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Integrating Human Factors in Protocol Design: Decision Strategies in Digitalized Simulation Environments

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Abstract

INTRODUCTION: In high-stakes industrial and operational contexts, such as aerospace, human factors heavily influence effectiveness under uncertain and dynamic conditions. Integrating simulation-based environments and digital tools in protocol development provides a valuable lens through which to assess cognitive and behavioural responses. As digitalization and Industry 4.0 accelerate the shift toward cyber-physical and human-in-the-loop systems, it becomes essential to understand how decision-making is affected in such digitalized settings.
OBJECTIVES: This study aims to analyse the impact of uncertainty, time pressure, and cognitive complexity on human decision-making during protocol implementation in a simulated space mission. It also explores the implications of these insights for the design of digitalized, human-centred protocols pertinent to industrial transformation scenarios.
METHODS: A mixed-methods approach was employed. Participants took part in a simulated space mission scenario using pre-defined protocols within a controlled, uncertainty-driven environment. Behavioural responses, timing, deviations, and verbal feedback were recorded and analysed. The quantitative data were supplemented with qualitative insights from participant interviews and session logs.
RESULTS: Findings indicate operational uncertainty and time constraints significantly influenced participants' decision pathways. Deviations from scripted protocols revealed how stress and perceived role clarity influence real-time choices. Furthermore, the analysis contextualizes these findings within Industry 4.0 frameworks, highlighting parallels with decision-making challenges in smart manufacturing, digital twin monitoring, and automated safety systems.
CONCLUSION: The results underscore the necessity of embedding human-centred principles in protocol design, particularly when deploying digital technologies in complex, mission-critical environments. The study provides strategic recommendations for integrating adaptive, resilient, and cognitively compatible decision support tools into digitally transformed industrial processes.

Keywords: Analog Missions, Communication Delay, Decision-Making, Digital Twins, Human-Machine Interaction, Industry 4.0, Interface Design, Protocol Design

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1. Introduction

Human decision-making in extreme environments such as space missions or remote industrial operations presents one of the most complex and risk-intensive challenges in systems engineering. In these contexts, prolonged isolation, communication delays, cognitive overload, and operational uncertainty can impair mission safety and effectiveness [1,2]. Traditional command-and-control protocols often prove inadequate in high-autonomy scenarios, where decision support must dynamically adapt to human and environmental variables.

To address these challenges, analog space missions have emerged as valuable platforms for simulating human-in-the-loop systems. These Earth-based simulations reproduce extra-terrestrial environments' physical, psychological, and

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procedural stressors, offering a controlled setting to assess operational strategies and team performance [2,3]. Examples include the CHILL-ICE campaign (Construction of a Habitat Inside a Lunar-analogue Lava-tube), conducted in Iceland's lava tubes under time constraints and adverse conditions. Similarly, missions such as the Underground Lunar Extravehicular Simulation and other Mars Desert Research Station campaigns systematically investigate behavioural responses to delayed communications and operational uncertainty [3].

Despite these advances, integrating human performance insights into digitally enabled protocols, especially those aligned with Industry 4.0 principles, remains underexplored. Cyber-Physical Systems (CPS), real-time monitoring, and protocol automation are becoming essential in aerospace and high-reliability industries. However, translating biometric and cognitive performance data into real-time adaptive decision-support tools poses conceptual and technical challenges [4]. Operator-focused CPS research demonstrates that adaptive interfaces and sensing-based risk models can significantly enhance system resilience and situational awareness [5].

This study frames analog space missions as high-fidelity environments for testing digitally supported operational protocols. Drawing on principles of Industry 4.0, such as human-centred automation, real-time analytics, and digital twins, it proposes a structured experimental design for embedding human factors into mission-critical decision-making. The extended protocol combines biometric stress tracking, structured communication interfaces, and time-delayed collaborative tasks to evaluate how teams manage uncertainty and performance under high-stakes conditions.

Unlike previous protocols, which focused on asynchronous communication or delay management in isolation, this approach offers a comprehensive framework for evaluating how interface design, communication latency, and time-critical decisions interact to shape performance and team dynamics.

Transitioning from low Earth orbit operations to deep-space missions and high-autonomy industrial environments presents new cognitive, operational, and human-machine interface (HMI) challenges. These missions and systems increasingly demand independent decision-making, stress-resilient behavior, and intuitive communication protocols. The emerging paradigm of Industry 4.0 and its applications in space and industrial processes further amplify the need for digitized, human-centric performance models [6].

Over decades, robotics, artificial intelligence (AI), and interface design innovations have shaped human spaceflight and industrial automation. In long-duration or high-risk scenarios, the cognitive and psychological states of the operators play a vital role in ensuring safe and effective outcomes [7,8]. Consequently, modern systems demand technical robustness and seamless human integration, particularly in environments characterized by stress, ambiguity, or delayed feedback [9].

To better prepare for the challenges of space exploration, missions that share similarities to space conditions are conducted on Earth – analog missions. These missions have long been employed to simulate space missions' stressors, delays, and isolation. They provide valuable insights into how human crews adapt to extreme conditions, particularly when real-world testing is impractical or dangerous [10]. However, their potential as experimental platforms for testing digitalized decision-support systems and adaptive protocols remains underexplored. In light of Industry 4.0 priorities, these simulations offer a fertile ground for testing cyber-physical systems, interface adaptations, and behavioural monitoring tools [11,12].

This paper proposes and tests an extended protocol to simulate human performance and communication in time-delayed, high-stakes environments. It integrates biometric stress tracking, structured communication interfaces, and experimental team-based problem-solving tasks. Although previous protocols have examined asynchronous communication elements, none have systematically investigated the combined impact of communication delays on task performance, team dynamics, and cognitive load under conditions that simulate urgency and high operational stakes. This protocol addresses that gap by offering a structured approach to replicate real-world stressors, enabling a more holistic assessment of communication tools and their influence on space mission effectiveness.

To better simulate the urgency and high-stakes nature of spaceflight conditions, this paper introduces a protocol designed for use in future analog studies. The protocol is intended to evaluate team dynamics, decision-making, and task performance in the presence of communication delays, while also examining how practical interface design can help mitigate these challenges and support mission effectiveness. Drawing on prior research [13] that emphasizes the importance of structured text-based communication, this approach incorporates innovative interface solutions to improve collaboration in delayed communication scenarios. By embedding dynamic, time-critical tasks and systematically applied communication delays, the protocol increases ecological validity and accurately reflects the cognitive demands, operational pressures, and decision-making challenges encountered during real space missions.

The results are framed within a Digital Twin-inspired approach, aligning with Industry 4.0's core principles, including human-in-the-loop systems, cyber-physical simulations, and cognitive-aware interfaces [6,10-12]. While space analog missions remain the focal setting of this study, the results have broader implications for domains facing similar digital and operational stressors, such as autonomous logistics, offshore energy, and remote healthcare. By simulating urgency, cognitive workload, and communication breakdowns, this work aims to advance the design of resilient human-machine protocols for future-ready industrial systems.

To this end, the study proposes a structured protocol to investigate how communication delays impact task performance and team dynamics in simulated space flight scenarios. Specifically, it explores whether more structured communication interfaces, such as email-like tools, can mitigate these effects. The protocol was designed in response to previous findings [13] and is structured based on the following objectives (SOi):

SO1: Measure the impact of time-delayed communication on task performance in time-critical scenarios.

SO2: Examine changes in team dynamics, problem-solving strategies, and leadership behaviours in delayed vs. real-time contexts.

SO3: Evaluate how interface design (chat-like vs. email-like tools) influences team effectiveness under different communication latencies.

SO4: Assess perceived stress and cognitive workload using physiological and self-reported data.

These objectives frame the experimental design subsequently presented in the following sections.

2. Background

To contextualize the protocol, this section reviews research on human performance in extreme environments, decision-making interfaces under pressure, and the role of human factors in digitalized industrial systems, highlighting how communication delays, cognitive load, and adaptive technologies shape high-stakes operations.

2.1. Human performance in isolated and delayed conditions

Isolated, confined, and extreme (ICE) environments such as space missions, polar research stations, submarines, and long-duration offshore installations present unique challenges to human performance. These contexts often share a set of stressors: restricted movement, limited social interaction, high operational stakes, and, critically, delays in communication with decision-support authorities [14]. In deep-space exploration, decision-making and communication errors are among the most critical contributors to mission mishaps [15]. Furthermore, communication delays between Earth and spacecraft will increase with mission altitude, reaching up to 20 minutes one way on Mars missions. This latency restricts synchronous dialogue and increases the cognitive and emotional burden on astronauts, who must operate with greater autonomy [16]. Past research from NASA's HERA and NEEMO projects has shown that these delays can compromise task performance and team cohesion if not properly mitigated [13].

Recent research has highlighted the interplay between isolation, uncertainty, and cognitive performance. A 2024 study [17] demonstrated that even short communication delays can significantly impair trust between remote team members, increasing error rates in collaborative decision-making. Similarly, another study [18] found that latency correlates with increased cognitive workload and frustration, especially in mission-critical simulations.

In addition, psychological stress from isolation, workload pressure, and reduced support leads to reduced resilience and increased likelihood of errors, emphasizing the importance of individual adaptability, team composition, and support strategies in maintaining performance during long-duration missions [18]. These findings are equally relevant to industrial sectors where shift work, automation, and remote control are the norm.

2.2. Interface design for decision-making

Interface ergonomics and feedback timing are essential for maintaining situational awareness. Poor interfaces can amplify cognitive overload for operators under time pressure and lead to communication breakdowns. Because of this, human-machine interface (HMI) design has advanced considerably in recent years, moving toward adaptive systems that respond in real-time to user states such as stress, workload, or error patterns. Similar principles in manufacturing or emergency response settings are now being embedded into digital control panels and wearable displays to improve operator engagement and clarity [19,20].

The design of communication and operational interfaces is central in determining task success, particularly under high workload or time-delayed conditions. In the space sector, structured communication protocols, such as those tested during NEEMO-18 and NEEMO-19, focused on enabling distant collaboration in asynchronous systems, have been developed. Although this research suggests that these protocols help remote team members keep track of conversational threads and the temporal sequence of messages, it also proposes further improvements, such as a less chat-like and more email-like text tool. This would allow features like subject headers and links between related messages to make it easier for conversational partners to follow a conversational thread. that include subject headers, message linking, and visual status indicators [13].

In high-risk domains like aerospace and energy, efforts are underway to develop interfaces that dynamically adjust based on operator state. Recent research [21] introduces an interface that adapts text density and alert frequency in real time based on biometric stress markers, showing improved user experience and decision accuracy in simulated emergencies.

2.3. Digitalization and Industry 4.0 applications

Industry 4.0 marks a transformative phase in industrial development characterized by the fusion of digital and physical systems, widespread connectivity, and real-time data processing. Key components include the Internet of Things (IoT), AI, Additive Manufacturing, and, increasingly, the concept of Digital Twins (DT), which are virtual replicas of physical systems that can simulate, predict, and optimize performance in real-time. Recent literature focuses on incorporating human behavioural models into digital twins to create adaptive and safe work environments. This includes modelling stress and workload as input parameters for system optimization [22,23].

For example, a framework for stress-sensitive machine scheduling in smart factories has been proposed using wearable biometric inputs to reassign tasks in real time [22]. Meanwhile, another study has illustrated how behavioural logs from analog simulations can be mapped onto predictive maintenance dashboards, improving system uptime and human operator support [23].

Additional literature has emphasized the role of implementation-oriented, real-time AI systems within DT frameworks. For instance, an incremental-learning DT for manufacturing processes that uses streaming data to model equipment states and perform real-time anomaly detection, enabling more flexible and effective performance monitoring, has been developed [24]. More recently, a diagnostic DT for a floating offshore wind turbine, using unsupervised learning on operational data to detect anomalies with high confidence well before failure, has been implemented [25].

These examples illustrate how integrating AI-driven decision loops into DT environments can directly enhance situational awareness and system resilience in operational contexts. They also demonstrate the timeliness and applicability of protocols like the one presented in this study, which blend behavioural observation with technical performance metrics under controlled experimental conditions. The study offers a test environment that mirrors complex, digitalized industrial settings by simulating time delays, capturing interaction patterns, and evaluating subjective workload. These insights can inform the design of future cognitive support tools, predictive alert systems, and adaptive HMIs used in autonomous production lines, control centres, and mission-critical environments.

3. Protocol design for analog studies

To operationalize the insights discussed previously, this section outlines a controlled experiment designed to test how communication latency and interface design affect task performance, cognitive workload, and team dynamics in analog mission settings.

Figure 1 presents a schematic overview of the experimental protocol illustrating the sequential structure of the study, including task assignments, communication modalities, interface types, and biometric monitoring used during the pilot implementation.

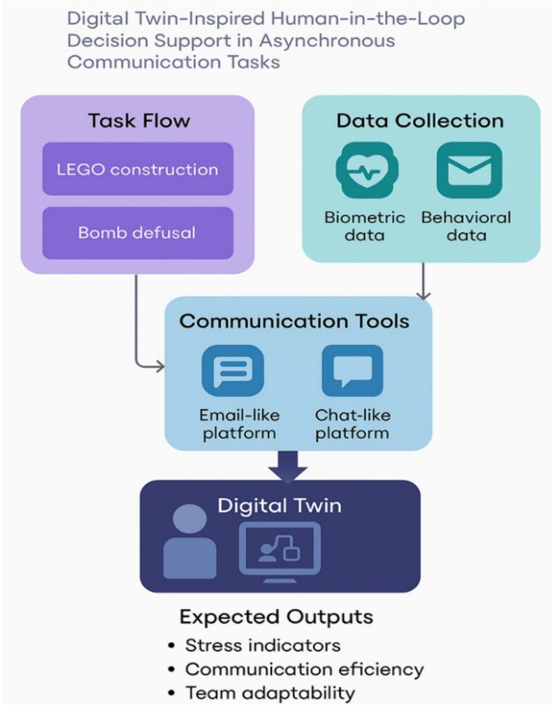

Figure 1. Schematic overview of the experimental protocol.

3.1. Experimental design

The protocol uses an experimental design intervention in which communication delay acts as the independent variable. Its effects on task performance, stress levels, and team dynamics, dependent variables, are assessed under a controlled environment. Two different tasks will be used to simulate high-stress and communication-dependent problem-solving:

(i) **LEGO Construction**: A physical assembly task requiring step-by-step instruction.
(ii) **Virtual Bomb Defusal Game:** A time-critical digital task (video game “Keep Talking and Nobody Explodes”) requiring fast, accurate coordination.

Participants are divided into two roles in both tasks: Crew (task execution) or Mission Control (instruction and support).

In the first task (LEGO construction), the crew is provided with the building pieces, and mission control has the instruction manual. Mission Control must send instructions remotely on how to build the structure, and the Crew is to build it accurately, within two hours. In the second task (Bomb Defusal Game), the Crew can see and interact with the bomb; however, like in the previous activity, only Mission Control can access the bomb defusal manual. The Crew has one hour to defuse the bomb, with only three mistakes allowed, otherwise, the bomb explodes.

The study population requirements for this study determine that participants must be over 18, give consent, and have no prior experience with the study tasks. A mix of genders and academic backgrounds is required for generalization. The only exclusion is health conditions that could be exacerbated by stress or cognitive load (e.g., severe anxiety disorders).

Sessions should be conducted in controlled laboratory settings, with each team isolated in separate rooms and monitored by facilitators. Two groups, one with a chat-like text tool and the other with an email-like text tool, will participate in LEGO construction and bomb defusal tasks under the condition of real-time communication to establish a baseline for comparison. The other groups will participate in each activity under the condition of delayed communication, some with a chat text tool and some with an email-like text tool.

3.2. Equipment and measurements

To evaluate performance, stress, and communication quality, a comprehensive suite of equipment should be used:

(iii) **Physical and digital material:** LEGO City Interstellar Spaceship (Ref. 60430), a moderately complex LEGO set; computer with the video game "Keep Talking and Nobody Explodes" (Microsoft Windows version) installed;

(iv) **Communication tools**: Two computers or tablets with access to a messaging app that allows for timed message delays and that has a subject feature (e.g., Google Groups) and chat-based communication tools;

(v) **Biometric sensors**: Biometric indicator devices (e.g., smartwatch) to capture heart rate and heart rate variability (HRV), which serve as physiological indicators of stress.

(vi) **Performance metrics**: *LEGO Task:* Task duration, number of errors (corrected and uncorrected), completion accuracy; *Bomb Defusal*: Number of mistakes, success/failure outcome, task duration.

(vii) **Communication metrics**: Message logs, time between response and instruction, number of clarifications, use of confirmation statements.

(viii) **Subjective measures**: NASA Task Load Index (NASA-TLX), post-task surveys, and qualitative feedback on perceived difficulty, communication quality, and stress.

3.3. Session workflow and procedures

Each experimental session should proceed in a standardized sequence as follows:

(i) **Briefing and Consent**: Participants receive a briefing on the study's purpose and procedures, sign the informed consent form to participate, and are placed in separate rooms.

(ii) **Training Phase**: Participants practice using the communication tools and receive an overview of the tasks (LEGO and game).

(iii) **Task 1:** LEGO Construction:

- Baseline session: Mission control provides step-by-step building instructions to the crew in real-time; The time taken, number of errors, and completion status should be recorded; Qualitative data on team dynamics and stress levels via surveys and interviews should be collected.
- Delayed communication session: A communication delay (e.g., 2 to 5 minutes) is to be implemented using the messaging app; Mission control sends instructions with the imposed delay to the crew; The same performance metrics and qualitative data as in the baseline session should be collected.

(iv) **Task 2:** Bomb Defusal Game

- Baseline session: Mission control provides step-by-step defusal instructions to the crew in real-time; The time taken to defuse the bomb, number of mistakes, and completion status should be recorded; Qualitative data on team dynamics and stress levels via surveys and interviews should be collected.
- Delayed communication session: A communication delay (e.g., 1 to 2 minutes) is to be implemented using the messaging app; Mission control sends defusal instructions with the imposed delay to the crew; The same performance metrics and qualitative data as in the baseline session should be collected.

Investigators are present in each room to ensure standardization and technical support.

3.4. Ethical considerations and risks

This protocol follows institutional ethical guidelines for research involving human participants and was reviewed and approved by the Ethics Committee of the University of Minho. All individuals must give informed consent. Participants will be briefed about their right to withdraw at any point, and breaks will be offered to mitigate stress. All data collection complied with the General Data Protection Regulation (GDPR), with participant identifiers anonymized, biometric data encrypted in secure storage, and access restricted to the research team.

There are minimal risks associated with this study. Participants may experience mild stress or frustration due to communication delays; however, breaks, water, and snacks will be provided, and participants may withdraw at any time.

3.5. Technical requirements

Table 1 details technical requirements to ensure consistency across sessions. These include standardized tools, controlled environments, and contingency support during data collection.

Table 1. Technical requirements for future analog studies.

Category	Requirement
Task Setup	Standard LEGO set; pre-configured video game (Keep Talking and Nobody Explodes).
Communication Setup	Real-time and delayed communication tools tested for functionality. For delayed communication, manual delays of 2 minutes during the LEGO task and 1 minute during the bomb task shall be introduced on Google Groups and Google Chat.
Data Collection	Metrics on task performance, communication logs, and stress indicators to be collected.
Environment	Controlled rooms with consistent lighting. Ensuring no interruptions from external sources, verified by session facilitators.
Participant Management	Training sessions, informed consent, diversity in gender and academic background.
Ethical and Regulatory Compliance	Adherence to ethical guidelines and data protection standards.
Technical Requirements	Technical support provided by session facilitators to address any issues with communication systems and data collection tools during the study.
Logistical Requirements	Adequate supervision during tasks to ensure protocols are followed and to offer support if needed, by ensuring an investigator is in each room.

3.6. Protocol design flowchart

Figure 2 illustrates the step-by-step process involved in designing and implementing the protocol. The process begins with defining research objectives, followed by task planning, metric selection, and securing ethical approval. Eligibility criteria are established, and participants are recruited and scheduled. After preparatory steps are completed, a pilot study is conducted, and the resulting data are analysed. Based on the findings, revisions to the protocol are made as needed before final reporting. This iterative approach ensures continuous refinement of the study design for full-scale execution.

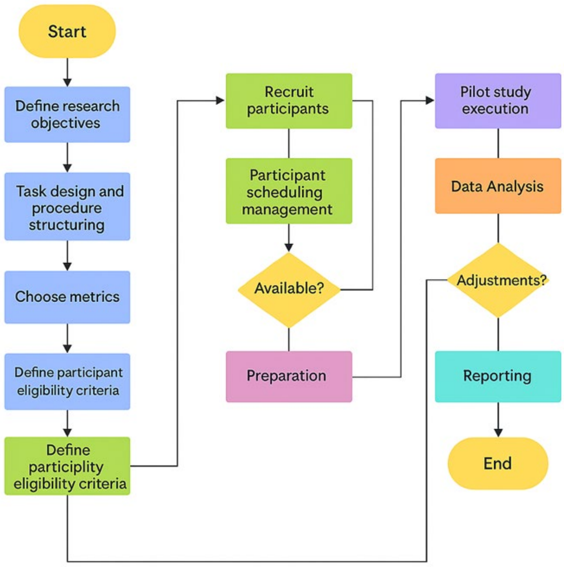

Figure 2. Protocol design flowchart.

4. Results and analysis

To validate the proposed protocol [26], a pilot study with a small sample size was conducted, focusing on two key tasks: LEGO construction and bomb defusal. The primary aim was to observe the effects of communication delay and interface design on team performance, stress levels, and communication efficiency.

Initially, the experimental design planned for six groups: two to serve as control groups (using real-time communication with either a chat-like or email-like tool) and four experimental groups (using delayed communication across both interface types). However, due to recruitment limitations, only three groups participated. Consequently, the LEGO construction task employed the email-like interface under delayed communication, while the bomb defusal task employed the chat-like interface. One group was the control group (real-time communication), and the other operated under communication delays.

The communication tools used in this study were Google Groups and Google Chat. Google Groups is useful for threaded discussions, as it allows users to create discussion groups with email-like threads, where messages are organized by subject. On the other hand, Google Chat is a real-time chat app that provides instant messaging capabilities, allowing participants to communicate quickly and continuously.

Stress-related data were collected via Apple Watch, tracking heart rate and HRV, which can serve as proxies for stress. Stressful situations cause an elevated heart rate. HRV measures the variation between heartbeats, so a lower HRV reflects higher stress and reduced recovery capacity, whereas a higher HRV indicates better resilience to stress.

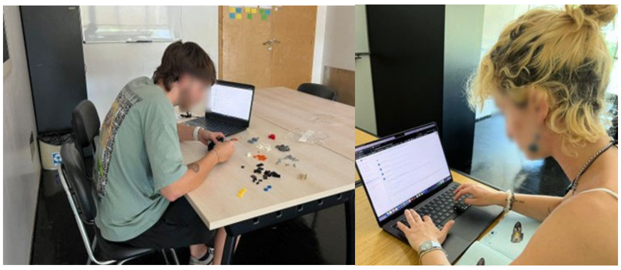

Figure 3. Crew team (left) and Mission Control team (right) performing the LEGO task under delayed communication.

4.1. LEGO construction task

Quantitative and qualitative data from the LEGO construction task revealed clear performance differences between real-time and delayed communication conditions.

For this task, errors were defined as misplaced or missing LEGO pieces, classified as “corrected” if fixed before completion or “uncorrected” if left in the final build. Groups with delayed communication (groups 2 and 3) made more errors overall and while both groups managed to correct some, only the real-time communication group corrected all errors and completed the task successfully. These results suggest that communication delays increased task complexity and affected participants' ability to complete it accurately.

The heart rate data revealed peaks that were analysed alongside communication logs from Google Groups. Elevated heart rates corresponded to moments of high stress, particularly when communication delays caused confusion or errors.

After analysing the communication logs, it was noticeable that the control group (group 1), which had no imposed communication delays, was much more active than the other groups. These findings align with statements made by some of the participants about not wanting to communicate because the delays made it so frustrating.

The data collected through observation checklists during the LEGO task showed that teams employing strategies such as confirmation messages (e.g., "Step completed – awaiting next instruction") could better navigate the delay. One notable observation came from a test group that, unlike other groups, attempted to reduce message frequency to save time by eliminating confirmation steps. This approach reduced the quality of team coordination and, as a result, confusion about task progress and duplicated steps led to more uncorrected errors. This supports findings from a similar study on voice-delayed communication [27], emphasizing the importance of maintaining status updates in delayed communication settings.

In summary, in the control group (real-time communication), participants completed the task with fewer errors, more efficient coordination, and minimal reported stress. In contrast, participants in the delayed conditions faced increased frustration, slower response rates, and elevated error frequency.

4.2. Bomb defusal game task

The digital bomb defusal game, Keep Talking and Nobody Explodes, provided an opportunity to test how communication delays affect rapid decision-making and problem-solving under pressure. In this task, real-time communication allowed the control group to defuse the bomb successfully with only one error. In contrast, both test groups failed to complete the defusal within the time limit.

The time sensitivity of this task made every message exchange critical. Under the one-minute communication delay, test groups faced a significant disadvantage. Situations that required immediate clarification (e.g., colour of wires, symbol combinations) resulted in cascading misunderstandings and long pauses. As the bomb's timer approached zero, participants in the test groups exhibited rising stress levels, both in observed behaviour and biometric indicators. Meanwhile, for group 1, there was a sudden rise in bpm that corresponded to the moment of the incident, which led to one error that was made during this task.

In this task, all groups encountered two key challenges identified in a similar study [27]. The first was time wastage. Given the task’s shorter time limit and its reliance on communication between teams, any delays caused by waiting for instructions proved critical. Misunderstandings further compounded the issue, as resolving them consumed additional time. The second challenge stemmed from the ground team’s inability to support the crew during the initial phase of an emergency. As a result, when errors occurred and the simulated bomb approached detonation, mission control was not immediately informed. This finding also aligns with another study [28] in which participants reported that communication delays hindered crewmembers from receiving timely assistance, thereby disrupting the progression of task procedures. These difficulties were especially pronounced in scenarios requiring frequent back-and-forth exchanges, such as the bomb defusal task.

Once again, communication logs showed how much less communicative the test groups were compared to the control group. It is also possible to see how communication initiation was more balanced for this task than in the previous task, since the crew teams also had to describe the bomb instead of only receiving instructions.

In summary, the resulting data from the bomb defusal task showed delays created decision bottlenecks. Crew members hesitated to act without feedback, while mission control struggled to anticipate the crew's next move. In some cases, outdated instructions arrived after the crew had already attempted a solution, increasing confusion. In the absence of real-time clarification, errors compounded quickly. These results underscore the need for communication protocols designed specifically for asynchronous conditions, including predictive instruction design, pre-emptive task planning, and structured confirmation cues.

4.3. Post-study participant survey

Table 2 summarizes participant feedback on task complexity, communication dynamics, and stress levels, as reported in the Post-Study Participant Survey.

Table 2. Post-Study Participant Survey results

Category	Survey Item	Group 1	Group 2	Group 3
Task Performance and Difficulty	How difficult was it for you to find the tasks?	Neutral	Easy	Neutral
	How would you rate the clarity of the instructions you received? (Crew)	Neutral	Neutral	Very Clear
	Did you encounter any significant challenges during the tasks? (Please describe)	Limited time, high level of task difficulty and communication delays	Communication delays	---
Communication and Team Dynamics	How effective was the communication within your team?	Neutral	Neutral	Effective
	How often did communication delays (if applicable) affect your performance?	---	Very often	Sometimes
	How did you and your team cope with communication delays (if applicable)?	---	By remaining calm	---
	Did any conflicts arise within your team?	Minor conflicts, resolved easily	No conflicts	No conflicts
	If there were conflicts, how were they resolved?	Re-reading instructions step-by-step from the start	---	---
	How practical was it for you to find the communication tool Google Groups?	Not practical	Not practical	Practical
	Did you find the "Subject" feature in Google Groups useful? How so?	Not useful, a regular chat tool would be better	Not useful	Yes, it’s a communication channel where it’s possible to send messages regarding a subject and receive individual replies
Stress and Coping	How stressed did you feel during the tasks?	Somewhat stressed	Somewhat stressed	Neutral
	How did you manage stress during the tasks?	Trying to provide more illustrative communication and remaining calm	By waiting for instructions and calmly read them	By taking deep breaths and writing messages as clearly as possible

Category	Survey Item	Group 1	Group 2	Group 3
Overall Experience	Did the communication condition (real-time or delayed) impact your stress levels?	No impact	Yes, significantly	Yes, moderately
	How satisfied are you with your overall experience in the study?	Very satisfied	Satisfied	Very satisfied
	What did you enjoy most about participating in this study?	The challenge of trying to complete the tasks on time New and fun experiences	How challenging it was.	Had a fun time seeing how delayed communications impact the decisions made and how crucial instructions are. Tasks were fun.
	What did you enjoy least about participating in this study?	The communication platform	Lack of experience in the tasks. Communication delays.	Waiting for messages. It's stressful to wait for delayed replies under a time limit.
	Do you have any suggestions for improving this study?	Changing the communication platform. Improve the time-difficulty ratio	Make instructions more practical instead of interpretation-based.	No suggestions

Overall, participants reported that communication delays were a source of stress and frustration. To manage this stress, they commonly adopted strategies such as maintaining composure, communicating as clearly as possible, including more information in each message, acknowledging received messages, and indicating whether a response was required. These approaches are consistent with the strategies noted in other studies [27].

Crew teams operating under communication delays frequently expressed reluctance to send additional messages due to the frustration caused by the delays. This sentiment is reflected in the communication directionality analysis, which highlights a reduced initiation of communication by crew members during the LEGO task and a lower overall message frequency across both tasks. These findings align with another paper [28], which reported that communication delays were associated with increased stress and frustration.

Most participants did not utilize the 'Subject' feature in the Google Groups communication tool and indicated a preference for Google Chat, which was used during the bomb defusal task. However, those who used the 'Subject' feature found it highly beneficial, noting that it facilitated well-organized conversations. Table 3 summarizes the participants' experiences with the communication tools used in this study and their effects on performance.

Table 3. Comparison of chat-like and email-like tools in terms of performance, communication quality, stress, and participant preference

	Google Chat (Chat-like)	Google Groups (Email-like)
Performance and Communication Quality	Higher message frequency, more spontaneity, but harder to track complex instructions	Lower message frequency, better organization when 'Subject' is used
Stress and Cognitive Load	Faster perceived pace, but higher stress under delay	Lower stress when threaded discussions followed, but frustration when unused
Participant Preference	Preferred by most participants for immediacy	Preferred by a minority who valued structure

This suggests that, while Google Groups may not be the most effective communication platform, email-like tools can be valuable when used appropriately. Purpose-built platforms such as Mattermost, Slack with persistent threads, or custom HMI-integrated messaging systems could offer richer status tracking, integration with operational dashboards, and automated confirmation prompts to support structured communication under latency.

Overall, consistent with the findings of various studies [28], the data from this analog study suggest that communication delays negatively impact task efficiency, team collaboration, and individual well-being, particularly in terms of stress and frustration. Another common denominator between the two studies is the observed decline in communication quality within the delay groups compared to the control group.

4.4. Cross-task trends and team dynamics

Across both tasks, the most successful teams were those that adopted adaptive strategies early, such as:

(i) Using subject tags and message threading to organize instructions
(ii) Sending batch messages to reduce reliance on constant back-and-forth
(iii) Confirming every step completed to maintain situational awareness
(iv) Assigning a single point of contact within the team to streamline communication

Teams that failed to implement these strategies experienced more errors, confusion, and stress.

The combination of biometric, observational, and subjective data suggests that communication structure and clarity directly influence emotional regulation and task effectiveness. The study highlights the potential for interface tools and decision-support systems that anticipate user needs and streamline message flow, particularly in industrial or space contexts where latency is unavoidable.

5. Discussion

DT technologies have become a cornerstone of Industry 4.0, enabling real-time modelling and simulation of physical systems to optimize operations, predict anomalies, and personalize interventions. While traditionally associated with mechanical systems or production environments, the application of DT concepts to human-in-the-loop systems, especially under communication latency and operational stress conditions, is gaining traction [29]. This study contributes to that effort by demonstrating how analog mission protocols can serve as a foundation for developing behaviour-aware digital twins that include the human operator as a key component.

Integrating real-time biometric feedback (e.g., heart rate and HRV) with behavioural and communication data enables dynamic modelling of human states. In a DT context, such integration can inform adaptive systems that adjust interface complexity, notification cadence, or task allocation in response to user stress level or cognitive workload [30]. For example, decreased HRV or delay in communication turnaround time could serve as triggers for support mechanisms or workflow adjustments in an industrial setting.

The collected data, particularly the combination of performance metrics, communication patterns, and subjective workload assessments, can feed machine learning models capable of predicting operator states and behaviour under varying conditions. This supports the development of digital twins that do not simply reflect system states, but also anticipate human limitations and needs, allowing for the creation of adaptive decision-support systems that evolve in response to operator input and state [31,32].

The environments simulated in this study (e.g., high-stakes, time-sensitive, multi-agent tasks with intermittent feedback) are increasingly common in industrial operations. These include:

(i) Remote maintenance and diagnostics
(ii) Control room operations in energy and transport sectors
(iii) Teleoperated robotic systems
(iv) Smart factories with human-machine co-working interfaces

Communication lags, interface clarity, and cognitive overload remain barriers to safety and productivity in each of these applications. The findings from this protocol implementation suggest that DT systems equipped with behavioural monitoring can proactively adjust workflow, suggest protocol changes, or even train operators using feedback derived from simulated stress scenarios.

This integration of cognitive data into cyber-physical systems opens the door to more personalized and resilient industrial environments where the operator is not just an end-user, but an actively modelled component of the system [33,34].

This study presents a disruptive yet practical approach to exploring human performance in environments where digital systems, human behaviour, and operational pressure intersect. The findings emphasize the urgent need for adaptive systems that capture the state of machinery and processes and model and respond to human cognitive dynamics. The protocol offers a versatile testbed for several applied domains by simulating realistic time-delayed scenarios and analysing multimodal data.

Recent literature also reinforces the importance of behaviour-aware decision support. For example, a 2023 paper highlighted that AI systems integrating biometric feedback can reduce critical errors during complex tasks by over 30%, particularly in high-risk operations like air traffic control and remote diagnostics [35]. Similarly, other research has demonstrated how digital twins using human behavioural inputs improved task delegation efficiency in industrial robotics [36]. These findings support the validity and timeliness of embedding communication protocol design and human data logging into broader cyber-physical infrastructures.

The implications of this research extend to multiple domains, from astronaut training programs and smart manufacturing systems to emergency response coordination and industrial supervision.

5.1. Implications for AI decision-support systems

Incorporating human-centred metrics into digital twins allows AI-driven decision-support systems (DSS) to move beyond rule-based automation toward adaptive, personalized support. For instance, AI can detect performance degradation through task patterns or elevated physiological stress and respond by simplifying information displays, delaying non-critical alerts, or prompting collaborative reassessment. These intelligent DSS can also learn from interaction history to optimize communication pacing and task assignment, particularly in safety-critical environments like space missions or chemical processing plants.

5.2. Applications in operator training

The analog protocol developed here can be expanded as a training module for high-risk industries. When embedded into extended reality (XR) environments or DT simulators, these protocols can simulate stress, ambiguity, and delays, enhancing preparedness for real-world crises. Training modules that use this model can help trainees develop habits for structured communication, efficient problem-solving under pressure, and adaptability to communication breakdowns. Such scenarios also support evaluating trainees' leadership, collaboration, and stress-regulation skills under repeatable, measurable conditions.

5.3. Remote diagnostics and supervision

In aerospace maintenance, nuclear energy, or offshore engineering, remote experts often supervise tasks with delayed or incomplete communication from field operators. The results from this study can inform the development of interface protocols and interaction models for such remote supervision contexts. Predictive models based on communication logs and biometric proxies can flag escalating stress or confusion, prompting real-time coaching, interface adjustment, or workload redistribution. Furthermore, the structured messaging systems tested in this analog protocol could be adapted to smart maintenance dashboards and Industrial Internet of Things communication layers.

5.4. Personalized industrial processes

As Industry 4.0 evolves toward mass customization and worker-centred automation, it is increasingly clear that no two operators react similarly to stress, delay, or cognitive load. This research lays the groundwork for personalizing industrial workflows based on real-time operator modelling. By integrating behavioural insights into cyber-physical systems, organizations can improve efficiency, safety, worker satisfaction, and resilience.

The next step is integrating this protocol into a continuous feedback loop, where experimental findings feed AI agents that adaptively manage workflow, guide team communication, and recommend personalized task strategies in digital twin environments.

6. Conclusion and future work

This study presented a novel, integrative protocol designed to examine human performance, decision-making, and team coordination in analog environments simulating space missions' communication delays and operational constraints. Grounded in principles of human-in-the-loop systems and cyber-physical integration, the protocol addresses key gaps in previous approaches by combining multimodal physiological data, behavioural data, and communication, with high-pressure, collaborative tasks.

Unlike previous approaches that tend to isolate performance metrics or focus narrowly on stress, this protocol integrates the complexity of real-time tasks and the need for collaborative problem-solving in the presence of communication delays. These components are essential for accurately simulating the demands of space missions. Interactive and fast-paced tasks, such as the bomb defusal task, are particularly effective in capturing the nuances of decision-making under time pressure, something simpler tasks often fail to achieve. Another strength of this protocol is its flexibility, making it suitable for use in various analog research settings. By examining how cognitive load, fatigue, and emotional stress influence performance and decision quality, the protocol offers deeper insight into the impact of delayed communication on crew operations. These contributions directly address the overarching research aim to explore how structured protocols, informed by Industry 4.0 and DT concepts, can support resilient human-machine interaction in digitally mediated environments.

The findings demonstrate that communication delays have a pronounced effect on task execution (SO1). Participants subjected to delayed communication made notably more mistakes than those in the control group. Elevated psychological stress, triggered by the delayed interactions, negatively impacted both performance and decision-making, emphasizing the importance of maintaining psychological health during operations. These performance discrepancies also serve as tangible evidence of reduced cognitive capacity, highlighting how delays in communication impair the ability to process information and respond to critical events effectively. Additionally, responses from the post-task survey revealed that participants in the delay condition experienced higher frustration levels.

The data provided valuable insights regarding team coordination and communication patterns (SO2). Teams experiencing communication delays engaged in fewer exchanges, and the mission control side initiated most of the communication. This behaviour suggests that crews tend to depend more on ground support under delayed conditions, particularly when facing uncertain or challenging situations. Building on prior research, the study incorporated a less chat-oriented and more structured communication tool, featuring subject headers and message threading, to test a user interface designed to minimize strain and improve clarity (SO3). Although most participants favoured regular chat platforms such as Google Chat, those who used the subject-based format in Google Groups reported that it helped maintain organized conversations. These findings imply that while Google Groups may not be ideal for operational use, structured, email-style platforms can enhance communication efficiency when utilized correctly.

Regarding the fourth objective (SO4), the research investigated how delays influence stress and coping behaviours. Participants in the delayed conditions frequently reported heightened frustration and adopted coping strategies such as staying composed and condensing more information into each message to offset communication limitations. The inclusion of physiological monitoring tools, such as heart rate HRV, provided preliminary insights into stress responses. However, a broader range of measures will be necessary to better understand how communication delays affect crew well-being over time.

Despite its contributions, the study faced some limitations. The sample size, limited duration, and logistical constraints restricted ecological realism, particularly in replicating long-duration isolation, microgravity, or multi-week team dynamics. Despite these limitations, the findings emphasize the critical need for effective communication systems, real-time feedback mechanisms, and robust stress management strategies in high-pressure environments. The limited sample size and restricted access to technology and facilities also impacted the study's generalizability, shaping the tasks' complexity and the types of data that could be collected.

Future research will address these constraints by incorporating a wider array of physiological and psychological assessment tools, adaptive AI agents to simulate collaborative DSS, and targeted stress mitigation strategies. Expanding the duration of simulations will also allow for a deeper exploration of how communication delays affect crew adaptability, resilience, team interactions, and individual stress responses over time. Additionally, integrating real-time monitoring and feedback technologies may enhance operational performance and reduce stress, ultimately supporting mission success in future space exploration efforts. Expanding participant recruitment with balanced gender representation and a wider range of professional backgrounds will also allow for statistically robust subgroup analyses. Furthermore, future iterations will explore XR integration to create immersive training and simulation environments that more closely replicate operational conditions in spaceflight and industrial contexts.

Framing the findings within a DT paradigm, this work sets the stage for behaviour-aware simulation environments where the human operator is not a passive element but a dynamically modelled component. Such integration is crucial in next-generation Industry 4.0 systems, where cyber-physical infrastructures must account for technical parameters and cognitive, emotional, and team-based human responses.

Ultimately, this research demonstrates that a structured, digitally supported protocol can be a versatile testbed for evaluating performance under uncertainty. It offers actionable insights for developing adaptive human-machine systems in space missions, remote diagnostics, autonomous industrial operations, and other high-risk domains. By evolving into a full-scale experimental framework, the protocol contributes to building smarter, safer, and more human-centred cyber-physical systems: a necessary step toward realizing the full potential of Industry 4.0 and DT ecosystems.

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