

Operational Evaluation of Artemis EVA Telemetry Display Concepts Using ISS EMU Simulations

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Telemetry displays for Artemis extravehicular activity (EVA) operations must enable mission control operators to interpret complex suit and system data quickly, accurately, and with manageable cognitive workload. To inform the design of next-generation controller-facing EVA displays, this study designed and evaluated three telemetry display concepts (instrument panel, schematic, and tabular) using ISS Extravehicular Mobility Unit (EMU) simulation data in operationally representative mission control training scenarios. Mission control subject-matter experts completed scenario-based monitoring tasks and post-scenario surveys. Measures included response time, anomaly event detection, perceived workload, usability, and situation awareness. Display format significantly affected response time, workload, and usability. The instrument panel display supported the fastest response times, while the tabular display produced the highest usability ratings and lowest perceived workload. Event detection and situation awareness were similar across display types. These results identify key tradeoffs between rapid anomaly recognition and low-workload information access, providing evidence-based guidance for refining telemetry display architectures for future Artemis EVA operations.

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I. Introduction

CREWED exploration missions under NASA's Artemis program demand telemetry display systems capable of supporting rapid, accurate decision-making in environments characterized by high cognitive load, time pressure, and procedural complexity. As extravehicular activity (EVA) operations evolve to accommodate increasingly autonomous crew activities and more diverse mission profiles, the need for telemetry interfaces that integrate human-centered design principles with operational constraints has grown substantially. For mission control flight controllers, telemetry displays must not only present large volumes of suit and system data, but also support efficient interpretation, anomaly recognition, and decision-making during time-critical operations.

This study builds on prior work in human-centered telemetry display design for NASA exploration missions by evaluating how different display concepts affect operator performance and perception in an operationally representative setting. A core component of this work involved structured, scenario-based evaluations of multiple prototype telemetry display concepts during Flight Controller Part Task Trainer (FCPTT) simulation sessions with flight controllers and subject-matter experts. These evaluations were designed to assess user performance, situational awareness, interpretive clarity, and workload under realistic mission control simulation conditions.

Participants completed monitoring tasks using three display formats: instrument panel, schematic, and tabular. Quantitative data included response time, anomaly event detection, usability, workload, and situation awareness measures, while participant feedback provided additional insight into the strengths and limitations of each display approach. These measures were used to identify which design features most effectively support operational decision-making in EVA telemetry contexts.

By combining empirical evaluation with human-centered display design principles, this study advances a research-to-practice pipeline for telemetry displays that are both operationally useful and human-system aware. The outcomes contribute to broader human-systems integration objectives for EVA operations and provide an evidence-based foundation for refining telemetry display architectures intended for Artemis and future exploration missions. This paper addresses the following research questions:

- RQ1: How does telemetry display format affect flight controller performance during EVA monitoring tasks?

- RQ2: How do instrument panel, schematic, and tabular displays affect perceived usability, workload, and situation awareness?
- RQ3: What display design tradeoffs should inform future Artemis EVA telemetry display architectures?

II. Background

Mission control flight controllers rely on telemetry displays to monitor system state, detect off-nominal conditions, and support time critical decisions during human spaceflight operations. For Artemis EVA operations, these displays must help flight controllers interpret high volume suit and system data while maintaining awareness of mission context, procedure status, crew safety, and evolving operational constraints. Prior aerospace display research has shown that display augmentation and information presentation can affect operator performance in time sensitive, remotely operated spaceflight tasks, reinforcing the importance of display design for operational decision support [1]. The design problem is therefore not simply how to present telemetry, but how to organize mission critical information so that flight controllers can recognize changes quickly, understand their operational meaning, and coordinate appropriate responses.

Evaluating controller-facing EVA telemetry displays requires attention to EVA operational risk, human-centered design, situation awareness, cognitive workload, and display usability. In spaceflight contexts, human-centered design is closely tied to safety because interfaces must account for user variability, stress, risk communication, and timely access to mission critical information [2, 3]. These areas frame display evaluation as more than a question of data availability; the displays must also support operator performance, manageable workload, and situation awareness.

EVA is a high-risk operational activity in which crew safety and mission success depend on the effective management of suit systems, crew health, task execution, and operational constraints. Planetary EVA has been identified as one of the most dangerous activities in human space exploration, with risk mitigation needs related to spacesuit design, operational concepts, human health, environmental exposure, and communication constraints [4]. In EVA operations, flight controllers must monitor and interpret multiple streams of mission critical information, including spacesuit life support status, consumables, environmental control parameters, biomedical or physiological data, timelines, and off-nominal system indications [4,5]. These risks illustrate why EVA telemetry displays must support rapid access to suit and system information while also helping operators maintain awareness of the broader operational context.

Biomedical and physiological monitoring are also important components of EVA support. Real-time monitoring of astronauts' physiological parameters during EVA has been demonstrated through biomedical sensor systems designed to support operational awareness of crew health status [5]. This reinforces the need for displays and supporting systems that can communicate biomedical information in a way that is timely, interpretable, and operationally useful. For mission control personnel, physiological data are not viewed in isolation; they must be interpreted alongside suit consumables, environmental control parameters, procedure status, mission timelines, and off-nominal system indications.

Surface EVA operations also introduce complex task planning and execution demands. EVA task planning and execution have been examined using dynamic value stream mapping, including indicators such as task time, energy consumption, and mission value [6]. This work emphasizes that EVA activities place high demands on mission process design, task allocation, and operational execution. These demands are relevant to telemetry display design because flight controllers must monitor changing system states while also supporting timeline execution and decision making during dynamic operations.

Cognitive workload is another central concern for future surface EVA. Surface EVA has been identified as one of the most cognitively demanding activities astronauts can perform, and future exploration missions require better characterization of the cognitive capabilities needed for safe and effective EVA performance [7]. Although much of this work focuses on astronaut cognitive performance, the same operational context creates demands for mission control flight controllers, who must interpret telemetry, assess risk, coordinate with multiple disciplines, and support decision making under time pressure. Telemetry displays should therefore be designed to reduce unnecessary information search demands and support clear interpretation of mission critical data.

Human-centered design provides a useful basis for addressing these challenges because it emphasizes alignment between system interfaces, user needs, task demands, and operational context. For EVA telemetry displays, the challenge is not simply to make data available, but to organize information in a way that supports how flight controllers monitor systems, recognize off-nominal conditions, and make decisions. User feedback is most useful in usability evaluation when it is collected systematically and interpreted in relation to the operational task rather than treated only as general preference data [8]. In this study, participant feedback was used alongside performance and survey measures to better understand why particular display formats supported or hindered EVA telemetry monitoring.

Situation awareness is also central to EVA telemetry monitoring. Situation awareness involves the perception of relevant elements in the environment, comprehension of their meaning, and projection of their future status [9]. For flight controllers, this means understanding the current state of suit and mission systems, recognizing changes over time, and anticipating the implications of off-nominal trends. Display format can influence these processes by shaping which parameters are visually salient, how relationships among data are represented, and how easily operators can move between detailed parameter checks and broader system level understanding.

A related design challenge is balancing information richness with operator comprehension. Modern telemetry systems can create human factors risks when information is difficult to integrate or interpret [10]. Synoptic displays provide an integrated visual representation of system state by organizing information according to system structure, function, or flow rather than presenting telemetry as isolated numeric values. To this end, synoptic display concepts can improve access to higher level system information, but they require careful visual organization, so aggregation does not obscure important details or create overreliance [11]. These findings are directly relevant to EVA telemetry, where flight controllers may need to monitor suit status, consumables, physiological indicators, vehicle or surface-system interfaces, timelines, and caution and warning information simultaneously.

Research on display technologies in spaceflight and aviation further reinforces the importance of visual organization, salience, and workload management. Augmented reality visor displays for EVA operations have used in-view guidance and spatial cues to support astronaut task performance [12]. Although this work focuses on astronaut-facing interfaces rather than controller-facing mission control displays, it illustrates the broader value of integrating contextual information into operational workflows. Head-worn displays in aviation can improve information access, but poorly designed symbology or cluttered overlays can increase attentional demands and reduce effective situation awareness [13]. These findings reinforce the need to design telemetry displays that provide useful information without increasing visual or cognitive burden.

Usability and workload measurement are also central to evaluating candidate display designs. Validated usability and user experience methods provide a structured basis for assessing both subjective and objective aspects of interface performance [14]. Measures such as system usability scales and workload assessments are useful because they capture how operators perceive an interface in addition to how they perform with it. For EVA telemetry displays, both types of evidence are important. A display that enables fast anomaly detection may still impose high workload, while a

display that feels easy to use may not support the fastest response to time critical events. Evaluating both performance and perception is therefore necessary for understanding display design tradeoffs.

Future Artemis EVA operations will also occur within a more integrated surface architecture than current International Space Station (ISS) EVA operations, which provide the basis for current mission control telemetry displays. EVA will interface not only with spacesuit systems, but also with lander systems, surface mobility assets, payloads, and other lunar surface infrastructure. NASA's Extravehicular Activity and Human Surface Mobility Program identifies Exploration EVA suits, the Lunar Terrain Vehicle, and the Pressurized Rover as key elements of future surface operations, and related compatibility standards describe EVA as a capability that must integrate with Gateway, Human Landing System, surface mobility systems, surface habitation systems, payloads, and other lunar assets [15, 16]. This broader operational architecture reinforces the need for telemetry displays that support suit monitoring while also helping mission control operators integrate information across multiple systems during real-time decision support.

Although the literature provides strong theoretical and operational grounding, several gaps remain. Much of the existing spaceflight display research focuses on astronaut-facing displays, pilot displays, head-up or head-worn displays, and onboard systems. However, controller-facing telemetry displays used by ground-based EVA flight controllers have received less empirical attention. These operators work within multi-role decision environments, interpret high density telemetry across multiple systems, and coordinate responses under procedural and time constraints, making controller-facing display evaluation a necessary step in preparing telemetry architectures for Artemis EVA operations.

There is also limited empirical work evaluating high density, multi-stream telemetry interfaces under mission representative conditions. Many display principles have been studied in aviation, nuclear operations, healthcare, and other high consequence domains, where visual display design is used to support information interpretation, situation awareness, and safe decision making [17,18,19]. However, they are less often tested in mission control environments using realistic telemetry and expert flight controllers. In addition, relatively little work has examined how layered information structures, synoptic displays, and context-dependent visual cues affect workload, usability, and situation awareness in EVA mission control settings. Artemis EVA operations further increase the importance of this issue because future missions are expected to involve larger and more integrated telemetry sets across spacesuits, landers,

rovers, and other surface systems. As a result, display architectures must support both rapid anomaly recognition and low workload access to detailed information.

The present study addresses these gaps by evaluating three prototype EVA telemetry display formats in an operationally representative mission control training environment. The instrument panel, schematic, and tabular displays each represent a different approach to organizing the same telemetry information. By comparing these displays using response time, anomaly event detection, usability, workload, and situation awareness measures, this study provides empirical evidence to inform the design of controller-facing telemetry display architectures for Artemis EVA operations.

III. Methods

An experiment was conducted to evaluate participant performance and perceptions across the three prototype EVA telemetry display interfaces for mission control operations. The study used a within-subjects design in which each participant interacted with all three display formats: instrument panel, schematic, and tabular. Display order was varied across sessions to reduce potential order and learning effects. The study received approval from the Colorado State University Institutional Review Board (IRB) under Protocol #7517.

A. Participants

A total of 20 participants completed the study. All participants were Mission Control Center (MCC) flight controllers at NASA Johnson Space Center in Houston, Texas. Participants varied in MCC experience, ranging from less than one year to 25 years (mean = 9 years, standard deviation = 8.5 years). This range allowed the evaluation to include both newer and more experienced operators, capturing potential differences in familiarity with traditional alphanumeric telemetry formats that could influence usability, workload, and response behavior.

B. Displays

Three telemetry display formats were developed for this study: instrument panel, schematic, and tabular. These displays were based on subject-matter expert interviews synthesized in prior work on human-centered telemetry display design for NASA exploration missions [20]. Each display presented the same underlying ISS Extravehicular Mobility Unit (EMU) suit telemetry data but used a different visual organization strategy. This allowed the study to isolate the effect of display format while holding the telemetry content constant.

The instrument panel display (see Figure 1) presented telemetry through graphical elements such as gauges, bars, thermometers, switches, oxygen tanks, and battery indicators. This format was intended to support rapid visual interpretation of system status and anomaly recognition.



Fig. 1 Example of instrument panel display.

The schematic display (see Figure 2) mapped telemetry values onto an EMU suit schematic, positioning data near the corresponding suit components or sensor locations. This format was intended to support spatial understanding of system relationships and to help users connect telemetry values to physical suit architecture.

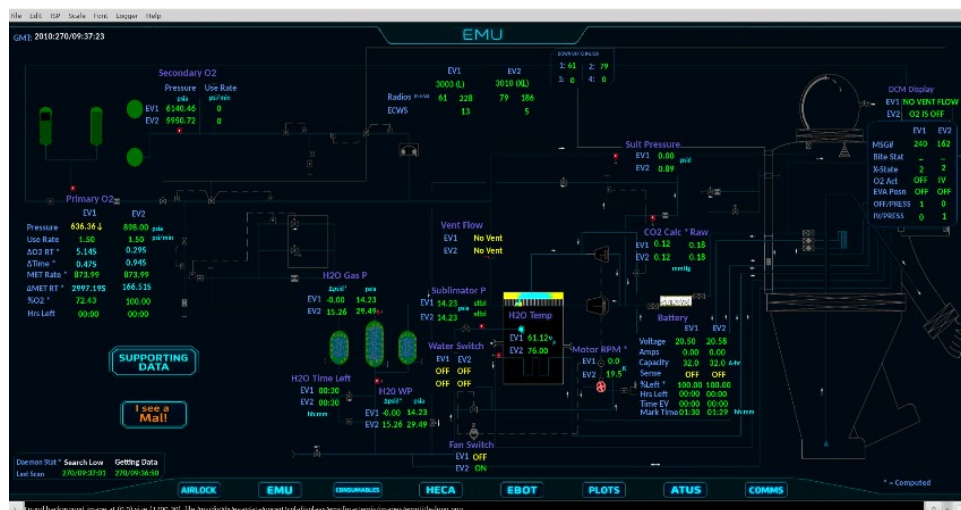


Fig. 2 Example of schematic display.

The tabular display (see Figure 3) resembled the legacy alphanumeric EMU display used for ISS mission operations. However, related data were grouped into titled sections, and the display used a modernized color-coding scheme that differed from the legacy design. This format was intended to preserve the familiarity of tabular telemetry while improving organization and readability.



Fig. 3 Example of tabular display.

C. Procedure

The study was conducted across three sessions in the Flight Controller Part Task Trainer (FCPTT) at NASA Johnson Space Center. Four participants completed the first session, eight completed the second session, and eight completed the third session. Each participant completed one session lasting approximately 90 minutes. Each session used a different display order so that the sequence of instrument panel, schematic, and tabular displays varied across participants.

Participants were seated at individual FCPTT simulation consoles, with a study facilitator positioned at the back of the room. The simulation used ISS EMU suit maintenance tasks that are regularly used for flight controller training. Live suit data from the simulation were presented on each participant's console using the display format being tested. Each participant completed three trials, one for each display type.

Participants were instructed to monitor suit and vehicle systems during the EMU suit maintenance tasks. During each trial, one safety critical anomaly event was programmed to occur at a randomized time. Examples of anomaly events included oxygen pressure or water temperature moving outside normal operating thresholds. Participants were instructed to press a response button on the display when they detected the anomaly event. The button was embedded in each display and was visually distinguished using a blue border and bright orange text reading "I see a Mal!" Each button press automatically generated a timestamp that was logged by the server. This button is visible on each of the display screenshots provided in Figures 1-3.

After each trial, participants completed short post scenario surveys about their experience using the display. These surveys included the NASA Modified System Usability Scale (NMSUS) [21], NASA Task Load Index (NASA-TLX) workload questions [22], and Situation Awareness Global Assessment Technique (SAGAT) questions [23]. These measures were selected to capture both objective task performance and subjective operator experience across the three display formats.

D. Independent Variables

The independent variable in this study was telemetry display type, with three levels: instrument panel, schematic, and tabular. Each participant interacted with all three display styles in a randomized within-subjects design. This design allowed for evaluation of how display format influenced response time, workload, usability, and situational awareness under operationally realistic FCPTT simulation conditions while reducing variability caused by individual differences in experience, monitoring strategy, or familiarity with EVA telemetry.

E. Dependent Variables

Five dependent variables were measured to capture participant performance and perceptions. Performance measures included response time and anomaly event detection. Perception measures included display usability, perceived workload, and situation awareness.

Response time was measured in seconds from the onset of the anomaly event to the participant's button press indicating detection. Shorter response times indicated faster anomaly recognition. Response time was calculated using automatically logged timestamps from the MCC simulation computers.

Anomaly event detection was measured as a binary variable indicating whether the participant detected the anomaly event during each trial. Responses occurring more than 60 seconds after anomaly onset were coded as misses. Detection performance was analyzed separately from response time because a participant could either fail to detect the event within the defined response window or detect it with varying speed.

Display usability was measured using the eight NMSUS items on a five-point Likert scale ranging from strongly disagree to strongly agree. Half of the items were reverse coded. A composite usability score was computed by summing the coded item responses and multiplying by 3.125, yielding possible scores from 0 to 100, where higher scores indicated greater perceived usability.

Perceived workload was measured using the six NASA-TLX items on an 11-point scale from 0, indicating not at all, to 10, indicating extremely. An average workload score was computed across the six items, with possible scores ranging from 0 to 10. Higher scores indicated greater perceived workload.

Situation awareness (SA) was measured using four SAGAT questions per display trial, where each display had a different set of SAGAT questions so that participants could not rely on recall from previous trials or anticipate repeated questions. Each question was multiple choice with one correct answer. Scores ranged from 0 to 4, with higher scores indicating greater situation awareness.

F. Data Cleaning and Analysis

Data cleaning and analysis were performed using Microsoft Excel and RStudio. Statistical significance was assessed using $\alpha = 0.05$. Repeated measures analyses of variance (ANOVAs) were used to evaluate the effect of display type on response time, usability, perceived workload, and SA while accounting for the within-subject design. When significant main effects were observed, Tukey-adjusted post hoc comparisons were used to evaluate pairwise differences between display types.

For response time, only trials in which participants detected the anomaly event within 60 seconds were included in the analysis. This ensured that response time results reflected detection speed rather than missed events. Since anomaly detection was a binary outcome, it was analyzed using a mixed effects binary logistic regression model rather

than an ANOVA. In this model, display type was included as a fixed effect, and participant was included as a random intercept.

IV. Results

Results are presented by dependent variable. Response time and anomaly event detection are reported first as measures of operator performance, followed by display usability, perceived workload, and situation awareness as measures of participant perception and cognitive state. This structure aligns with the study objectives of evaluating both performance differences and human-centered design tradeoffs across the three display formats.

A. Response Time

Response time differed significantly by display type, $F(2, 35) = 64.86$, $p < 0.001$. Mean response time was fastest for the instrument panel display, followed by the schematic display, and slowest for the tabular display. Tukey-adjusted post hoc comparisons indicated significant differences between all display pairs: instrument panel and schematic ($p < 0.001$), instrument panel and tabular ($p < 0.001$), and schematic and tabular ($p < 0.001$), as shown in Figure 4.

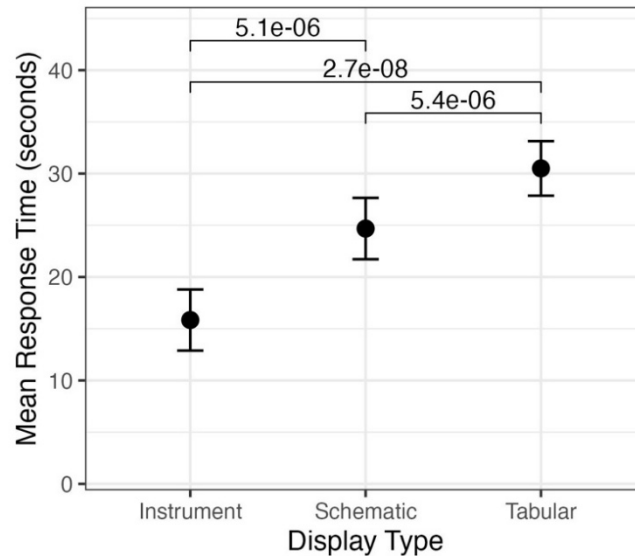


Fig. 4 Mean response time with 95% CI by display type for anomaly detection event

B. Anomaly Event Detection

Anomaly event detection was high across all three display types. As shown in Figure 5, the proportion of participants who detected the anomaly event was similar for the instrument panel, schematic, and tabular displays.

Detection was slightly lower for the tabular display, but the mixed-effects binary logistic regression model showed no significant fixed effect of display type on detection performance. These results indicate that participants were similarly likely to detect the anomaly event across the three display formats, even though response time differed significantly by display type.

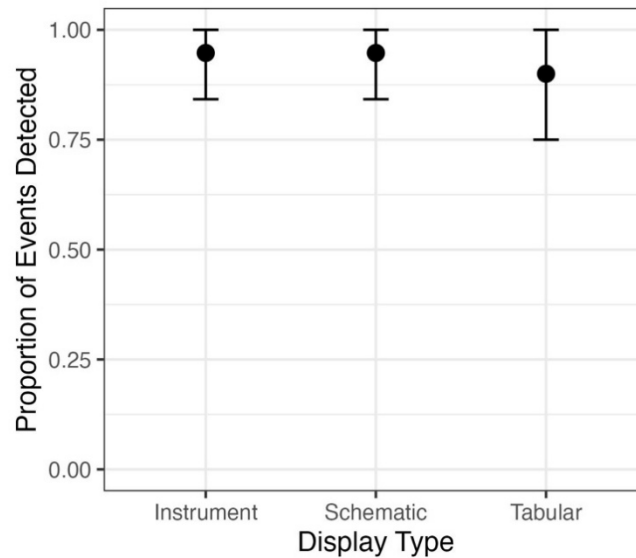


Fig. 5 Proportion of anomaly events detected with 95% CI by display type.

C. Display Usability

Perceived usability, as measured by the NMSUS, differed significantly by display type, $F(2, 53) = 19.50$, $p < 0.001$. The tabular display received the highest usability ratings, followed by the instrument panel display and then the schematic display. Pairwise comparisons showed that the tabular display was rated significantly higher than both the instrument panel and schematic displays ($p < 0.001$). The instrument panel and schematic displays did not significantly differ from one another ($p = 0.082$), as shown in Figure 6.

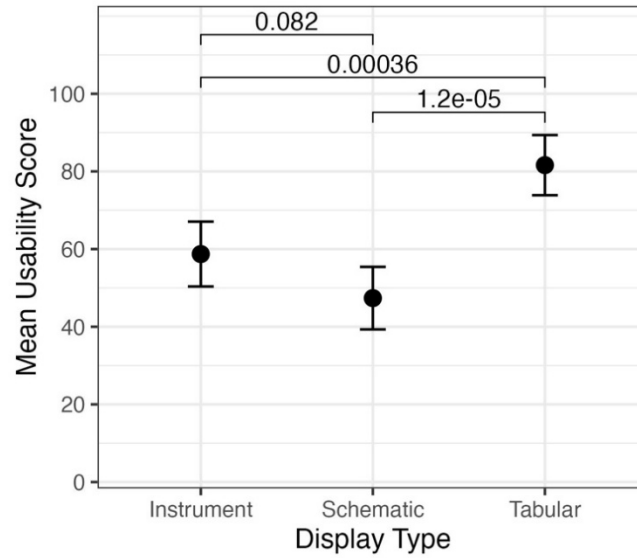


Fig. 6 Mean usability score with 95% CI by display type.

D. Perceived Workload

Display type had a significant effect on perceived workload, as measured by the NASA-TLX, $F(2, 36) = 13.46$, $p < 0.001$. Participants reported the lowest workload when using the tabular display and the highest workload when using the schematic display. Pairwise comparisons showed that the tabular display produced significantly lower workload ratings than both the schematic display ($p < 0.001$) and the instrument panel display ($p = 0.002$). The instrument panel and schematic displays did not significantly differ from one another ($p = 0.18$), as shown in Figure 7.

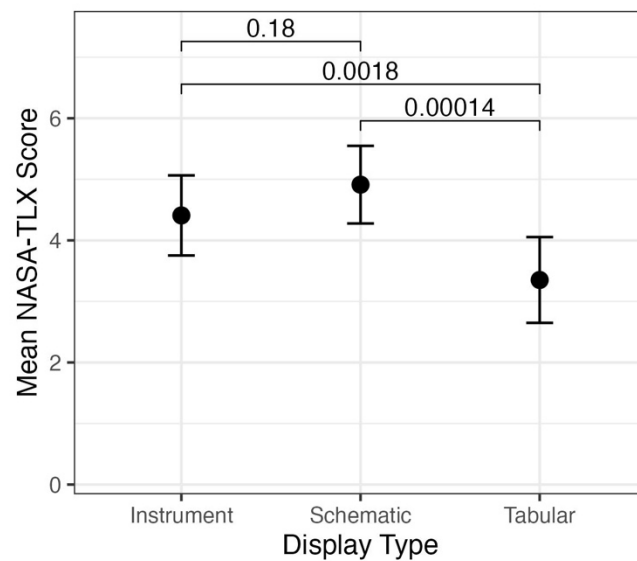


Fig. 7 Mean workload score with 95% CI by display type.

E. Situation Awareness

Situation awareness, as measured by the SAGAT questions, did not significantly differ by display type, $F(2, 45) = 0.33$, $p = 0.723$. Mean SAGAT scores were similar across the instrument panel, schematic, and tabular displays, as shown in Figure 8. These results indicate that display type did not significantly affect participants' situation awareness scores in this study.

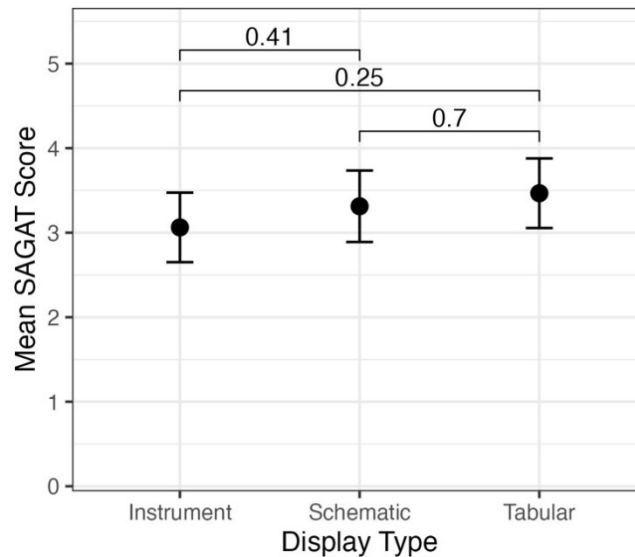


Fig. 8 Mean SAGAT score with 95% CI by display type.

F. Summary of Findings

A synthesis of the results is provided in Table 1. The tabular display received the highest usability ratings and lowest workload ratings but was associated with the slowest response times. In contrast, the instrument panel display was associated with the fastest response times and ranked in the middle for usability and workload. The schematic display generally produced less favorable perception outcomes, with the lowest usability ratings and highest workload ratings. Situation awareness scores and anomaly event detection rates were similar across the three displays, with no display showing a significant advantage for these outcomes.

Table 1 Summary of performance and perception outcomes by display type

Dependent Variable	Instrument Panel Display	Schematic Display	Tabular Display
Response Time	Best (fastest)	Middle	Worst (slowest)
Usability	Middle	Worst (lowest)	Best (highest)

Workload	Middle	Worst (highest)	Best (lowest)
Situation Awareness	Similar	Similar	Similar
Anomaly Event Detection	Similar	Similar	Similar

V. Discussion

The results demonstrate that telemetry display format can influence operator performance and perception during EVA monitoring tasks. Although anomaly event detection and situation awareness scores were similar across the three display types, response time, perceived workload, and usability differed significantly. These findings suggest that display format may not determine whether operators eventually detect an anomaly under the conditions tested, but it can affect how quickly they respond and how usable or workload intensive the display feels during monitoring.

The instrument panel display produced the fastest response times. This result suggests that graphical, object-based visual elements such as gauges, bars, tanks, and thermometers may support rapid perceptual recognition of abnormal system states. In time constrained EVA operations, this type of visual organization may help operators identify changes quickly because critical parameters are represented through familiar status indicators rather than primarily through numeric values. This finding aligns with prior human factors work emphasizing perceptual organization, visual salience, and rapid interpretation in complex telemetry environments [10,11].

In contrast, the tabular display produced the highest usability ratings and lowest perceived workload, despite producing the slowest response times. This contrast suggests that the display perceived as easiest to use may not be the display that best supports rapid anomaly response. One likely explanation is participant familiarity. Prior work on technology acceptance has identified past experience and perceived ease of use as factors that can influence users' acceptance of and reliance on automated or technical systems [24]. Many MCC flight controllers have prior experience with traditional alphanumeric or tabular telemetry displays used for ISS operations, and the tabular display evaluated in this study more closely resembled those familiar operational formats than either the instrument panel or schematic displays. This familiarity may have contributed to higher usability ratings and lower workload ratings, even though the format required more time for anomaly recognition. Prior remote operation interface research also shows that interface design can affect operator cognitive workload under varying task demands [25]. The tabular display may therefore remain valuable for tasks that require detailed verification, parameter comparison, or low workload access

to stable system information. However, the slower response times suggest that tabular displays may be less effective as the primary display format for time-critical anomaly recognition.

The schematic display did not show a clear advantage in the measured outcomes. Although the schematic format was designed to support spatial understanding by mapping telemetry values onto the EMU suit layout, it produced the lowest usability ratings and highest workload ratings. This may reflect the additional cognitive effort required to integrate spatial layout, numeric values, and system relationships during real-time monitoring. Similar concerns have been raised in display research on head-worn and visually rich interfaces, where increased information availability can create attentional demands if symbology, layout, or hierarchy are not carefully designed [13]. The schematic display may still have value for subsystem level reasoning, troubleshooting, or training contexts where understanding physical relationships is more important than rapid detection. However, the present results suggest that the schematic design would require refinement before serving as a primary operational monitoring display.

The similarity in anomaly event detection across display types provides an important contrast to the response time findings. Participants were generally able to detect the anomaly event regardless of display format, but the time required to respond differed substantially. This indicates that the displays supported eventual detection under the tested conditions but differed in the efficiency of anomaly recognition. For EVA mission control, this distinction is operationally meaningful because delayed recognition of off-nominal telemetry may reduce the time available for diagnosis, coordination, and response.

Situation awareness scores also did not differ significantly across display types. One possible explanation is that all three displays contained the same underlying telemetry information, which may have allowed participants to maintain similar understanding of system state despite differences in visual format. Another possibility is that the SAGAT questions captured broad system understanding rather than display specific differences in information access or interpretation. Therefore, the lack of a significant situation awareness effect should not be interpreted as evidence that display format has no effect on operator cognition. Rather, within the scope of this study, display format affected response speed, workload, and usability more clearly than it affected the measured situation awareness outcome.

These findings align with prior work showing that display design influences workload, situation awareness, and operator performance in high consequence operational environments. In aviation, iteratively designed head-up displays have been shown to support workload management and situation awareness under degraded visual conditions [26]. In aerospace remote monitoring contexts, three-dimensional visualization and virtual reality displays have also

been explored as ways to support operator understanding of complex system states [27]. The present results extend this broader display design literature to controller-facing EVA telemetry displays by showing that visualization format can produce measurable tradeoffs between response time, workload, and perceived usability.

These findings highlight a central design tradeoff for Artemis EVA telemetry displays. Instrument style displays may better support rapid anomaly recognition, while tabular displays may better support usability, familiarity, and lower perceived workload. No single display format optimized all outcomes. A hybrid display architecture may therefore provide the most operationally useful approach by combining the rapid perceptual advantages of instrument style views with the organizational clarity and familiarity of tabular views. Schematic views may be most useful when incorporated selectively for subsystem context, physical mapping, or troubleshooting support rather than as the primary monitoring interface.

These results extend prior work on human-centered telemetry display design by providing empirical evidence from mission control flight controllers using operationally representative simulation data. They also reinforce the need to evaluate display concepts using both performance and perception measures. If only response time were considered, the instrument panel display would appear most effective. If only usability or workload were considered, the tabular display would appear most effective. Considering these outcomes together provides a more complete basis for refining future EVA telemetry display architectures.

A. Recommendations

The findings support several recommendations for future EVA telemetry display development. These recommendations reflect the observed tradeoffs among response time, anomaly event detection, usability, perceived workload, and situation awareness, while also considering the likely influence of operator familiarity with traditional alphanumeric telemetry formats.

First, instrument panel displays should be considered for primary real-time monitoring tasks where rapid anomaly recognition is critical. The instrument panel display produced the fastest response times while maintaining high anomaly detection and comparable situation awareness scores. This format appears well suited for time critical monitoring, single parameter trend awareness, and initial fault recognition.

Second, tabular displays should be considered as secondary or supporting views for detail rich monitoring tasks. The tabular display produced the highest usability ratings and lowest perceived workload, suggesting value for detailed

status checks, parameter comparison, and stable phases of operations. However, because this display was associated with the slowest response times, it may be less appropriate as the primary interface for time critical anomaly detection.

Third, schematic displays should be refined before operational adoption as primary monitoring displays. Although the schematic display may support system level understanding by mapping telemetry to physical suit architecture, it produced the highest workload ratings and lowest usability ratings in this study. Future iterations should reduce visual complexity, improve hierarchy, and clarify the relationship between spatial layout and actionable telemetry information.

B. Limitations and Future Work

Several limitations should be considered when interpreting these findings. First, the study used ISS EMU telemetry within FCPTT simulations. Although these data provided a realistic operational load for mission control flight controllers, future Artemis EVA operations are expected to involve broader and more integrated telemetry sets, including exploration suit architectures, lander interfaces, lunar surface mobility systems, and other surface assets. As a result, the trends observed in this study may not fully capture the cognitive and operational demands of next-generation lunar surface EVA operations.

Second, although the participants were actual MCC flight controllers with a wide range of operational experience, the study included 20 participants. This sample provided valuable expert user feedback, but future studies with larger participant groups would support stronger statistical power and allow more detailed analysis of experience level, console role, training background, and prior familiarity with different display formats.

Third, each trial included a single programmed anomaly event. This controlled design enabled direct comparison across display formats, but it may underrepresent the complexity of actual EVA operations, where multiple off-nominal indications, parallel timelines, competing communication demands, and multi-console coordination may occur simultaneously. Future evaluations should include more complex anomaly scenarios, multiple telemetry trends, and tasks requiring coordination across flight control roles.

Finally, display familiarity may have influenced participant perceptions. Many flight controllers have prior experience with alphanumeric or tabular telemetry formats used in ISS operations, which may partly explain the higher usability ratings and lower workload ratings for the tabular display despite its slower response times. Future work should include longer training periods, repeated exposure to each display type, and longitudinal evaluation to

determine whether usability, workload, and response time differences persist as operators become more familiar with newer display formats.

Future work should evaluate implementation paths for Artemis EVA telemetry displays, including separate displays for different operational needs, a hybrid display architecture, or a single tabular format for simplicity and maintainability. Based on the present findings, a hybrid architecture may provide the most balanced path by combining instrument style visual cues for rapid anomaly recognition, tabular organization for detailed status verification, and schematic views for subsystem level reasoning or troubleshooting. Future design iterations should evaluate whether such layered or integrated architectures improve response speed while preserving usability and manageable workload. They should also consider development cost, training burden, scalability, and operational effectiveness before final adoption.

VI. Conclusion

This study evaluated three controller-facing EVA telemetry display concepts using ISS EMU simulation data, mission control training scenarios, and feedback from experienced MCC flight controllers. The results showed that display format significantly affected response time, perceived workload, and usability, while anomaly event detection and situation awareness were similar across the instrument panel, schematic, and tabular displays.

The findings highlight an important design tradeoff for future Artemis EVA telemetry displays. The instrument panel display supported the fastest anomaly response, suggesting value for time critical monitoring and rapid recognition of off-nominal conditions. The tabular display produced the highest usability ratings and lowest perceived workload, suggesting value for detailed status checks, parameter comparison, and lower workload monitoring. The schematic display provided a spatial representation of suit telemetry, but its higher workload and lower usability ratings indicate that further refinement is needed before it can support primary monitoring tasks.

Overall, these results show that no single display format optimized all performance and perception outcomes. Future Artemis EVA telemetry architectures may benefit from hybrid or layered approaches that combine rapid visual cues, familiar tabular organization, and selective schematic context. By grounding display evaluation in operationally representative simulation data and actual flight controller feedback, this work provides empirical guidance for refining next generation EVA telemetry displays that support operator performance, workload management, and real-time decision support during lunar surface operations.

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