function and pathology, with a strong tradition of applying linear system theory to explain gross deficits in oculomotor or visual-vestibular function
- Oculometrics have been shown as reliable biomarkers of visuomotor function (e.g., Stone et al, 2019).
  - Quantitatively measure visual perception
  - Small within-subject test-retest variability
  - Excellent (> 0.7) reliability scores
  - Little to no learning effects (0-2% improvement/run)
- Oculometrics provides powerful new tool to efficiently and objectively assess human visuomotor performance by collecting dozens of standard measures reflecting neural function in different parts of the brain in a 5-10 minute test

For more information: Lee Stone, PhD
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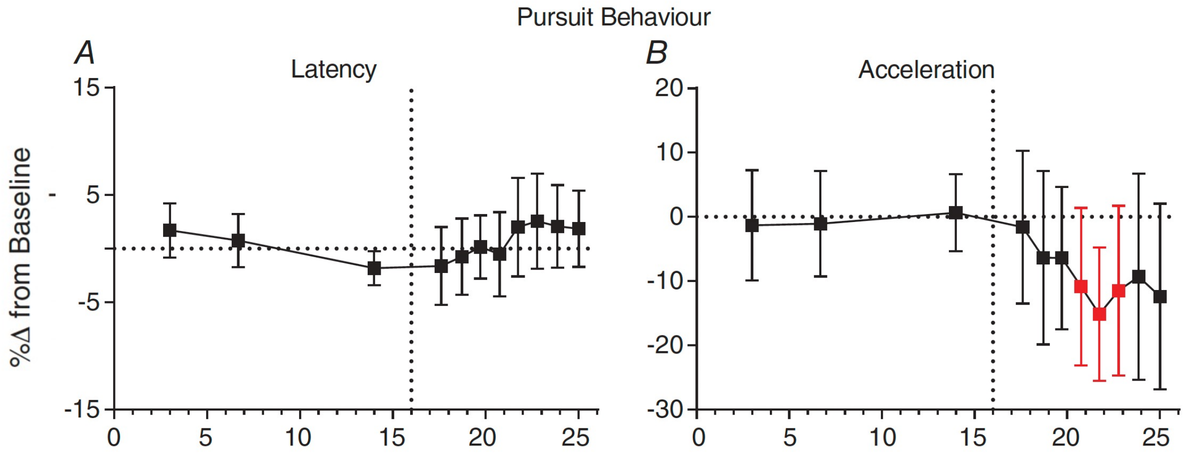
Step 2: MEASURE DOSE-RESPONSE



Quantitative measurement of human performance as a function of induced environments (i.e., the system's allowable specifications) enables better requirement

➔ Such dose-response curves (recorded in Agency standards – Step 3) enable a missions/programs to decide on what requirements to mandate on a system

➔ Selecting the acceptable performance decrement (here, response latency/delay or gain/accuracy) allows for more quantitative risk assessment

➔ Requirements written as "The system shall maintain condition X below value Y" are unambiguous and help guide engineering design

How is mission safety analyzed and measured?

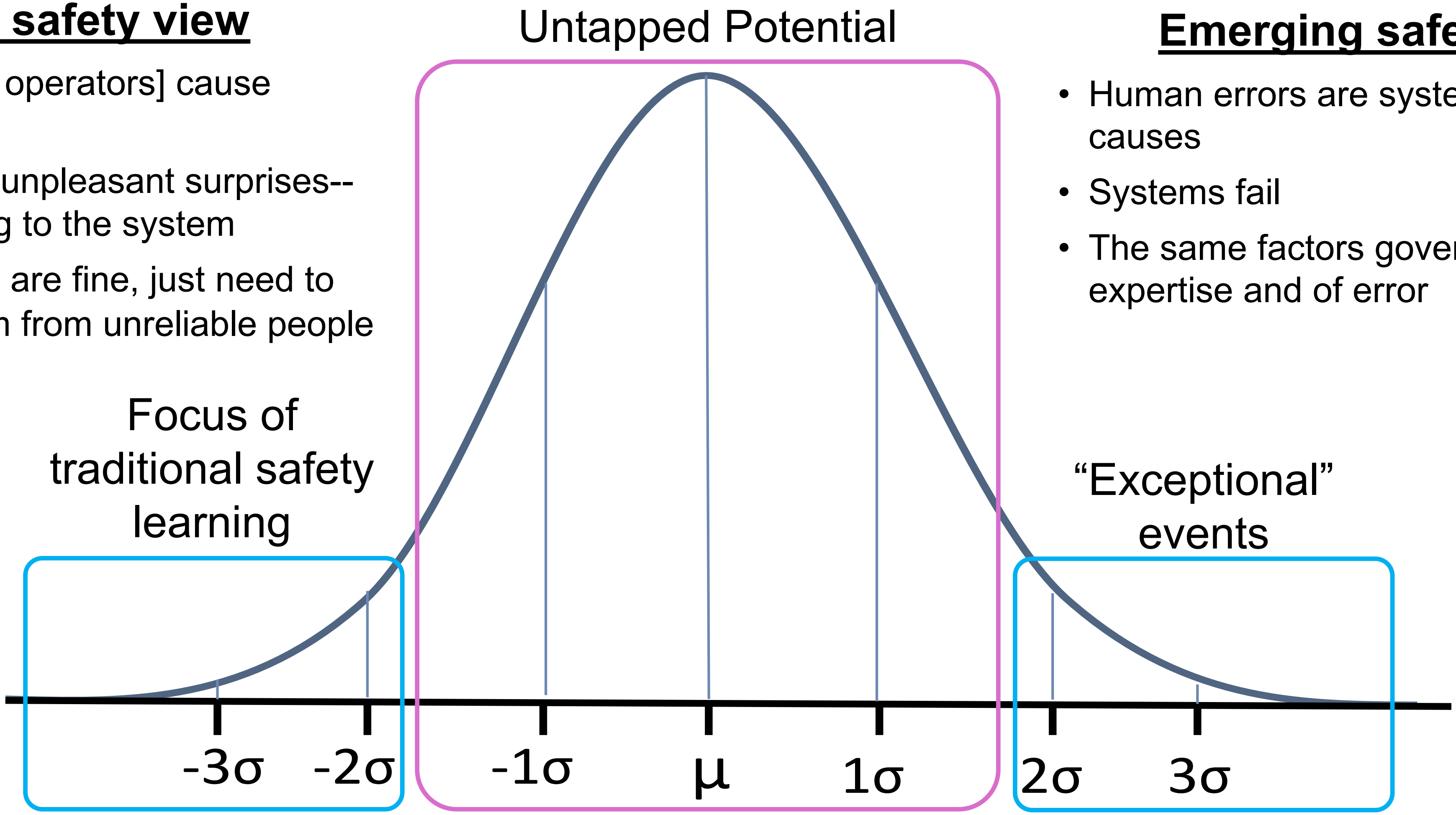
Safety systems are often only triggered by rule violations, close calls, or accidents

Traditional safety view

- Human errors [by operators] cause accidents
- Failures come as unpleasant surprises--they do not belong to the system
- Complex systems are fine, just need to protect the system from unreliable people

Emerging safety view

- Human errors are system symptoms not causes
- Systems fail
- The same factors govern expression of expertise and of error



Humans *produce* safety far more often than they *reduce* it

- Human error has been implicated in up to 80% of accidents in civil and military aviation[1]
- Pilots intervene to manage aircraft malfunctions on 20% of normal flights[2]
- World-wide jet data from 2007-2016[3]
  - 244 million departures
  - 388 accidents

Attributed to Human Intervention	Outcome: Not Accident	Outcome: Accident	
No	195,199,690	78	195,199,768
Yes	48,799,922	310	48,800,232
	243,999,612	388	244,000,000

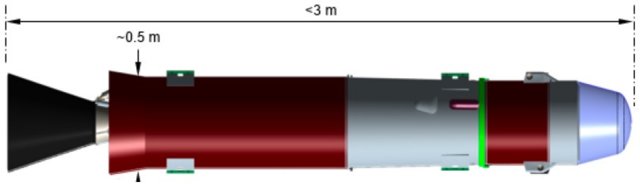
Frequently Studied

Rarely Recognized

Learn more: Holbrook, J. (2021). Exploring methods to collect and analyze data on human contributions to aviation safety. In *Proceedings of the 2021 International Symposium on Aviation Psychology.* https://aviation-psychology.org/wp-content/uploads/2021/05/ISAP_2021_Proceedings_FINAL.pdf

(1) Weigmann & Shappell, 2003; (2) PARC/CAST, 2013; (3) Boeing, 2017

Human Systems Integration Design Influence on Mars Ascent Vehicle Mars Sample Return Mission

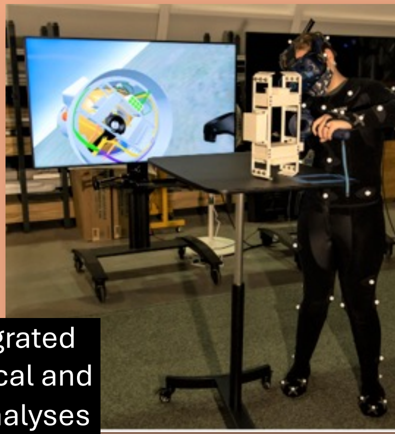


MAV design, assembly, and ground processing operations

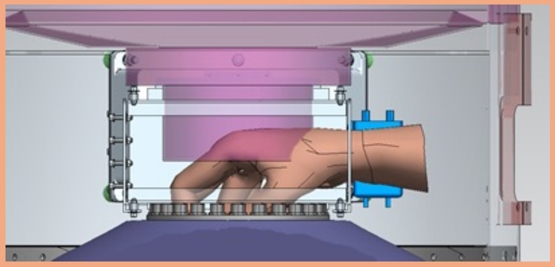
- Established HSI requirements
- Worksite analyses for assembly and integration
- Use of Ground Support Equipment

Findings:

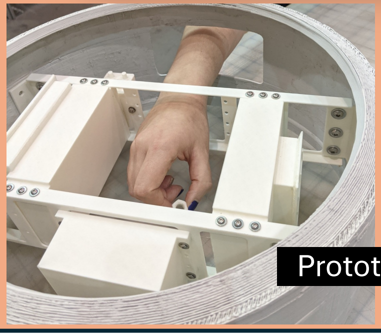
- All hands assessed violated keep out zones
- Access was very limited and awkward for users
- Inadequate clearance for tools



Integrated Physical and VR Analyses



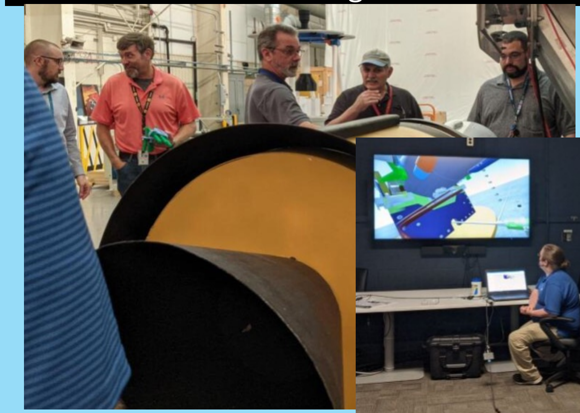
75th Percentile Male



Prototypes

- Allows fast changing design layouts to be analyzed
- Increases understanding of scale and density of component layout
- Allows for real-time discussion of design for decisional purposes

Disciplines used the Virtual Environments Lab (VEL) and prototypes for TIM discussions and faster onboarding of new teams.

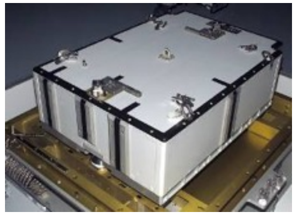


For more information: Tanya Andrews Tanya.C.Andrews@nasa.gov

Supporting a Human Mission to Mars

NASA's mission operations paradigm is one of near-complete **real-time dependence** on experts on the ground to control and manage the combined state of the mission, vehicle, and crew.

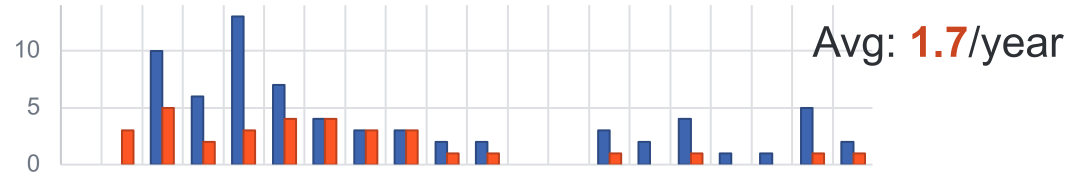
The ISS relies on frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle



MCC-H constantly manages the state of the vehicle

Mission Control provides crew with real-time direction and oversight for complex task execution

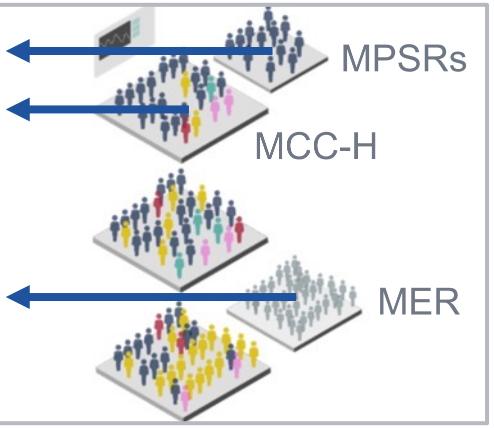
ISS: High Priority IFIs, Significant Incidents in Vehicle Systems Requiring Urgent Diagnosis



Mission Control Expertise:

(Mission Control Center (MCC-H), Mission Evaluation Room (MER), and support rooms)

- **85+** specialists available
- **~660** years combined on-console experience
- **22** unique console disciplines



NASA's mission operations have evolved but approach has not fundamentally changed…

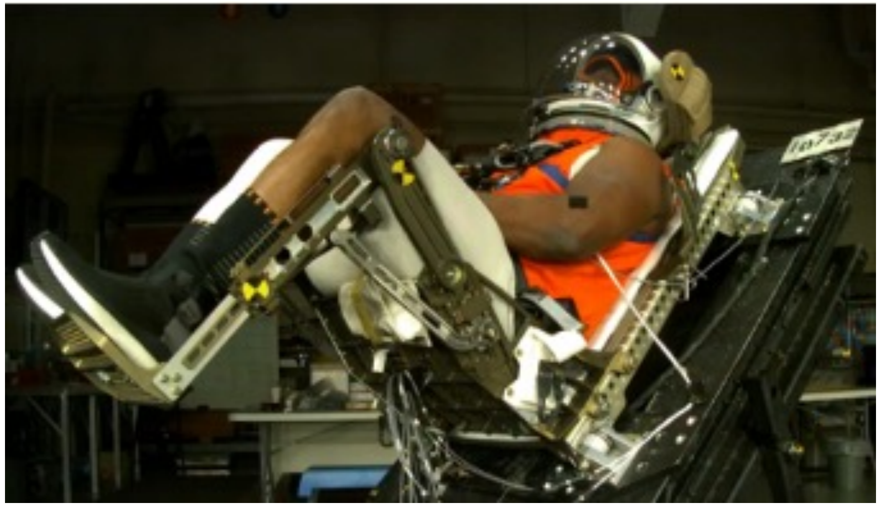
Apollo, 1961 - 1973

ISS, 2000 - present

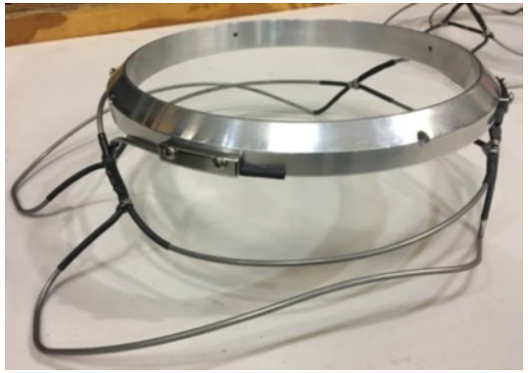
For more information: Alonso Vera, Ph.D.
Alonso.H.Vera@nasa.

Dealing with Risks that have Conflicting Solutions

- Background
  - Depressurization of a vehicle near the Moon would require crew to survive in pressurized suits for days
  - Necessary elements to provide air, water, and food to crewmembers add significant mass to the head
  - **Increased head-borne mass greatly increases injury risk**
  - Motor sports employ a device to couple the helmet to the chest in the event of a crash
    - Helmet is different than spaceflight helmet
    - Principal direction of force is different



Helmet moving with torso in human subject test



- Conclusion
  - Developed lightweight device that uses belt loads to hold the helmet to the chest
  - Tested device with dummies and human volunteers
  - Tests showed the device taking up the load rather than the neck
  - **Design enabled a suit that can support a weeklong journey back to earth without compromising safety during landing**

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Using human performance modeling for determining crew size

Problem Description

- NASA did not have a quantitative, systematic, repeatable process to determine the number and composition of crew necessary to successfully accomplish Mars missions.

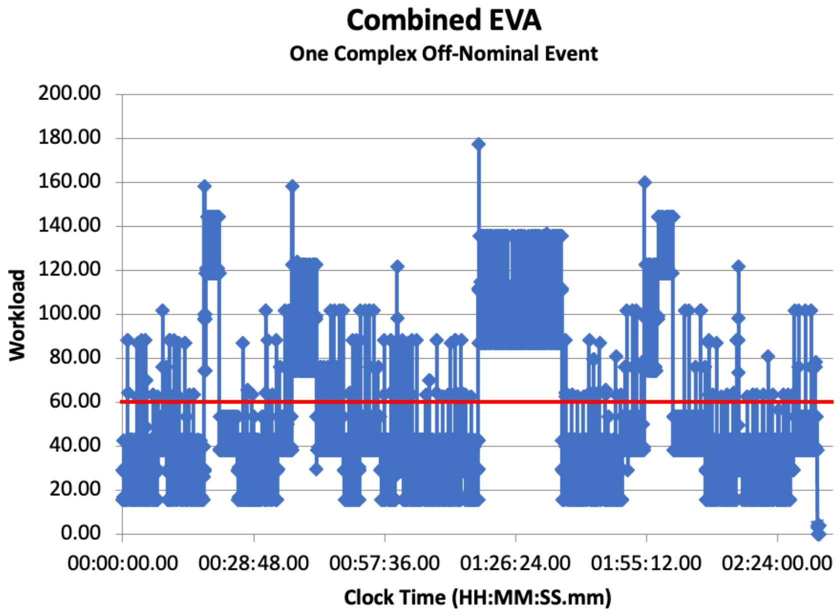
Proposed Solution

- Developed a methodology for performing trade space analysis for crew size determination using quantitative data (mental workload, crew time, and expertise) from human performance modeling.

Recommendations

- Agency decision-makers should consider the crew workload and expertise within the crew necessary to accomplish primary mission objectives and respond to unforeseen failures when considering trades for crew size for Mars missions.
- After the Agency makes a final decision on crew size for Mars missions, ESDMD, SOMD, and STMD should continue to update human performance modeling to ensure acceptable workload and the necessary expertise as mission architectures evolve.

Model Outputs



	Time Averaged Workload	Percent Time in Overload	Peak Workload
One Complex Off-Nominal Event	52.17	24.02	177.49

Hypothetical Combined EVA, EVA Task and EMU Position Workload

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Conclusions & next steps

A key HSI challenge - Summary

- **Challenge**: Designing to enable resilient behavior
- **Concerns**:
  - ***Designing new systems without acknowledging the role of human resilient performance through the life cycle***
    - Creating an unanticipated increase in (complexity of) task demands
    - Operators forced into managing the interface instead of managing the safety-critical processes
  - ***Designing new systems without understanding human capabilities***
    - Moving (or removing) information that was not understood to be critical to human performance
    - Consolidating task demands to narrow time window
  - ***Designing new systems without enhancing HSI methods, models, and measurement***
    - Protecting from error can reduce needed flexibility for unexpected events
    - Design parameters for an interdependent human-machine system look very different than for a machine designed to maximize its autonomy

Next steps

- ✓ Include expertise in human performance on your design team
- ✓ Recognize system failures as both routine and unavoidable – account for that in design and in testing
- ✓ Measure what happens, not just what fails
- ✓ Don’t simply design out failure factors without considering the possible reduction of preparation and recovery factors
- ✓ Question dogmatic assumptions about what people are “bad at” or “good at”
- ✓ Support capability for resilient performance through system designs that align with how our cognitive systems (evolved to) work

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Thank you!