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Karen S. Young, K. Han Kim, Sudhakar Rajulu. *Anthropometric Changes in Spaceflight*. pp. 977–987.

Objective: This study aims to identify the change in anthropometric measurements during spaceflight due to microgravity exposure. **Background:** Comprehensive and accurate anthropometric measurements are crucial to assess body shape and size changes in microgravity. However, only limited anthropometric data have been available from the astronauts in spaceflight. **Methods:** A new photogrammetry-based technique in combination with a tape-measure method was used for anthropometric measurements from nine crewmembers on the International Space Station. Measurements included circumference and height for body segments (chest, waist, bicep, thigh, calf). The time-dependent variations were also assessed across pre-, in-, and postflight conditions. **Results:** Stature showed a biphasic change with up to 3% increase at the early flight phase, followed by a steady phase during the remaining flight. Postflight measurements returned to a similar level of the preflight. Other linear measurements, including acromion height, showed similar trends. The chest, hip, thigh, and calf circumferences show overall decrease during the flight up to 11%, then returned close to the preflight measurement at postflight. **Conclusion:**The measurements from this study provide critical information for the spacesuit and hardware design. The ground-based assessments for spacesuit fit needs to be revalidated and adjusted for in-flight extravehicular activities from this data. **Application:**These data can be useful for space suit design as well as habitat, vehicle, and additional microgravity activities such as exercise, where the body shape changes can affect fit, performance, and human factors of the overall design.

Christopher R. Reid, Jacqueline M. Charvat, Shane M. Mcfarland, Jason R. Norcross. *Modeling Occupational Fingernail Onycholysis Disorders in the Population of US Astronauts Who Have Engaged in Extravehicular Activity*. pp. 988–1000.

Objectives: Spacesuits are designed to be reliable personal spacecraft that preserve the life and well-being of the astronaut from the extremes of space. However, materials, operating pressures, and suit design requirements often result in a risk of musculoskeletal discomfort and injury to various areas of the body. In particular, this investigation looked at fingernails and their risk of developing onycholysis. **Methods:** An onycholysis literature review was followed by a retrospective analysis of injury characteristics, astronaut suited training and spaceflight events, hand anthropometry, glove sizing, and astronaut demographics. Multiple logistic regression was used to assess the likelihood of onycholysis occurrence by testing potential risk variables against the dataset compiled from the retrospective data mining. **Results:** The duration of event exposure, type of glove used, distance (delta) between the fingertip and the tip of the glove, sex, and age were found to be significantly related to occurrence of onycholysis (whether protective or injurious). **Conclusion:** An initial risk formula (model) for onycholysis was developed as a result of this investigation. In addition to validation through a future study, further improvement to this onycholysis equation and spacesuit discomfort and injury in general can be aided by future investigations that lead to better definition of the threshold between safe and risky exposure for each type of risk factor. **Application:** This work described a potential method that can be used for EVA spacesuit glove onycholysis injury risk analysis for either iterative glove design or between glove comparisons, such as during a product downselect process.

Marc Dalecki, Fabian Steinberg, Rainer Beurskens. *Rapid Dual-Task Decrements After a Brief Period of Manual Tracking in Simulated Weightlessness by Water Submersion*. pp. 1001–1013.

Objective: Investigating dual-task (DT) performance during simulated weightlessness by water submersion, using a manual tracking and a choice reaction task. In contrast to previous work, we focus on performance changes over time. **Background:** Previous research showed motor tracking and choice reaction impairments under DT and single-task (ST) conditions in shallow water submersion. Recent research analyzed performance as average across task time, neglecting potential time-related changes or fluctuations of task-performance. **Method:** An unstable tracking and a choice reaction task was performed for one minute under ST and DT conditions in 5 m water submersion and on dry land in 43 participants. Tracking and choice reaction time performance for both tasks were analyzed in blocks of 10 seconds. **Results:** Tracking performance deteriorated underwater compared to dry land conditions during the second half while performing one minute in DT conditions. Choice reaction time increased underwater as well, but independent of task time and type. **Conclusion:** Tracking error increased over time when performing unstable tracking and choice reaction together. Potentially, physiological and psychological alterations under shallow submersion further strain the human system during DT operations, exceeding available recourse capacities such that DT performance deteriorated over time. **Application:** Humans operating in simulated weightlessness underwater should be aware of substantial performance declines that can occur within a short amount of time during DT situations that include continuous tracking.

Fabian Möller, Uwe Hoffmann, Tobias Vogt, Fabian Steinberg. *Exercise-Related Effects on Executive Functions During a Simulated Underwater Extravehicular Activity*. pp. 1014–1028.

Objective: Investigation of cognitive performance during extravehicular activities (EVAs) in a space-analog setting. **Background:** EVAs performed by humans in microgravity on

the International Space Station (ISS) call for high cognitive performance during upper-body workload. Higher cardiovascular demands interact with cognitive performance, but no knowledge exists about EVA's special requirements. This study simulates EVA-training underwater to investigate its effects on the executive functions inhibition and switching. **Method:** In a counterbalanced crossover design, 16 divers (age: 28 ± 2.4 years; eight females) performed two conditions (i.e., EVA vs. Inactivity [INACT]) in 3–5 m submersion (diving gear; not in a space-suit). EVA included 30 min of moderate-, followed by 30 min of high-intensity upper-body exercise intervals, paired with EVA-specific cognitive-motor tasks. INACT included no exercise in submersion and neutral buoyancy. Both conditions included cognitive testing at pre, mid (after the first 30 min), and post (after the second 30 min) on a tablet computer. Reaction times (RTs) and response accuracy (ACC) were calculated for both tasks. **Results:** ACC was significantly lower during EVA compared with INACT for inhibition (post: $p = .009$) and switching (mid: $p = .019$) at post ($p = .005$). RTs for inhibition were significantly faster during EVA ($p = .022$; $\eta p2 = 0.320$). **Conclusion:** Specific physical exercise, intensity, duration, and tasks performed during the EVA might differently affect the exercise-cognition interaction and need further investigation, especially for future long-term space travel. **Application:** Future research might serve to improve mission success and safety for EVAs and long-term space travel.

Linh Q. Vu, James H. Shaw, K. Han Kim, Elizabeth Benson, Sudhakar L. Rajulu. *Spacesuit Center of Gravity Assessments for Partial Gravity EVA Simulation in an Underwater Environment*. pp. 1029–1045.

Objective: The objective is to analytically determine the expected CG and build hardware to measure and verify the suited subject's CG for lunar extravehicular activity (EVA) training in an underwater environment. **Background:** For lunar EVAs, it is necessary for astronauts to train with a spacesuit in a simulated partial gravity environment. NASA's Neutral Buoyancy Laboratory (NBL) can provide these conditions by producing negative buoyancy for a submerged suited subject. However, it is critical that the center of gravity (CG) for the human-spacesuit system to be accurate for conditions expected during planetary EVAs. **Methods:** An underwater force-transducer system and individualized human-spacesuit model was created to provide real-time measurement of CG, including recommendations for weight placement locations and quantity of weight needed on the spacesuit to achieve a realistic lunar spacesuit CG. This method was tested with four suited subjects. **Results:** Across tested weighout configurations, it was observed that an aft and high CG location will have large postural differences when compared to low and fore CG locations, highlighting the importance of having a proper CG. The system had an accuracy of ±5lbs of the total lunar weight and within ± 15 cm for fore-aft and left-right CG directions of the model predictions. **Conclusion:** The developed method offers analytical verification of the suited subject's CG and improves simulation quality of lunar EVAs. Future suit design can also benefit by recommending hardware changes to create ideal CG locations that improve balance and mobility. **Application:** The developed methodology can be used to verify a proper CG location in future planetary EVA simulations such as different reduced gravity training analogs (e.g. active cable offloading systems).

Kritina Holden, Maya Greene, E. Vincent, Anikó Sándor, Shelby Thompson, Alan Feiveson, Brandin Munson. *Effects of Long-duration Microgravity and Gravitational Transitions on Fine Motor Skills. pp. 1046–1058.*

Objective: Assess the effects of long-duration microgravity and gravitational transitions on fine motor skills using a tablet-based test battery of four fine motor tasks: Pointing, Dragging, Shape Tracing, and Pinch-Rotate. **Background:** While there have been some studies on fine motor skills in microgravity, few have measured the fine motor skills that

are core components of interaction with computer-based devices, and none have measured performance systematically, to include preflight, inflight, and postflight space mission time periods. **Methods:** Seven astronauts completed the Fine Motor Skills test battery 30–40 times before, during, and up to 30 days after standard duration International Space Station missions, while a matching set of seven ground-based control participants also completed the battery over a comparable period of time. Response time and accuracy were the primary outcome measures. **Results:** Relative to controls, astronauts experienced fine motor skill decrements at gravitational transitions (first week on orbit, and first month post landing). No decrements were found inflight after the first week of adaptation **Conclusion:** Gravitational transitions appear to negatively impact fine motor skills needed to operate small controls with accuracy, such as those on touchscreen interfaces. This raises concerns for future long-duration crewmembers who will land on a planetary surface and need to perform critical tasks accurately, such as configuring spacesuits, powering up a habitat, or teleoperating rovers. **Application:** Results from this study highlight the need for confirmatory research, and the possible need for countermeasure development. The Fine Motor Skills test battery may have application outside of NASA as a fine motor skills diagnostic screening, rehabilitation, or readiness-to-perform tool.

Hannah Weiss, Andrew Liu, Amos Byon, Jonathan Blossom, Leia Stirling. *Comparison of Display Modality and Human-in-the-Loop Presence for On-Orbit Inspection of Spacecraft*. pp. 1059–1073.

Objective: To investigate the impact of interface display modalities and human-in-the-loop presence on the awareness, workload, performance, and user strategies of humans interacting with teleoperated robotic systems while conducting inspection tasks onboard spacecraft. **Background:** Due to recent advancements in robotic technology, free-flying teleoperated robot inspectors are a viable alternative to extravehicular activity inspection operations. Teleoperation depends on the user's situation awareness; consequently, a key to successful operations is practical bi-directional communication between human and robot agents. **Method:** Participants (n = 19) performed telerobotic inspection of a virtual spacecraft during two degrees of temporal communication, a Synchronous Inspection task and an Asynchronous Inspection task. Participants executed the two tasks while using three distinct visual displays (2D, 3D, AR) and accompanying control systems. **Results:** Anomaly detection performance was better during Synchronous Inspection than the Asynchronous Inspection of previously captured imagery. Users' detection accuracy reduced when given interactive exocentric 3D viewpoints to accompany the egocentric robot view. The results provide evidence that 3D projections, either demonstrated on a 2D interface or augmented reality hologram, do not affect the mean clearance violation time (local guidance performance), even though the subjects perceived a benefit. **Conclusion:** In the current implementation, the addition of augmented reality to a classical egocentric robot view for exterior inspection of spacecraft is unnecessary, as its margin of performance enhancement is limited in comparison. **Application:** Results are presented to inform future human–robot interfaces to support crew autonomy for deep space missions.

Peter G. Roma, Lauren Blackwell Landon, Cara A. Spencer, Alexandra M. Whitmire, Thomas J. Williams. *The Subjective Habitability & Acceptability Questionnaire (SHAQ): Development and Validation*. pp. 1074–1104.

Objective: Describe the development and validation of the Subjective Habitability & Acceptability Questionnaire (SHAQ). **Background:** Habitat area size, layout, and design may impact individual and team behavioral health and performance (BHP) outcomes in operational environments. However, there are no standardized measures of these relationships. **Method:** SHAQ is a modular survey consisting of two 6-item scales: BHP

Outcomes (Performance of Individual Activities, Performance of Group Activities, Mood, Psychological Stress, Sleep, and Social Interactions) and Habitability Moderators (Privacy, Social Density, Efficiency, Control, Comfort, and Convenience). We collected SHAQ data from NASA's Human Exploration Research Analog (HERA) crews (n = 19) in reference to multiple habitat areas (Sleep/Bedroom, Hygiene/Bathroom, Work/Office/Workshop, and Food Preparation/Kitchen/Galley) in the HERA operational environment, private hotel rooms, and individual home habitats. **Results:** SHAQ has high construct validity (single factor solutions, mean item factor loading = 0.760, mean % variance = 60.37), internal consistency and reliability (item mean α = 0.880, mean ω=0.894, mean ICC = 0.430), concurrent validity (mean item r with System Usability Scale = 0.42), and discriminant validity (e.g., significantly higher facilitation of group activities in HERA Work/Office/Workshop and Food Preparation/Kitchen/Galley areas vs. Hygiene/Bathroom and Sleep/Bedroom areas; significantly higher ratings of privacy, comfort, and convenience in hotel vs. HERA). **Conclusion:** SHAQ is a reliable, valid, and sensitive measure of BHP impacts of habitat size and layout. **Application:** SHAQ can be used to inform evidence-based recommendations and thresholds for habitat area size, layout, and design options to support individual and team BHP in operational environments.

Tripp Driskell, Eduardo Salas, C. Shawn Burke, James E. Driskell. *A Lexical Approach to Assessing Stress: Development and Proof-of-Concept*. pp. 1105–1129.

Objective: We describe a methodology that provides a nonobtrusive means of detecting stress and related deficits through the assessment of spontaneous verbal output in ongoing communications. **Background:** In high-demand environments, operational personnel are exposed to an array of environmental, task, and interpersonal stressors that can negatively impact performance as well as jeopardize safety and well-being. In these settings, the requirement exists to assess cognitive and emotional state "at a distance" and without interfering with ongoing performance. **Method:** We describe a lexical approach to assessing stress effects from ongoing or spontaneous verbal output. This approach is examined in a spaceflight analog setting.

Results: We assess stress effects in terms of five core dimensions and develop lexical indicators of these core stress dimensions and relevant sub-facets. We establish the proof-of-concept of this approach by presenting representative data from a spaceflight analog. **Conclusion:** This approach provides an unobtrusive means to evaluate ongoing task communications at the individual and team level in order to assess cognitive/emotional states such as workload, negative affect, attentional focus, anxiety, and team orientation. **Application:** There are many high-demand settings in which it is valuable to monitor the potential negative effects of stress on operational personnel. These environments include spaceflight, the military, aviation, law enforcement, and medicine.

Aleksandra S. Stankovic, Alyssa Pryputniewicz, Sherrie Holder, Stephen P. York, Patrick M. Handley, John A. Karasinski, Stephen K. Robinson, John J. West, Kevin R. Duda. *Longitudinal Impacts of Simulated Long-Duration Spaceflight Missions on Operationally Relevant Measures of Human Performance Using a Portable Simulation Platform*. pp. 1130–1141.

Objective: This project quantifies operationally relevant measures of flight performance and workload in a high-fidelity long-duration spaceflight analog, longitudinally across mission duration, using a portable simulation platform. **Background:** Real-time performance measures allow for the objective assessment of task performance and the timely identification of performance degradations. **Methods:** Measures of flight performance on a piloted lunar lander task were collected on 32 total crewmembers

across 8 simulated space missions of 45 days each (623 total sessions). **Results:** Mission duration demonstrated a significant effect on measures of flight performance across all campaigns. Flight measures showed a general pattern of peaking in accuracy during the middle-late quartiles of overall mission time, then degrading again towards baseline. On the workload measure, however, a general linear decrease in workload consistent with progressive task learning was observed in both campaigns. **Conclusion:** This investigation demonstrated the disruptive effect of time in mission on some, but not all, aspects of task performance. While mission interval differentially impacted measures of flight accuracy, workload, by contrast, seemed to steadily decrease with in-mission time. **Application:** While more work is needed, the observed discrepancy between progression of flight performance and workload assessment highlights the importance of sensitive and specific measurement tools for the tracking of distinct performance metrics.

Jacob R. Kintz, Neil T. Banerjee, Johnny Y. Zhang, Allison P. Anderson, Torin K. Clark. *Estimation of Subjectively Reported Trust, Mental Workload, and Situation Awareness Using Unobtrusive Measures*. pp. 1142–1160.

Objective: We use a set of unobtrusive measures to estimate subjectively reported trust, mental workload, and situation awareness (henceforth "TWSA"). **Background:** Subjective questionnaires are commonly used to assess human cognitive states. However, they are obtrusive and usually impractical to administer during operations. Measures derived from actions operators take while working (which we call "embedded measures") have been proposed as an unobtrusive way to obtain TWSA estimates. Embedded measures have not been systematically investigated for each of TWSA, which prevents their operational utility. **Methods:** Fifteen participants completed twelve trials of spaceflight-relevant tasks while using a simulated autonomous system. Embedded measures of TWSA were obtained during each trial and participants completed TWSA questionnaires after each trial. Statistical models incorporating our embedded measures were fit with various formulations, interaction effects, and levels of personalization to understand their benefits and improve model accuracy. **Results:** The stepwise algorithm for building statistical models usually included embedded measures, which frequently corresponded to an intuitive increase or decrease in reported TWSA. Embedded measures alone could not accurately capture an operator's cognitive state, but combining the measures with readily observable task information or information about participants' backgrounds enabled the models to achieve good descriptive fit and accurate prediction of TWSA. **Conclusion:** Statistical models leveraging embedded measures of TWSA can be used to accurately estimate responses on subjective questionnaires that measure TWSA. **Application:** Our systematic approach to investigating embedded measures and fitting models allows for cognitive state estimation without disrupting tasks when administering questionnaires would be impractical.

Debra Schreckenghost, Kritina Holden, Maya Greene, Tod Milam, Chris Hamblin. *Effect of Automating Procedural Work on Situation Awareness and Workload*. pp. 1161–1172.

Objective: In future deep space exploration missions, crew will have to work more autonomously from Earth. Greater crew autonomy will increase dependence on automated systems. This study investigates the performance effects of different strategies to automate procedural work for space exploration operations.

Background: The following strategies are investigated for performing procedural work:

- Manual Work uses no procedure automation and crew performs all actions.
- Shared Work uses procedure automation to perform some actions within a procedure while crew performs other actions.

- Supervised Work uses procedure automation to perform procedure actions while crew supervises the automation.

Method: Twenty-seven participants participated in a planetary habitat scenario-based simulation using electronic procedures with automatable actions to investigate the effect of these strategies on situation awareness (SA) and workload. This study used a modification of the Situation Presence Assessment Method to measure SA and the Bedford Workload Scale to measure subjective workload. **Results:** Mean response times and accuracy for SA queries show no significant difference among the three strategies. Bedford Workload ratings compared across the three strategies indicate that participants rated their workload as highest in the Manual Work condition, followed by the Shared Work condition, and lowest in the Supervised Work condition. **Conclusion:** The study hypothesized that increased levels of automation would lead to lower subjective workload and decreased SA. Although no significant difference in SA was observed, subjective workload was lower in automation strategies. Based on subjective ratings, 93% of participants preferred some form of automation, with 56% preferring the Shared Work automation condition.

Zachary Glaros, Robert E. Carvalho, Erin E. Flynn-Evans. *An Evaluation of Sleepiness, Performance, and Workload Among Operators During a Real-Time Reactive Telerobotic Lunar Mission Simulation*. pp. 1173–1182.

Objective: We assessed operator performance during a real-time reactive telerobotic lunar mission simulation to understand how daytime versus nighttime operations might affect sleepiness, performance, and workload. **Background:** Control center operations present factors that can influence sleepiness, neurobehavioral performance, and workload. Each spaceflight mission poses unique challenges that make it difficult to predict how long operators can safely and accurately conduct operations. We aimed to evaluate the performance impact of time-on-task and time-of-day using a simulated telerobotic lunar rover to better inform staffing and scheduling needs for the upcoming Volatiles Investigating Polar Exploration Rover (VIPER) mission. **Methods:** We studied seven trained operators in a simulated mission control environment. Operators completed two five-hour simulations in a randomized order, beginning at noon and midnight. Performance was evaluated every 25 minutes using the Karolinska Sleepiness Scale, Psychomotor Vigilance Task, and NASA Task Load Index. **Results:** Participants rated themselves as sleepier (5.06 ± 2.28) on the midnight compared to the noon simulation (3.12 ± 1.44; $p < .001$). Reaction time worsened over time during the midnight simulation but did not vary between simulations. Workload was rated higher during the noon (37.93 ± 20.09) compared to the midnight simulation (32.09 ± 21.74; $p = .007$). **Conclusion:** Our findings suggest that work shifts during future operations should be limited in duration to minimize sleepiness. Our findings also suggest that working during the day, when distractions are present, increases perceived workload. Further research is needed to understand how working consecutive shifts and taking breaks within a shift influence performance.

Jessica J. Marquez, Tamsyn Edwards, John A. Karasinski, Candice N. Lee, Megan C. Shyr, Casey L. Miller, Summer L. Brandt. *Human Performance of Novice Schedulers for Complex Spaceflight Operations Timelines*. pp. 1183.

Objective: Investigate the effects of scheduling task complexity on human performance for novice schedulers creating spaceflight timelines. **Background:** Future astronauts will be expected to self-schedule, yet will not be experts in creating timelines that meet the complex constraints inherent to spaceflight operations. **Method:** Conducted a within-subjects experiment to evaluate scheduling task performance in terms of scheduling efficiency, effectiveness, workload, and situation awareness while manipulating

scheduling task complexity according to the number of constraints and type of constraints. **Results:** Each participant (n = 15) completed a set of scheduling problems. Results showed main effects of the number of constraints and type of constraint on efficiency, effectiveness, and workload. Significant interactions were observed in situation awareness and workload for certain types of constraints. Results also suggest that a lower number of constraints may be manageable by novice schedulers when compared to scheduling activities without constraints. **Conclusion:** Results suggest that novice schedulers' performance decreases with a high number of constraints, and future scheduling aids may need to target a specific type of constraint. **Application:** Knowledge on the effect of scheduling task complexity will help design scheduling systems that will enable self-scheduling for future astronauts. It will also inform other domains that conduct complex scheduling, such as nursing and manufacturing.

Alina Lungeanu, Jessica R. Mesmer-Magnus, Ashley A. Niler, Leslie A. DeChurch, Noshir S. Contractor. *Organizing for Mars: A Task Management Perspective on Work within Spaceflight Multiteam Systems*. pp. 1199–1220.

Objective: The aim of this study was to examine how task, social, and situational factors shape work patterns, information networks, and performance in spaceflight multiteam systems (MTSs). **Background:** Human factors research has explored the task and individual characteristics that affect decisions regarding when and in what order people complete tasks. We extend this work to understand how the social and situational factors that arise when working in MTSs affect individual work patterns. **Methods:** We conducted a complex multi-site space analog simulation with NASA over the course of 3 years. The MTS task required participants from four teams (Geology, Robotics, Engineering, and Human Factors) to collaborate to design a well on Mars. We manipulated the one-way communication delay between the crew and mission support: no time lag, 60-second lag, and 180-second lag. **Results:** The study revealed that team and situational factors exert strong effects: members whose teams have less similar mental models, those whose teams prioritize their team goal over the MTS goal, and those working in social isolation and/or under communication delay engage longer on tasks. Time-on-task positively predicts MTS information networks, which in turn positively predict MTS performance when communication occurs with a delay, but not when it occurs in real-time. **Conclusion:** Our findings contribute to research on task management in the context of working in teams and multiteam systems. Team and situational factors, along with task factors, shape task management behavior. **Application:** Social and situational factors are important predictors of task management in team contexts such as spaceflight MTSs.

Steven Yule …[et al.]. *Crew Autonomy During Simulated Medical Event Management on Long Duration Space Exploration Missions*. pp. 1221–1234.

Objective: Our primary aim was to investigate crew performance during medical emergencies with and without ground-support from a flight surgeon located at mission control. **Background:** There are gaps in knowledge regarding the potential for unanticipated in-flight medical events to affect crew health and capacity, and potentially compromise mission success. Additionally, ground support may be impaired or periodically absent during long duration missions. **Method:** We reviewed video recordings of 16 three-person flight crews each managing four unique medical events in a fully immersive spacecraft simulator. Crews were randomized to two conditions: with and without telemedical flight surgeon (FS) support. We assessed differences in technical performance, behavioral skills, and cognitive load between groups. **Results:** Crews with FS support performed better clinically, were rated higher on technical skills, and completed more clinical tasks from the medical checklists than crews without FS support.

Crews with FS support also had better behavioral/non-technical skills (information exchange) and reported significantly lower cognitive demand during the medical event scenarios on the NASA-TLX scale, particularly in mental demand and temporal demand. There was no significant difference between groups in time to treat or in objective measures of cognitive demand derived from heart rate variability and electroencephalography. **Conclusion:** Medical checklists are necessary but not sufficient to support high levels of autonomous crew performance in the absence of real-time flight surgeon support. **Application:** Potential applications of this research include developing ground-based and in-flight training countermeasures; informing policy regarding autonomous spaceflight, and design of autonomous clinical decision support systems.

Kathleen L. Mosier, Ute M. Fischer. *Meeting the Challenge of Transmission Delay: Communication Protocols for Space Operations*. pp. 1235–1250.

Objective: Several studies were conducted to assess media-specific communication protocols as a countermeasure to challenges of asynchronous space–ground communication. **Background:** Previous research demonstrated that transmission delay can negatively impact space–ground communication, collaboration, and task performance. We created media-specific protocols designed to mitigate identified problems associated with asynchronous communication and examined their effects on team communication and task performance. **Methods:** The lab study included 24 teams of three who collaborated remotely via voice or text on computer-based tasks simulating failures in a spacecraft's life support system. Training and availability of communication protocols was the between-groups variable. Perceived usability, criticality, and effectiveness of the communication protocols were also assessed in space–analog simulations. **Results:** Lab study data revealed that communication protocols facilitated some aspects of team communication; specifically, they reduced threats to common ground and information splitting but not instances of miscommunication. Analog data indicated that protocol compliance was high, participants evaluated most elements as highly important, and protocols maintained perceived communication effectiveness between space crews and mission control during time delay comparably to no-time-delay conditions. **Conclusion:** Converging data attest to the feasibility, usability, and effectiveness of empirically derived communication protocols as a countermeasure to the negative impacts of transmission delay and also point to technological solutions. **Application:** The communication protocols have been adopted for training in NASA analog simulations involving time-delayed communication. They could also support communication among remote team members in medical operations, command-and-control teams, or disaster response under asynchronous conditions or when time is limited and precise communication is critical.

Jessica L. Wildman …[et al.]. *Team Self-Maintenance during Long-Duration Space Exploration: A Conceptual Framework*. pp. 1251–1265.

Objective: We developed a conceptual framework of Team Self-Maintenance (TSM) within long-duration space exploration (LDSE), which we define as the process of monitoring, adjusting, and maintaining the psychological well-being of a team in the absence of external support. **Background:** Specific to LDSE and isolated, confined, and extreme (ICE) environments, periods of routine can have a debilitating effect on the crew's well-being and performance, and TSM is a critical process for avoiding these detrimental effects. **Method:** Based on themes drawn from nine subject matter expert interviews combined with an extensive literature review on related concepts, we developed an integrative conceptual framework of the key inputs, processes, and outputs involved in TSM within LDSE contexts. **Results:** Our TSM framework suggests team well-being as a key outcome that must be maintained during LDSE and information sharing, self-regulation, resource recovery, and emotional support as the key processes that enable team well-being. We also identify several contextual inputs that can serve as

intervention points for enabling effective TSM. **Conclusion:** Our framework suggests that future research and practice aimed at effective LDSE should emphasize team well-being, rather than just performance, and that there are many open questions in terms of how teams will manage their own socio-emotional needs (e.g., conflict, recovery activities, and boredom) without external systems and support. **Application:** This conceptual framework describes the primary inputs, processes, and outcomes involved in the team self-maintenance process. This framework reflects context-specific theorizing most likely to be applicable only to LDSE contexts.

Allison Anderson, Aleksandra Stankovic, Devin Cowan, Abigail Fellows, Jay Buckey, Jr. *Natural Scene Virtual Reality as a Behavioral Health Countermeasure in Isolated, Confined, and Extreme Environments: Three Isolated, Confined, Extreme Analog Case Studies*. pp. 1266–1278.

Introduction: Isolated, confined, extreme (ICE) environments are accompanied by a host of stress-inducing circumstances: operational pressure, interpersonal dynamics, limited communication with friends and family, and environmental hazards. We evaluated the effectiveness of attention-restoration-therapy-based immersive Virtual Reality (VR) in three ICE environments: the Canadian Forces Station—Alert (CFS Alert), the 12-month HI-SEAS IV expedition, and the 8-month HI-SEAS V expedition. **Methods:** Thirty-one individuals (29 male, 2 female) at CFS Alert, and 12 total crewmembers (7 male, 5 female, six crewmembers per sessions) at HI-SEAS participated. All participants viewed immersive VR scenes, but scene content varied by deployment. Data collection included pre- and post-intervention surveys and semi-structured post-mission interviews. Survey data were analyzed by scene content within each analog using nonparametric approaches. **Results:** Acceptability and desirability of the VR content varied significantly by ICE analog, as well as by participants within a given analog. The two initial exploratory protocols enabled a more directed study in HI-SEAS V to identify the importance of differences in scene content. **Discussion:** Use and perceived utility of the VR varied considerably across participants, indicating that psychological support needs to be individualized. Overall, natural scene VR was broadly considered restorative, but after long periods of isolation, dynamic and familiar scenes including those with people were also appealing. Immersive, nature-based VR was highly valued by some, but not all participants, suggesting that this intervention tool holds promise for use in ICE settings but needs to be tailored to the setting and individual.

Jessica J. Marquez, Lauren Blackwell Landon, Eduardo Salas. *The Next Giant Leap for Space Human Factors: The Opportunities*. pp. 1279–1288.

Objective: Propose areas of future space human factors research. **Background:** Deep space, long-duration human spaceflight missions to the Moon and Mars still require advances in space human factors research. Key drivers relate to astronauts living and working in isolation, new novel technologies required to accomplish exploration missions, and the longer durations of these. **Results:** Three areas of research are proposed for methods and techniques: (1) to enable more autonomous astronauts; (2) to monitor crew and improve ground team situation awareness; and (3) to detect and support changes in long-duration team coordination. **Conclusions:** Future human exploration missions will benefit from advances in space human factors research. **Application:** Human factors researchers can contribute to human spaceflight by prioritizing these research topics.