ENSURING SAFE DECISION-MAKING ON THE MOON AND MARS: COGNITIVE PERFORMANCE ASSESSMENT FOR EXPLORATION CLASS MISSION EVA

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ABSTRACT

Extravehicular activity (EVA) is one of the most dangerous and cognitively demanding actions that astronauts can execute, and the cognitive demands associated with future partial gravity EVAs on the Moon and Mars are expected to be higher compared to microgravity EVAs currently conducted from the International Space Station. Decrements in cognitive performance present an important risk to crew safety during exploration mission class EVA. Yet there is currently insufficient data to characterize cognitive performance prior to, during, and following EVA. Furthermore, it is still unclear which cognitive domains are most important for conducting mission critical decisions with crew safety implications. To address this gap, we conducted a cognitive task analysis (CTA) of EVA to characterize the procedures, the cognitive demands required, and the critical safety decisions associated with decrements in cognitive performance. We conducted a cognitive task analysis with 15 astronauts and subject matter experts in EVA operations and research. Interviews focused on surface exploration EVA and elicited feedback from experts on the cognitive skills required for specific EVA tasks, including cognitive strategies, critical cues, and decision-making strategies. A cognitive demands table was assembled to consolidate and synthesize the information from all interviews. The information from this cognitive task analysis informs ongoing exploration EVA for Moon to Mars. This work identifies the specific cognitive challenges that astronauts are likely to encounter during surface exploration EVA, and provides the foundation for: (1) prioritized and targeted cognitive performance measurement and functional performance tests, (2) EVA simulation design at varying levels of cognitive workload, and (3) the development of training and other technologies that can improve safe decision-making and inform EVA planning on future spaceflight missions to the Moon and Mars.

INTRODUCTION

Decrements in cognitive performance present an important risk to crew safety during exploration mission class EVA. Yet the cognitive performance capabilities that will be required of crewmembers, the degree to which cognitive performance changes over the course of exploration EVA, and how conducting exploration EVA impacts cognition is still not understood. Research suggests that there are cognitive performance changes during spaceflight; however, these changes are still not well understood (Strangman, Sipes, & Beven, 2014). Anecdotal evidence from astronauts reporting “space fog” and other cognitive impacts while in space (Clément et al., 2020), as well as evidence from spaceflight and spaceflight analog research studies, suggests that environmental stressors present during specific phases of spaceflight may impact cognitive functioning and performance. The stressors present during spaceflight that are likely to impact cognition are numerous and include altered gravity, radiation, social isolation, sleep decrements, circadian misalignment, high workload, communication delay, spacesuit adaptation, off-nominal mission schedule changes, and motion sickness. One study found that the most important predictors of astronaut vigilant attention on the International Space Station (ISS) were prior cognitive performance, self-reported fatigue and stress, and temperature and radiation dose (Tu et al., 2022). In a study of 25 astronauts completing 6-month missions on ISS, cognitive performance was found to be generally stable over time, however there were changes in performance on certain cognitive subtests during specific mission phases. Namely, the astronauts demonstrated slower performance in tasks of processing speed, visual working memory, and sustained attention in the early flight phase, and a decrease in risk-taking propensity during the late flight and post flight mission phases (Dev et al., 2024). The NASA Twins study (Garrett-Bakelman et al., 2019), which compared data from twin astronauts after one spent a year in space and the other lived on Earth, found evidence of reduced cognitive performance in specific domains (abstract matching, visual object learning, vigilant attention) primarily in the post-flight period. This could have important implications for astronaut readiness for future Mars missions, where they would be expected to conduct EVA and attain mission objectives after a flight duration that could last nearly a year. A study of astronaut-like individuals participating in NASA’s Human Exploration Research Analog (HERA) found that there were deficits in emotion recognition and vigilant attention following a 36-hour sleep deprivation period (Nasrini et al., 2020).

A smaller number of studies have utilized simulated environments and spacesuits to examine cognitive performance during the physically and cognitively demanding set of tasks that comprise EVA. During high intensity activities like lunar surface EVA, high workload is likely to result in mental and physical fatigue (Scheuring et al., 2007). Simulated EVA performed during a 14-day stay at the Mars Desert Research Station resulted in increased mental and physical workload (Rai, Kaur, & Foing, 2012). Novel gait patterns associated with partial gravity, such as during exploration EVA on the Moon or Mars, was found to increase astronaut-like subject cognitive load in the form of increased prefrontal cortex activity and reduced memory recall (Smith, Sagovia, & Salmon, 2023). In simulated EVA conducted in water submersion, response accuracy during inhibition and switching cognitive tasks was lower during EVA compared with a control condition, while reaction times for the inhibition task were faster during EVA (Möller et al., 2021). In a small-sample simulated EVA study conducted in NASA's Active Response Gravity Offload System (ARGOS), there were non-significant trends of decrements in vigilant attention and processing speed following two simulated EVAs conducted over a three-day period (Schlotman et al., 2023).

METHODS

To address our gap in understanding of cognitive performance and exploration EVA, we conducted an applied cognitive task analysis (Militello & Hutton, 1998) with astronauts and subject matter experts in EVA operations and research at NASA Johnson Space Center in summer 2024. There were two interview protocols, with different sets of experts interviewed for each protocol. Each interview was led by a PhD-level scientist in the NASA Behavioral Health & Performance Laboratory with expertise in health psychology and cognitive neuroscience (first author) and notes were taken by a Master's-level research coordinator in the BHP Laboratory (second author). Interviews were recorded on Microsoft Teams to assist with notetaking.

Participants. A total of 15 astronauts and subject matter experts in EVA operations and research participated in the applied cognitive task analysis interviews from July to September 2024. Experts had an average of 7.5 (range = 2-19, SD = 5.3) years of experience with EVA across multiple spaceflight and spaceflight analog settings (i.e., ISS, NBL, ARGOS, Field Test, VR, NEEMO). Astronauts had a total of 71 hours 33 minutes of EVA time on ISS. Experts were familiarized with the 11 EVA tasks and 32 subtasks determined through a prior EVA task analysis. Experts then ranked their expertise in the EVA tasks. Experts reported a spread of expertise across the EVA tasks and most often ranked the following tasks as highest in expertise: Worksite Setup/Cleanup (5 experts), EVA Prep/Post Ops (4 experts), Maintenance Tasks (3 experts), and Traverse (3 experts).

Interview 1: EVA task ratings and knowledge audit. In the first interview, experts were asked about the specific tasks and cognitive demands associated with EVA. This informed a Task Diagram, which provided a high-level overview of the steps involved in the major tasks conducted during exploration EVA, as well as which of the steps require the most cognitive skill. EVA tasks were populated from a previous task analysis conducted in the Human Health & Performance (HHP) Directorate at JSC, which was based on Artemis mission concept of operations and internal NASA documentation. Experts ranked 11 EVA tasks derived from the task analysis in order of their level of expertise or familiarity with the task (1 = most familiarity/expertise) and in order of relative cognitive demand (1 = most cognitively demanding). Experts then went through 32 subtasks associated with the EVA tasks and were asked, *How much cognitive and perceptual activity do you think would be required for effective performance of this subtask,* on a scale from 0 = Low to 100 = High.

Next, experts completed a knowledge audit, which employs a set of probes designed to describe types of domain knowledge of skill and elicit appropriate examples. The knowledge audit focused on the EVA tasks with which the expert indicated they had the most familiarity and expertise. There were eight probes per EVA task: Past and Future, Big Picture, Noticing, Job Smarts, Opportunities/Improvising, Self-Monitoring, Anomalies/Off-Nominal Situations, and Equipment/Spacesuit Difficulties. Participants who had not completed a real or simulated EVA firsthand were asked to respond to knowledge audit probes based on their experience observing EVA completed by others.

Interview 2: EVA simulation scenario and linkage analysis. In the second interview, a separate set of experts first completed an EVA simulation scenario, which provided specific context that allowed probing around relevant issues such as situational awareness, how situational awareness impacts a course of action, and potential errors or critical safety incidents. The simulation focused on an Incapacitated Crew Rescue (ICR) scenario (Walton et al., 2024). In the scenario, developed for this interview, an extravehicular crewmember (EV1) has strained their back while conducting field geology two kilometers away from a landing vehicle and has become incapacitated on the surface of the Moon, requiring rescuing by the other crewmember (EV2). Participants were asked to imagine that they were the crewmember on the Moon who has not been incapacitated in the incident (EV2) and to list the major events that would characterize their response in this situation (e.g., initial response, walk assist back to landing vehicle, communication with MCC). Responses to the simulation scenario were categorized into Events, Actions, Assessment, Critical Cues, and Potential Errors, with feedback from the expert.

Then experts were asked to identify the knowledge, skills, and abilities (KSAs) underlying each EVA task. Experts were asked to provide the following ratings for each KSA: 1. *How important is this KSA for effective performance of this task* (0 = Not Important, 1 = Somewhat Important, 2 = Important, 3 = Very Important, 4 = Critical) and 2. *How much cognitive and perceptual activity do you think would be required for effective performance of this KSA* (0 = Low, 100 = High).

At the end of all interviews, experts were asked two questions on the topic of factors that could contribute to cognitive performance during surface EVA. First, they were asked to list what they thought were the most likely and consequential critical safety incidents related to decrements in cognitive performance that could occur during future exploration EVA on the Moon and Mars. Next, experts were asked to provide feedback on how a lunar communication delay might impact an astronaut's cognitive performance on future Artemis missions. Both closing questions were intended to fill in gaps and address relevant topics to exploration EVA that may not have been addressed earlier in the interview.

Notes from each interview were verified against recordings where needed, then synthesized based on the specific goals of each interview section (i.e., task diagram, knowledge audit, simulation scenario, linkage analysis). Themes were extracted from the notes from each interview and compiled into a knowledge audit, simulation scenario, and cognitive demands table to summarize results across all interviews and extract insights. Interview content was analyzed using R Studio Version 4.4.1.

RESULTS

Cognitive Demand Rankings. Experts ranked the EVA tasks in terms of how much cognitive and perceptual activity is required for effective performance of that task. Perceived cognitive demand was distributed across multiple EVA tasks (Fig. 1). Experts ranked the following EVA tasks as highest (#1) in cognitive demand: EVA Prep/Post Ops (4 experts), Sample Identification (3 experts), Inspection of Surroundings (2 experts), and Maintenance Tasks (2 experts).

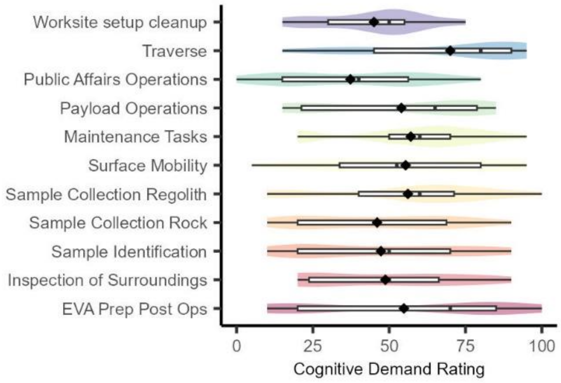
Figure 1
Cognitive Demand Rankings for EVA Tasks

Note. EVA tasks were ranked from 1 = Most Cognitive Demand. Rankings below 5 were excluded for visual readability. Thickness of bands indicates the number of experts who made that ranking.

Cognitive Demand Ratings. As part of the Task Diagram section of Interview 1, experts then provided continuous ratings on the cognitive demand of each EVA task in response to the question *How much cognitive and perceptual activity do you think would be required for effective performance of this task?* Ratings were provided on a continuous scale from 0 = Low to 100 = High. Experts participating in Interview 1 rated each subtask within each EVA task, while experts in Interview 2 rated each knowledge, skill, and ability (KSA) that was provided for each EVA task. Ratings from Interview 2 were averaged across KSAs to provide a single rating for each task. Overall, ratings were highly variable across tasks and subtasks. The following EVA Tasks were rated as having the highest cognitive demand by experts: Traverse (M = 70.0, SD = 27.0), Maintenance Tasks (M = 57.1, SD = 22.0), Sample Collection: Regolith (M = 56.1, SD = 26.3), Surface Mobility (M = 55.4, SD = 27.4), and EVA Prep/Post Ops (M = 54.8, SD = 33.8) (Fig. 2). EVA Tasks were overall rated as cognitively demanding (M = 51.7, SD = 26.1).

Figure 2

Cognitive Demand Ratings for EVA Tasks



Knowledge Audit. The knowledge audit section of Interview 1 elicited concrete examples in the context of surface EVA, cues and strategies used, and why it presents a challenge. The results of the knowledge audit for EVA Prep/Post Ops are presented in Table 1. Expert responses to the series of knowledge audit probes (e.g., Big Picture: *Can you give me an example of what is important about the Big Picture for EVA Prep/Post Ops?*) were categorized into Aspects of Expertise, Cues and Strategies, and Why Difficult? Several key points and themes emerged from the Knowledge Audit across all EVA Tasks. Specific tasks that were highlighted as cognitively challenging included EVA Prep Ops, which experts reported as one of the most safety critical tasks an astronaut can execute, with the cognitive demand higher for the support IV than the EV. Experts also highlighted navigation during traverse on the lunar surface as challenging and safety critical: getting lost on the Moon is a life-threatening scenario. Challenges during navigation include the visually similar landscape, lack of landmarks, low illumination, and permanently shadowed regions. Sample identification was also noted as a highly cognitively demanding task. Challenges mentioned by experts include remembering the scientifically precise geological terminology, being able to visually identify subtle differences in samples in low lighting conditions and identifying samples accurately to ground science team while also managing consumables, communication, navigation, and suit mobility.

Themes that emerged as relevant for cognitive performance across EVA tasks included that decision-making during EVA must simultaneously balance safety, time constraints, and mission objectives. Maintaining situational awareness (SA) is a key target of cognitive workload. Factors that increase SA include sufficient ground/IV support, sufficient sleep, clear visuals on environment, manageable physical workload. In contrast, factors that decrease SA include insufficient ground/IV support, fatigue due to insufficient sleep, poor visuals on environment (e.g., due to shadows, bright sunlight, or other obstruction), overly fixating on an off-nominal signal (e.g., unexpected equipment signal), and high physical workload (e.g., pushing heavy tool cart up steep incline). Indeed, high physical workload was highlighted as a major factor that can increase cognitive workload. EVA is physically demanding, and the physical demands of EVA may increase cognitive workload independent of cognitive demands. Cognitive resources can be depleted as the crewmember focuses their effort on managing the physical load, managing any presence of pain, and physically completing the task at hand.

Experts mentioned a few factors that could help reduce cognitive workload during surface EVA. One included effective teamwork: a good teammate can offload cognitive workload, while a suboptimal teammate (e.g., due to incompatible working or learning styles) can add to cognitive workload. In addition, experts mentioned that it is critical to have extensive pre-mission training and well-written procedures that crewmembers can effectively reference during the mission. Human factors considerations can help design procedure checklists that are easy to navigate (e.g., a touchscreen checklist with a color indicating current step).

Table 1

Knowledge Audit for EVA Prep/Post Ops

EVA Prep/Post Ops		
Aspects of Expertise	*Cues and Strategies*	*Why difficult?*
- Rely on extensive ground training to perform EVA prep/post ops effectively and safely - Ensure proper communication during spacesuit donning, airlock operations, and tool preparation - Safety is a tool to accomplish the task at hand - Accurately follow procedural steps without skipping a step - Effective teamwork to complete airlock ops safely and efficiently - Learn from experience to make certain checks even if they aren't on checklist	- Always aim to be ahead of schedule so that you can slow work tempo if needed; better to slow down than to rush - Formulate and discuss plan the night before with crewmates; make sure everybody is on the same page - Calling out procedure steps while completing them can help you keep track of progress and make sure everyone is on the same page - Check multiple pieces of data to make sure they all make sense with each other - Well-written procedures and human factors considerations can make a huge difference	- As support IV, suit donning is one of the most difficult and safety critical tasks an astronaut can execute - Prep Ops are more critical than Post Ops - Incorrect suit donning can impact EVA timeline and task completion - Poor suit fit can be detrimental to task performance - Completing UIA procedures incorrectly can lead to delays - Improperly following pre-breathe protocol can increase risk of DCS - It is possible to incorrectly assemble suit

Simulation Scenario. The results of the Incapacitated Crew Rescue (ICR) simulation scenario were summarized into the following sequence of high-level events:

1. Determine injured crewmember status
2. Check ICR procedures
3. Communicate with MCC and IV crewmember
4. Secure worksite
5. Configure ICR transport device
6. Secure injured crewmember to ICR transport device
7. Traverse back to lander with injured crewmember

A description of the summarized actions, assessments, critical cues, and potential errors for each event follows. For the first event of determining the crewmember status, the major actions were for the EV to traverse to the injured crewmember if separated, ask what happened, if they can walk, and how much pain they are experiencing. The assessment was whether the injured crewmember reports that they can't walk and if they report a high level of pain. Critical cues included the injured crewmember's body position, degree of mobility, facial expression, verbal report of pain, while potential errors included underestimating the injured crewmember's verbal or nonverbal pain indicators or failing to address more urgent issue if present (e.g., suit puncture).

The second event, check ICR procedures, had as the action that the EV refers to their cuff checklist for the correct ICR procedures. Assessments were the level of specificity determined in the cuff checklist, limitations of what procedures can be done in this scenario, and the level of crew autonomy to make decisions independent of MCC. Critical cues were making sure all individuals (EV, IV, MCC) are in agreement on the ICR procedures required in this specific situation and everyone referring to the same procedures. Potential errors were the EV choosing the wrong cue card and wrong procedures for the specific ICR scenario, disconnect between procedures EV and MCC are referring to, and overreliance on cue card to the detriment of critical environmental cues.

The third event, communicate with MCC and IV crewmember, had as actions that the EV reports conditions, actions, and needs to MCC, listens for further instructions from MCC, and updates IV on situation if not already aware, so they can go ahead and configure airlock for return. The assessment was that the flight surgeon develops a plan and makes a recommendation while the rest of the team assesses the impact of that recommendation on the timeline and science objectives. Critical cues included instructions from MCC/flight surgeon and the clarity of communication given lunar communication delay, while potential errors included miscommunication, providing too much or too little detail, not providing enough situational awareness to MCC, and assuming MCC would know something that they don't (due to potential shift changes over the course of an EVA).

For the fourth event, secure worksite, the action was that the EV salvages as much science as possible while prioritizing injured crewmember safety. Assessments were to confirm all tools and samples are present and prioritize retrieving samples over tools if it is the last EVA of the mission. Critical cues included the location of tools and samples in the worksite at the time of injury and MCC guidance on the status of science objectives and remaining timeline. Potential error was that if the injury event occurs early in the mission, leaving tools behind at the worksite may preclude further science objectives.

The fifth event, configure ICR transport device, had as actions to de-configure the device if current configuration is not ICR compatible and move transport device to a flat surface if on an incline. Assessments indicated that if the device were on an incline, it may not be safe for the injured crewmember, and assessing whether device is undamaged and has all equipment (e.g., straps) needed for securing the injured crewmember. Critical cues were the flatness of the lunar landscape where injury has occurred, the presence of rocks, craters, or other obstacles in the intended return traverse path. Potential errors were improperly de-configuring ICR transport device and failure to stabilize transport device before loading injured crewmember.

For the sixth event, secure injured crewmember to ICR transport device, the action was to assist the injured crewmember onto the ICR transport device; if not capable, strap the crewmember and haul onto the device. Assessments were whether the injured crewmember is securely fastened to ICR transport device and which direction the injured crewmember is facing (which impacts the EV's visual on their facial expressions). Critical cues included the injured crewmember's level of mobility and location of straps and other ICR-assistive equipment. Potential errors were failing to properly secure crewmember to transport device (risking further injury) and missing a step in the ICR procedures as an off-nominal scenario means there is likely less training and "muscle memory" to rely on.

For the seventh event, traverse back to lander with injured crewmember, the actions identified were to ask MCC if there are any hazards on route back to lander, to look at the map along with MCC instruction, walk forward with injured crewmember either being pushed or pulled, and build in waypoints for checking on navigation, consumables, and the injured crewmember's status on return route. Assessments were to identify the flattest and least hazardous return traverse path (i.e., free of craters, permanently shadowed regions, boulders) and identify a return path that both the EV and MCC agree upon. Critical cues were the level of consumables remaining for both crewmembers, hazards on traverse route not anticipated by MCC, the slope of traverse route, and the lighting of traverse route (avoid shadows as they could conceal hazards). There were multiple potential errors identified for this event. They included not factoring in consumable rate change due to emergency scenario, traversing on a slope without realizing it, choosing a traverse path that initially seems like a shortcut but that includes a steep slope on the other side of an incline, and losing track of location in the heat of the moment and getting lost.

Linkage analysis

KSA Cognitive Demand Ratings. The three EVA tasks that experts rated as most cognitively demanding (0 = Low to 100 = High) based on the knowledge, skills, and abilities (KSAs) they provided were: Traverse (M = 88.3, SD = 5.59), Maintenance Tasks (M = 83.3, SD = 5.16), and Sample Collection: Regolith (M = 61.4, SD = 13.4). Individual KSAs that were the highest in cognitive demand in these EVA tasks were: *Navigation skills* (Traverse), *How to do maintenance for each type of equipment* (Maintenance Tasks), and *Know geology terms* (Sample Collection: Regolith).

KSA Importance Ratings. As part of the linkage analysis, experts provided a rating of how important each KSA was for effective performance of each EVA task (0 = not important, 1 = somewhat important, 2 = important, 3 = very important, 4 = critical). Although KSAs were overall rated as highly important given that they were generated by the experts rating them, there was nevertheless variability among ratings. KSAs provided for Traverse (M = 3.33, SD = 0.71), Sample Collection: Regolith (M = 3.27, SD = 0.47), and EVA Prep/Post Ops (M = 3.20, SD = 0.86) were rated as highest in importance by experts.

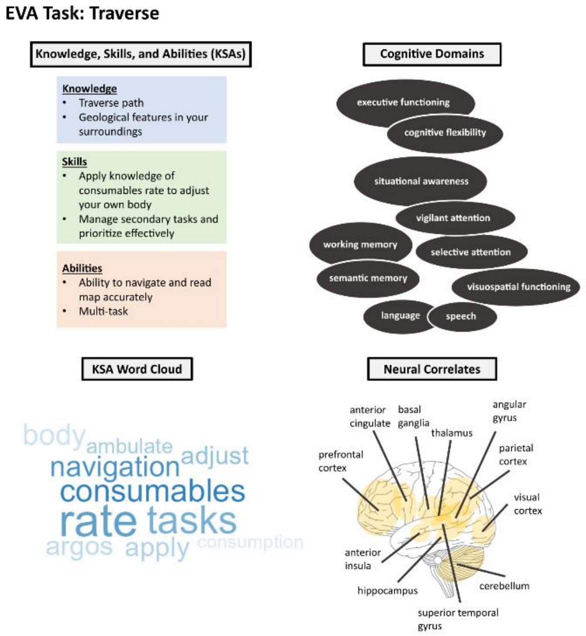
Linking KSAs to Cognitive Domains. Examining the three EVA tasks whose KSAs were rated as highest in cognitive demand (Traverse, Maintenance Tasks, Sample Collection: Regolith), we next linked them to their underlying cognitive domains and putative neural correlates.

Cognitive domains identified for Traverse KSAs (e.g., knowledge of geological features in path, skill to manage consumables, ability to read map) included executive function (involved in problem solving and conceptual understanding), cognitive flexibility (an aspect of executive function concerning the ability to adapt cognitive processing strategies to face new and unexpected conditions in the environment), situational awareness (knowing the information around you that is important for completing the task at hand), visuospatial functioning, vigilant attention, selective attention, working memory, semantic memory, and language. Neural correlates of these cognitive domains include fronto-parietal (prefrontal cortex, parietal cortex) regions, basal ganglia, and thalamic regions involved in executive function and cognitive flexibility, anterior cingulate cortex and anterior insula regions involved in attention, cerebellum which modulates attentional and executive function neural networks, fronto-parietal and hippocampal regions implicated in working and semantic memory, and superior temporal gyrus (Wernicke’s area), frontal (Broca’s area), and angular gyrus regions involved in speech production and language comprehension.

For Maintenance Tasks KSAs (e.g., knowledge of how tools and equipment work, skill to use tools to complete repairs on hardware, ability to plan ahead and manage time), cognitive domains identified included executive function, cognitive flexibility, situational awareness, vigilant attention, selective attention, language, speech, working memory, semantic memory, gross motor skills, and fine motor skills. Neural correlates of these cognitive domains include fronto-parietal, basal ganglia, and thalamic regions involved in executive function and cognitive flexibility; anterior cingulate cortex and anterior insula regions involved in attention; cerebellum which modulates attentional and executive function neural networks; fronto-parietal and hippocampal regions implicated in working and semantic memory; superior temporal gyrus, frontal, and angular gyrus regions involved in speech production and language comprehension; and motor and somatosensory cortex regions implicated in the gross and fine motor control required to complete complex maintenance tasks.

For Sample Collection: Regolith KSAs (e.g., knowledge of geology terminology for geological callouts, the skill to extract a drive tube sample, and the ability to physically drive tube into lunar soil density), cognitive domains identified included largely the same executive function, cognitive flexibility, situational awareness, attentional, language, speech, memory, and motor skills domains as Maintenance Tasks. Accordingly, the neural correlates for Sample Collection: Regolith would be largely overlapping with Maintenance Tasks as well.

Figure 3
Cognitive domain mapping for Traverse EVA task.



Note. Darker word cloud colors indicate higher frequency of that word.

Contributing Factors. As one of our closing questions on the topic of factors contributing to cognitive performance, we asked experts what they think are the most likely and consequential critical safety incidents related to decrements in cognitive performance that could occur on future EVAs on the Moon and Mars. Experts identified several different scenarios of concern. One of the most recurring comments concerned off-nominal and emergency scenarios, such as incapacitated crew rescue (ICR). Experts noted that these will be highly cognitively demanding for crew and that one's brain can seem to "shut down" during high-pressure situations, which can make it difficult to process new or less familiar information (such as a foreign language). This is especially true if already fatigued due to high physical workload or sleep decrements. Errors in navigation during traverse were also highlighted. Experts noted that getting lost on the Moon is a life-threatening scenario. Navigation during traverse will be challenging due to high-contrast shadows and visually similar lunar landscape, and any fall could lead to injury and ICR. The need to muti-task and track consumable and driving a rover will add further cognitively challenging element to navigation. Experts also noted that errors following procedures, such as missing procedural steps, will increase as crew becomes more physically and cognitively fatigued, especially if traversing without a rover and engaging in high-tempo EVA cadence. Errors in donning and doffing the suit due to lack of sleep and increased fatigue would be detrimental to safety and science objectives. Indeed, sleep was another key theme mentioned in this section. Inadequate sleep due to new vehicles and the complexity of mission phases (e.g., orbit, landing) leading up to surface EVA could have multiple downstream negative effects on cognitive and physical performance (Flynn-Evans et al., 2016). Decrements in situational awareness could lead to neglect of consumables monitoring, while decrements in attention to detail due to physical and cognitive fatigue could lead to losing track of details with crew safety implications. Finally, incomplete dust mitigation and inspection due to post-EVA fatigue could lead to cumulative hazardous lunar dust exposure.

Our other closing question asked experts how they think a 5–12s lunar (voice) communication delay might impact an astronaut's cognitive performance on future Artemis missions. A majority of experts agreed that a lunar communication delay is an area of concern that needs further characterization and research. Experts noted that a lunar communication delay would likely lead to repetition and possible talking over each other, which could cause frustration and annoyance among crewmembers and ground support. Mood states such as frustration and annoyance are known to impact cognitive performance due to the shared neural substrates of emotion and cognition (Dolcos et al., 2011). Consistent with responses to our previous question, experts noted that off-nominal and emergency scenarios will make any communication delay especially impactful as crewmembers will need to communicate with MCC in a time-sensitive and stressful situation. Finally, experts noted that there is a pressing need to develop guidelines for when and how to stop speaking to clarify communications. Procedure words used in military and aviation settings (e.g., "over", "copy") should be worked into EVA ground simulations and training and used consistently to prepare teams for future communication delay scenarios. Communication between crew and MCC in future missions may be different than is currently on ISS. The expectation that crew will be in near-constant communication with MCC may not be realistic during Artemis missions and could contribute to increased cognitive workload for crewmembers.

CONCLUSION

Cognitive Demands Table. A Cognitive Demands Table (Table 2) was generated as a synthesis and high-level summary of the information gathered in all cognitive task analysis interviews conducted. The table is organized into difficult cognitive elements and lists the challenges, cues and strategies, and cognitive domains associated with each element.

Table 2

Cognitive Demands Table

Difficult Cognitive Element	*Why Difficult?*	*Cues and Strategies*	*Cognitive Domains*
- Maintaining situational awareness	- Fatigue - Large amounts of information in environment	- Support from MCC/IV - Knowing when you can conserve cognitive resources	- Executive function - Sustained attention - Selective attention
- Navigation during traverse	- Lack of visually distinct landmarks on Moon, low illumination, long shadows, few navigation aids - No perfect ground analog for partial gravity EVA	- Good maps and pre-brief materials - Frequent communication with MCC/IV to confirm location - Handrails, backstops, waypoints, and landmarks to orient	- Executive function - Cognitive flexibility - Working memory - Language - Speech - Visuospatial functioning - Reading comprehension - Situational awareness
- EVA Prep Ops	- Critical procedure; error could endanger lives of crewmembers - Large number of procedural steps - Requires effective teamwork	- Aim to be ahead of schedule; easier to slow tempo than speed up - Formulate and discuss plan the night before with crewmembers - Call out procedure steps while completing them	- Executive function - Working memory - Sustained attention - Situational awareness - Language - Speech - Reading comprehension
- Managing safety, time constraints, and mission objectives simultaneously over entire course of EVA	- Requires decision-making and cognitive flexibility on relative importance of time management, safety, and mission objectives	- Safety is a tool for successful task completion - MCC can offload some of the cognitive load of managing time, safety, and mission objectives	- Executive function - Cognitive flexibility - Situational awareness - Sustained attention - Selective attention
- Remembering geological terminology and accurately applying it to samples	- Terminology can be complex and specific to this scientific discipline - Astronauts have diverse backgrounds and may not be geologists or scientists by training - Lunar rocks are visually similar and geologically significant differences may be subtle - Geological callouts must occur while multi-tasking to meet safety and mission objectives	- Extensive ground training in geology in lunar-like environments (e.g., Iceland) - Cue cards and cuff checklists - Geological callouts should be scientifically precise and succinct; excessive communication can crowd voice loops from other team members	- Executive function - Working memory - Semantic memory - Speech - Language
- Off-nominal and emergency scenarios	- Difficult to effectively simulate in ground training - Stressful and unexpected in real-life	- Cuff checklists can be referred to for certain emergency procedures (e.g., ICR) - Effective communication with MCC is key	- Executive function - Cognitive flexibility - Working memory
- 5-12s lunar (voice) communication delay	- Delay can lead to talking over each other, frustration, miscommunication	- Procedure words (e.g., "over") used consistently in ground training - Extensive training with crewmembers to learn communication style and anticipate speech cadence	- Executive function - Cognitive flexibility - Speech - Language - Working memory

Recommendations. The information gathered as part of this cognitive task analysis suggests several recommendations for future exploration class mission EVA. First, crew pre-mission training should include off-nominal and emergency scenarios such as incapacitated crew rescue (ICR) to prepare for these low likelihood but cognitively challenging and high consequence events. Second, situational awareness should be systematically measured in EVA simulation studies to characterize how and when there are decrements in SA that could affect performance. Third, physical workload and pain should be recognized as factors that can impact cognitive performance and managed accordingly prior to, during, and following EVA. Adequate sleep will be critical and especially challenging with new vehicles and multiple complex mission phases. On the lunar surface, astronauts will need as much navigational aid as technologically possible. To keep communication effective during lunar communication delays, there should be effort in ground simulations and training to implement consistent procedure words (e.g., "over", "copy") to deal with the challenges of communication delay. During geological operations, cue cards on astronaut cuffs should include reminders of geological terms to reduce cognitive workload associated with geology callouts. MCC should consider offloading some of the operator tasks of EVs while they are doing field geology to maximize the likelihood that high-quality science is conducted on the lunar surface. Other recommendations based on our findings include that crewmembers on the lunar surface may need extra time for suit mobility adaptation given the cognitive workload associated with it. If extra time for suit adaptation isn't built into the EVA timeline—separate from during traverse given the cognitive workload associated with that EVA task—there is likely to be increased cognitive workload early in the EVA as crewmembers adapt to moving in the suit in partial gravity. Finally, to maximize the cognitive offloading of effective teamwork, after flight selection crews should receive training to learn about cognitive offloading, managing different work styles, managing cognitive workload through teamwork, developing situational awareness, as well as other aspects of effective teamwork for exploration EVA (e.g., communication, coordination).

DISCUSSION

Ensuing safe decision-making on the Moon and Mars during future surface exploration EVA will require adequate characterization of the cognitive performance risks prior to, during, and following EVA. To be useful, this characterization should inform exploration EVA concept of operations, training prior to flight in simulation environments such as the Neutral Buoyancy Laboratory (NBL), just-in-time training in-flight, and countermeasures targeting all mission phases. The results of this cognitive task analysis will assist in current efforts to identify the key cognitive domains for safe decision-making during surface EVA. Our findings will inform functional cognitive and performance testing related to the identified cognitive domains and provide a link between cognitive domains and operationally relevant performance metrics that can be tracked by NASA mission operations to ensure safe decision-making for exploration class mission EVA. Our findings on the specific cognitive challenges that astronauts will face during exploration EVA can aid in the creation of products for cognitive performance monitoring capabilities and technologies, such as real-time data dashboards, that can be used by team members to keep track of cognitive workload and performance and adjust EVA timelines as needed to manage cognitive overload. Research into which information should be conveyed to the astronaut (i.e., useful as feedback without adding intensively to psychological demands of the EVA) is also needed. Additional research is needed to develop unobtrusive cognitive metrics that can be used to inform models, and to understand the optimal types and amount of data that should be presented in a dashboard, and how viewing this data may influence crewmember stress, mood, and performance.

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