Performance Risks During Surface Extravehicular Activity and Potential Mitigation Using Multimodal Displays

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BACKGROUND: Surface extravehicular activity (sEVA) will be a critical component of future human missions to the Moon. sEVA presents novel risks to astronaut crews not associated with microgravity operations due to fundamental differences in task demands, physiology, environment, and operations of working on the lunar surface. Multimodal spacesuit informatics displays have been proposed as a method of mitigating sEVA risk by increasing operator autonomy.

METHODS: A formalized literature review was conducted. In total, 95 journal articles, conference papers, and technical reports were included. Characteristics of U.S. spacesuits were reviewed, ranging from the Apollo A7L to the xEMU Z-2.5. Multimodal display applications were then reviewed and assessed for their potential in aiding sEVA operations.

RESULTS: Through literature review 25 performance impairments were identified. Performance impairments caused by the spacesuit represented the greatest number of sEVA challenges. Multimodal displays were mapped to impairments and approximately 36% of performance impairments could be aided by using display interfaces.

DISCUSSION: Multimodal displays may provide additional benefits for alleviating performance impairments during sEVA. Utility of multimodal displays may be greater in certain performance impairment domains, such as spacesuit-related impairments.

KEYWORDS: Artemis, Moon, bioastronautics, astronaut, human spaceflight, aerospace.

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Extravehicular activity (EVA) comprises work that astronauts complete outside of the spacecraft or habitat.[53] Surface extravehicular activity (sEVA) occurs when an astronaut completes this work on the surface of a planetary body, near-Earth asteroid, or a natural satellite (e.g., Earth's Moon). Compared to EVA performed in microgravity, sEVA presents distinct challenges[33] and has not been performed since the early 1970s during the U.S. Apollo program. Future sEVA concepts of operations (ConOps) call for astronauts to perform approximately three EVA per week,[2,33] totaling approximately 24 EVA hours per person per week. This is a marked increase compared to current missions and will likely necessitate new operational paradigms. Additionally, the Artemis program outlines long-term surface operations as a paramount goal for lunar operations.[82] These may include long-duration lunar stays of up to 2 wk of at least four crew.[29]

NASA's Human Research Roadmap has determined that any lunar visit/habitation or Martian EVA will require risk reduction associated with injury, compromised physical performance, and reduced cognitive performance before the risk disposition is acceptable.[24] Specifically, it states that "there is a possibility that crew injury and compromised physiological and functional performance may occur" due to the "physiological and functional demands of operating in a self-contained EVA […] suit." Multiple risk factors affect this assessment such as spacesuit habitability and design, task demand and training, and physical and cognitive states.[24]

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To reduce the stressors of sEVA, a focus on improving EVA informatics has grown within the human spaceflight community. In particular, multimodal displays (MMD) have been suggested as a method for improving operator safety and efficiency. MMDs are guided by Wickens'[93] multiple resource theory. This theory asserts that different sensory modalities each have their own resource allocation and processing channels in the brain. This can be leveraged to increase information bandwidth by spreading the amount of information being presented over multiple sensory modalities. MMDs use congruent and complementary sensory cues to pool multiple attention resources together. Within an EVA context, MMDs can be leveraged to improve spacesuit demand, offload task demand, and improve cognitive state. They have been shown to improve alert response time,[17,91] detection and localization of points of interest,[46,90] and improve situation awareness (SA).[45]

Previous MMD research has shown inconsistent improvement in task performance. Meta-analyses of MMD have shown that taskload protocols have not been manipulated in a systematic and reliable manner.[34] Cognitive workload (WL) and its interaction effects with MMDs are not confidently understood.[21,34] MMD research in sEVA has been accomplished by the Human Systems Integration division out of NASA Ames Research Center,[17,46,91] as well as joint investigations between academic institutions and NASA Johnson Space Center.[45] Previous research from these groups has focused on specific applications for sEVA such as navigation or procedure display. It may be possible, though, to use MMDs to mitigate additional sEVA risk due to their broad applicability. To identify whether this the case, a wholistic evaluation of MMDs and their efficacy in alleviating sEVA performance impairments is needed. This research addresses this gap by conducting a literature review on sEVA performance risks and then identifying the degree to which MMDs may mitigate the described performance impairments.

METHODS

A formalized literature review on extravehicular activity was conducted. References were identified by ScienceDirect and NASA Technical Report Server searches covering 1970 to September 2021 using the terms "EVA", "spacesuit", "Apollo", "Performance", "Lunar", and "Martian." In total, 104 journal articles, conference papers, and technical reports were reviewed. Of these, 95 are included in this review article after accounting for duplicated information between journal/conference publications and relevance to topic. Only U.S. spacesuits were reviewed, ranging from the Apollo A7L to the xEMU Z-2.5. From the literature review, impairments to performance were identified and developed into four thematic categories: spacesuit, physiology, environment, and operations. Multimodal display capabilities, previously identified through military, air traffic control, and automobile applications, were then cross-referenced to performance impairments identified.

RESULTS

Performance Impairments

From the literature review, four primary performance impairment categories were identified: spacesuit, physiology, environment, and operations. There were 25 performance impairments identified and listed in **Table I**. The categories used mirror NASA's EVA Risk Diagram,[24] though we have chosen to separate operations into operations and environment because this analysis focuses solely on sEVA, whereas the Risk Diagram encompasses all types of EVA. It should be noted that identified performance impairments may have multiple causal mechanisms; however, in this research we have chosen to categorize performance impairments by their primary impairment category. An expanded discussion of these impairments is described in the following sections.

The first category is spacesuit-induced performance impairments, wherein the physical limitations created by hardware or software impact performance. Spacesuit-induced performance impairments include limited field of view/regard,[31,60,74] helmet fogging/scratching,[9,77,89] ambient noise level,[8,16] sound reflection,[8,16] loss of fine-motor tactility,[19,27,86] reduced applied strength,[65,75,77] hand fatigue,[73,77,85] shifted center of mass,[6,73,74] and limited upper body[5,75] and lower body mobility.[7,12,59]

The second category is physiology-induced performance impairments, wherein physiological adaptations to space impact human operator performance or increased risk of injury.

Table I. Summary of All Performance Impairments Identified from the Literature.

PERFORMANCE IMPAIRMENT	CASUAL MECHANISM	MMD APPLICATION
Limited Field of View	Spacesuit	X
Loss of Fine Motor Tactility	Spacesuit	X
Limited Mobility	Spacesuit	
Hand Fatigue	Spacesuit	
Reduced Applied Strength	Spacesuit	
Helmet Fogging/Scratching	Spacesuit	
Shifted Center of Mass	Spacesuit	
Ambient Noise Level	Spacesuit	
Sound Reflection	Spacesuit	
Altered Proprioception	Physiology	X
Musculoskeletal Deconditioning	Physiology	
Vestibular Deconditioning	Physiology	
Acute Injury	Physiology	
Long Term Injury	Physiology	
Uneven/Hazardous Terrain	Environment	X
Altered Depth Perception	Environment	
Dust	Environment	
Radiation	Environment	
Altered Visibility Conditions	Environment	
Temperature Variation	Environment	
Limited Communications	Operations	X
Limited or Outdated Procedures	Operations	X
Missed Cautions, Warnings, Alarms	Operations	X
Limited Navigation Information	Operations	X
Limited Bandwidth	Operations	

Performance impairments are categorized by EVA causal mechanisms. Potential multimodal display applications and uses for each performance impairment and their causal mechanisms are denoted with the letter 'X'.

Physiology-induced performance impairments include vestibular deconditioning,[25,26,43] musculoskeletal deconditioning,[78,80] altered proprioception,[60] and acute and long-term injury.[12,77,78]

Environment-induced performance impairments are the third category, wherein the specific characteristics of a lunar, Martian, or near-Earth asteroid (NEA) environment impact performance.

Environment induced performance impairments include lack of atmosphere attenuation,[67,73,87] altered visibility conditions,[67] dust,[10,73,89] temperature changes,[67] hazardous terrain,[67,87] and radiation exposure.[76,87] Finally, operations-induced performance impairments include any changes from current microgravity EVA operations protocols which may negatively impact performance, productivity, or safety. Operational induced performance impairments include limited communications,[3,14,51] limited bandwidth,[3,14,51] limited navigational resources,[14,77] limited or outdated procedures,[28] and missed notifications or alarms.[28]

Each of these performance impairments (spacesuit-induced, physiology-induced, environment-induced, operations-induced) is discussed in detail in the following subsections.

Spacesuit-Induced

Astronaut visual perception impairments are considered the highest risk factor[77,87] due to the astronaut's heavy reliance on visual processing. Pressurized spacesuit testing suggests a decrease in field of view (FOV) from unsuited baseline by approximately 30% in horizontal FOV and 21% in vertical FOV.[5,58,60] In current and historical spacesuit helmet designs, FOV restrictions are unevenly distributed across the inferior and superior directions. A significant reduction in inferior direction was shown while the superior direction remained largely unaffected,[58] which future suit designers should take into account when integrating visual features such as heads-up displays or the Displays and Control Unit (DCU).

Further, lack of helmet neck bearings in current and historical extravehicular mobility unit (EMU) designs eliminate any field of regard (FOR) increases for visual perception. Helmet fogging and scratching[9,77,89] also degrade visual signal integrity and require further risk mitigation for future EVA.

The auditory environment is another consideration for performance decrement. Spacesuit-internal hardware generates and reflects noise while environmental noise is not present due to the lack of planetary atmosphere. Nominal internal background noise in Mark III suit testing averaged around 70dB(A).[16] Noise sources can be attributed to portable life support systems (PLSS) fans and pumps, sound reflection via helmet shape, and bearing or mechanical noise due to spacesuit movement.[8,16] During suited walk-back testing in the Mark III, air circulation within the suit resulted in a distinct "swooshing" sound reported by subjects.[16] Spacesuit internal noise reflection studied by Allen[8] and Begault and Hieronymus[16] found a medium to high level of ambient internal background noise in the spacesuit. With the xEMU incorporating an integrated communication system (ICS), ambient noise levels have the potential to interfere with communication intelligibility. Driving requirements for the xEMU's ICS specify a 90% English intelligibility, with early standalone tests suggesting these requirements have been met.[42] At this time, a complete hardware-in-the-loop test has not been conducted in flight-like environments,[42] but initial results are promising.

Tactile perception impairments are another concern. While EVA glove performance has been heavily studied (see Scheuring et al.[77] for a detailed review paper), only two papers were identified[19,86] that specifically included tactility metrics such as two-point discrimination testing, discussed below. Thompson et al.[86] evaluated a series of bumps resembling screw heads using a 4.3 psid pressurized phase VI glove. On average, a 748% increase in force was required to discern the same bump when participants (4 women, 4 men) donned an unpressurized glove relative to a barehanded baseline. A 1015% increase in force was required when wearing a pressurized glove. It is unclear how many participants correctly identified whether a bump was present. Bishu et al.[19] found gender and the level of pressure to be significant factors impacting performance during two-point discrimination testing and mean time for nut assembly and knot tying tasks.

Gas-pressurized spacesuits require the operator to dedicate some portion of their strength into physically flexing the spacesuit. On average, a 15–20% decrease in overall strength was found during pressurized suited testing,[36,65,75] though one study reported up to 90% decreases in grip strength.[13]

Existing NASA human-system integration requirements take a more conservative approach of up to 50% strength decrease during EVA.[28] During pressurized suited trials, maximum voluntary muscle contractility for a 1-s grip hold decreased by nearly 50% after 20–30 repetitions, though rest time between trials was not strictly controlled for.[13] Improper suit fit may cause joint and limb misalignment between the operator and the spacesuit, increasing relative torque forces required to flex the suit.

Additionally, nearly all pressurized suit studies do not account for any musculoskeletal deconditioning during transit or during extended periods of stay in the lunar or Martian environment. A study of 37 International Space Station (ISS) crewmembers who averaged 163 d (±38 d) in microgravity showed that even with an advanced resistive exercise device (aRED), isokinetic strength decreased by an average of 12% across knee and ankle flexion/extension.[36] Stamina and fatigue will become increasingly important during planetary habitation due to an increased frequency of EVA. Fatigue during Apollo has been documented through a series of interviews. Multiple astronauts identified hand fatigue as the primary limiting factor during their EVA.[27,73,85] Suited mobility and work envelope (WE) are largely dictated by suit bearing design and suit fit.

As such, measuring mobility or WE are restricted to specific spacesuit models or even test subjects, making generalized mobility or WE models difficult.[49] Recent advancements in spacesuit modeling have helped to bridge this gap,[30] but literature is still sparse. Alternative measurements for suited mobility based on metabolic costs are being investigated by NASA.[59]

Spacesuit bearing and programming can lead to altered movements and response execution strategies. The hip brief assembly from the Mark III, which will be featured in the xEMU lower torso assembly, has been studied extensively.[7,30,70] There are limitations associated with the Mark III hip brief assembly, primarily attributed to the three separate, single degree-of-freedom bearing design. The human hip joint is separated into three separate bearings in the hip brief assembly, leading to misalignment of joint hinges between the spacesuit and the human body. This results in changes to static and gait parameters, dynamic base parameters, and decreased bent torso stability.[6,30] Poor suit fit can also affect mobility and work envelope, but also contribute to injury, with hand and shoulder injuries occurring most often.[78] Suited injuries have been largely documented in the past,[12,77,78] though specific causal mechanisms are still being investigated.[11] Finally, it should be noted that increased mobility may not be beneficial to all tasks. In microgravity EVA simulations, stiffness of the lower torso assembly allowed astronauts to create more leverage when interacting with the articulating portable foot restraint.[7]

Shifted center of mass from the extravehicular mobility unit and portable life support system introduces risks which may become exaggerated during sEVA. Interviews with Apollo astronauts suggest that although the PLSS created a tendency to tip backward, most astronauts did not have serious problems maintaining balance.[73] However, when attempting to stand up after falling down, the risk of losing one's balance may become more exaggerated.[74] The effects of shifted center of mass in partial gravity environments were not easily assessed through literature. This issue can be studied in a variety of analog settings but remains difficult due to the imperfect nature of these representative environments.

Operational testing in NASA's Active Response Gravity Offload System (ARGOS) have focused on achieving a realistic center of gravity but is not a perfect analog for hypogravity due to harness contact points.[18] Parabolic flights are suitable analogs for hypogravity effects, but can only be achieved for a short duration. Underwater environments such as the Neutral Buoyancy Lab and NASA's Extreme Environment Mission Operations (NEEMO) can be used to study shifted center of mass, but water drag inhibits natural mobility and is prone to similar contact point issues as ARGOS.[18] Ultimately, the tradeoff between PLSS mass and mobility will need to be studied in greater detail.[6]

Physiology-Induced

Atrophy of bones and muscles is the primary risk concern in this category. Risk assessment of bone fracture[66] and compromised physiological performance[24] are currently under investigation by NASA. Bone atrophy in space is not heterogeneously distributed across the body.[52,88,92] Weight-bearing areas such as the hip have seen losses up to 1.7% per month while upper extremities such as the humerus may even gain a small percentage of bone density.[56,69] Muscle atrophy in space follow similar trends to bone atrophy. However, confounds such as diet, exercise level, and stress are difficult to rigorously control for, and may affect the amount of muscular atrophy observed.[20] On average, muscle volume losses in space are greater than what is expected from relevant bed rest studies.[20,55] Antigravity muscles, those involved in posture, such as the quadriceps, hamstrings, and soleus, experience the greatest amount of muscle volume loss in the high teens during long-duration spaceflight.[54] Lower extremity bone and muscle atrophy becomes increasingly important when considering sEVA wherein locomotion is essential to mission operations. Historical EVA data suggest musculoskeletal injuries occur at a rate of 0.26 per EVA.[78] Musculoskeletal deconditioning may also contribute to acute and long-term injury. However, due to multiple contributors to bone and muscle strength, the full impact of spaceflight on the musculoskeletal injury is unknown.[66] Suited fatigue is investigated through a mix of interview reports and strength/stamina studies.[13,27,77] Functional suited tests have been performed,[68] although to the authors' knowledge a functional suited test after being preemptively fatigued has not been performed.

This is an area of ongoing work at NASA. Similarly, the effects of musculoskeletal and vestibular deconditioning and spacesuit strength on functional performance is an ongoing area of interest. To study this effect, a suited functional test could be completed immediately following a bedrest study, though it should be noted that a bedrest study cannot replicate actual unloading of the vestibular system due to the presence of gravity on Earth.[48] Replicating the musculoskeletal loading from hypogravity is also a challenge to performing this kind of evaluation. Further, it is likely that different kinds of spacesuit injuries will occur during planetary ambulation than those accrued in microgravity EVA. Acute and long- term injury have been well documented,[12,77,78] but the causal mechanisms behind some injury hotspots are still unknown. Given the uncertainty around future suit injury paradigms, projecting the overall impact of the effects injury may have on overall mission success will be a challenge. More work is required to categorize the types of injury which can occur during sEVA and their impact on mission goals.

Vestibular perception is important, particularly on early EVA, where decrements are largely attributed to reduced gravity levels. Reduced gravity environments such as the Moon or Mars will introduce a neurovestibular adaptation which may take days or weeks to fully acclimate. Until complete sensorimotor adaption, these environments will induce a number of vestibular perception illusions such as underestimation of roll tilt.[25,26,43] This vestibular perception impairment is most likely to affect manual entry/descent/landing operations or emergency crew egress upon landing. Long-term vestibular adaptation in hypogravity will likely not be an issue for long-duration missions. Altered proprioception due to hypogravity, spacesuit volume, and spacesuit fit may also introduce challenges in future sEVA. Training reports from the Neutral Buoyancy Lab show that trainees often unknowingly bump into the ISS mockup due to lack of awareness because of the PLSS volume or helmet bubble.[60] This challenge may resolve itself after training, but the combined effects of hypogravity, spacesuit volume, and fit may only be resolved upon arrival to the EVA location due to our inability to fully replicate these effects.

Environment-Induced

Terrain hazards are the primary risk concern in this category. Dust may cause additional hardware-related performance impairments, such as extravehicular visor assemblies not being able to properly retract.[89] Lunar dust kicked up during navigation or routine operations may result in visual gray out[10] or important hardware being covered,[73] as was evident when an Apollo astronaut tore a cable loose from the Lander after accidentally walking over it. Lack of atmosphere attenuation further compounds issues with lunar surface composition, increasing errors in distance estimation and landmark recognition.[67,73,87] Uneven terrain and slopes upward of 30% during sEVA will increase physical WL.[68] Sloped traversal under suited partial gravity loads has limited data,[24] likely due to the high operational cost in order to test. Sloped terrain between 10–30% grade were shown to have a significant impact on metabolic load when ambulating in a spacesuit.[68] Analog environments may be sufficient in assessing the risk associated with this performance impairment, and is an area of ongoing work at NASA.

Planetary extravehicular crew will have to navigate and interact with their surroundings without environmental audio cues to help them maintain SA. External sound cues and effects, such as the Doppler effect, will be entirely nonexistent on the Moon. While sound propagation is present on Mars, any external sound perception will likely be unintelligible to extravehicular crew.[71]

Radiation exposure on planetary surfaces receive some protection when compared to interplanetary flight; however, the risk of high dose-rate exposure is still very high. Low radiation doses may be mitigated by the spacesuit material lay-up, but high-energy radiation is still a concern.[76]

Operations-Induced

Future exploration missions will need a new paradigm for EVA autonomy and self-reliance. Two drivers, one-way light time (OWLT) and limited data bandwidth, have spurred many space-analog missions to study the impact of these restrictions. Although Earth-Lunar OWLT is nearly nonexistent, proposed lunar ConOps have suggested the use of periodic communication models due to extremely high WLs on ground science support teams associated with constant communication models.[94] Further, a Mars-based communication protocol on the Moon allows lunar EVA to act as a proving ground for Martian EVA. OWLT between Earth and Mars ranges from 3–22 min depending on orbit alignment.[63] Two intravehicular crewmembers are likely required under these new conditions, with one focused on timeline operations and the other on science operations.[3,62] Visual-based communication was found to be favored over audio-based communication during the Biologic Analog Science Associated with Lava Tubes (BASALT) research program.[14,51,57] Limited bandwidth of visual imagery has shown mixed results, where one Desert Research and Technology Studies (DRATS) mission resulted in equivalent science data quality between low bandwidth (1.5 $mb \cdot s^{-1}$, typical bandwidth available through the Deep Space Network) and high bandwidth (6 $mb \cdot s^{-1}$), though ground science support teams reported higher WL with the low bandwidth condition.[3] Still imagery was found to be more constructive than video feed imagery,[51,57,62] though video feed worked well for SA and still-imagery backup. One study of Mars-based rover operations found little difference in science quality and productivity between a constant communication protocol vs. a 2× daily downlink.[4] However, they note that the twice daily downlink resulted in greater EVA team SA due to greater EVA communication, which occurred less frequently in the constant communication protocol. They attribute this to increased CAPCOM-EV communication during constant communication, which naturally led to less extravehicular team communication.

Many operational challenges associated with the lunar environment are largely based on Apollo interview studies and may represent an incomplete understanding of these performance impairments. These include effects of dust on hardware operation and lack of atmosphere attenuation.[67,87] Lack of atmosphere attenuation was attributed to increased errors in distance estimation and landmark recognition, but interviews from Apollo J-type missions suggest that astronauts may be able to adapt in a few days.[73,87] However, lack of ground-truth data from perceived distances to actual landmark distance decreases the reliability of these findings. These performance impairments may be difficult to study due to scarcity of representative materials (e.g., simulated regolith) on Earth.

DISCUSSION

From the identified performance impairments, the literature on MMDs was reviewed to identify those associated with sEVA that could be at least partially alleviated by MMDs. Of the 25 impairments, 9 were identified, including 2 spacesuit impairments, 1 physiological impairment, 2 environmental impairments, and 4 operationally related impairments. They are identified in Table I. Broadly, it was found that MMD can be leveraged to mitigate impairments through two means: increased safety and greater work efficiency.

Increased levels of SA have been shown to correlate with increased safety.[83] Limited FOV, uneven terrain, altered depth perception, limited navigation information, loss of tactility, vestibular deconditioning, and missed notifications can negatively impact operator SA during sEVA. Several techniques have been suggested as countermeasures for low SA, including SA camera displays,[1,23,45] audio support systems,[32,34,91] and tactile systems.[37,40] SA cameras and visual displays may be easy to implement, but research in this area often assumes a separate support team who analyze the incoming visual information.[32] This makes these types of technologies less promising for real-time SA when considering data bandwidth and one-way light time communication constrictions during Martian EVA (and to a lesser extent, lunar EVA). These types of systems may increase the overall team SA, but more research is required to investigate the impact on operator SA. Audio-based support systems have been used in a variety of navigation tasks.[35,44,81,84] The primary challenge with navigational aid systems is that they are heavily reliant on GPS, which currently does not exist for lunar operations. In the future, an audio SA support system may be well suited for increasing safety during sEVA if position localization becomes available. Tactile SA systems have been demonstrated in microgravity and shown to improve orientation SA in a weightless, shirt-sleeve environment.[39] Integration with the spacesuit poses challenges given the pure oxygen environment, limited volume to place hardware, and suit-induced tactile impairment against which this information would be overlaid. Ultimately, more research is needed to determine the cost-benefit of a tactile SA system for spacesuit environments. Vestibular stimulation through galvanic vestibular stimulation (GVS) has been studied in translation studies[41] and can be used to improve roll/tilt estimation.[50,95] In theory, GVS has some potential to counteract vestibular readjustment upon landing on a planetary surface but has not been demonstrated in research settings.

MMDs can also improve work efficiency, reducing the total risk exposure in this dangerous environment. Limited communication and outdated or limited procedure information can negatively impact work efficiency during sEVA. Communication between EVA and intravehicular activity (IVA)/ground support (GS) is limited due to data bandwidth and one-way light time constrictions. Reliance on traditional real-time audio communication systems may not be sufficient under these conditions. The primary technology for offloading these performance impairments has been through the visual modality. Providing a text-based messaging system has been shown as a useful method for goal-setting during analog planetary EVA.[32] Additionally, image-based messaging was shown to improve team SA under these contexts. Detailed or "enhanced" procedure information has been investigated by several universities through NASA's university-level challenge (Spacesuit User Interface Technologies for Students).[61,64,72] Subjective feedback from NASA engineers and astronauts through this challenge suggest that incorporating enhanced procedures is useful for EVA.

Importantly, MMDs leverage parallel sensory channel throughput when providing information to the user. However, under highly stressful situations, single channel sensory overload is more likely to happen.[79] Thus, although a multimodal display may be providing more information, the user may not receive the benefits of this increased bandwidth.[22] More research needs to be done in this field specifically as it pertains to space operations. Air traffic control can likely be used as a starting foundation for this research since both exhibit similar operational traits (e.g., high stress, high workload). Literature from air traffic control and multimodal displays suggests that increasing the amount of sensory channels correlates to increased operator SA.[15,38,47]

This research was confined to papers identified through the standardized search approach that was broadly available. Since a great deal of effort may have been performed internally at NASA or related commercial companies, it is possible that these results do not sufficiently capture internal work.

This research identified 25 performance impairments through literature review, divided into four categories of spacesuit, physiology, environment, and operational challenges. Performance impairments caused by the spacesuit represented the largest number of sEVA impairments. Of the 25 identified sEVA performance impairments, 9 were identified as able to be mitigated with MMDs. MMDs can offset multiple types of performance impairment causal mechanisms, but must be done in a manner that does not overly burden the operator's ability to process information. MMDs may serve as a viable candidate for mitigating risk associated with sEVA, but additional research into their ultimate integration for suited operations is needed.

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