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Exploratory study on time-delayed excavator teleoperation in virtual lunar construction simulation: Task performance and operator behavior

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ABSTRACT

Building sustainable habitats on the moon has been planned for decades. However, applying fully automated construction systems is still challenging in altered environments. Teleoperation, which is the remote control of the machine, can serve as an intermediate phase before achieving fully autonomous systems. Since the teleoperation between operators on the earth-ground and robots on the lunar surface introduces inevitable communication time delays under a deep space network system, it is important to understand its impact on task performance and operator behaviors in teleoperated construction tasks. This paper develops a simulated lunar environment for excavator teleoperation systems in virtual reality to examine task performance and operator behaviors in time delay conditions. The outcomes indicate that time delays significantly degrade task performance, and the operators modify their control strategies to cope with the time delay conditions. The findings will contribute to understanding human behaviors in time-delayed teleoperation of lunar construction tasks.

1. Introduction

Sustainable space exploration requires constructing and maintaining permanent infrastructure on extraterrestrial terrain (i.e., the Moon and Mars). However, there are many unique and challenging conditions in extraterrestrial construction operations compared to earth-ground work, such as unstable communication systems including long latency, limited power resources and supply time for machine operation, lack of illumination including permanent shadow area, extreme temperatures, and challenging terrain conditions, including lunar dust [1,2]. Particularly, the lunar surface terrain is about 95 % covered with regolith, which is a fine-grained soil and dust of less than 1 mm [3]. By deploying autonomous robots, we can reduce the risks and physical labor required to build lunar habitats in those hazardous and challenging environments [4]. Yet, despite the benefits of fully autonomous systems, interventions by human operators are not avoidable due to the underlying limitations of autonomous robots' capabilities. Human operators can make more complex decisions than automated or programmed robots in some challenging conditions. Teleoperation can be used at an intermediate stage between on-site operation and a fully autonomous system in construction [5–9]. The use of teleoperated excavators has the potential to assist in safer and more efficient performance in hazardous site conditions like disaster sites, underwater, and deep space areas [10,11]. In this paper, teleoperation indicates the remote-control system with a computer visual display for manipulating a robot excavator from a long distance by a human operator.

In the initial phase of the lunar construction, using construction machines is essential for site preparation to be equipped with infrastructure such as landing pads, power communication towers, roads, protective habitats, and dust-free zones. However, limitations in autonomous technology and challenging environments make relying on fully autonomous construction robots difficult. Effective human-machine interfaces in the teleoperation system are the key to enhancing the capabilities of robots for deep space operations in harsh conditions. Space teleoperation has been studied in terms of human-robot interface and operational methodologies [4,12–15], but there has been a general consensus that many issues still remain to be solved. In particular, communication time delay is one of the major challenges of teleoperation in the deep space network (DSN) system because of the long distances between operators and machines [14,16–19]. The time delay in a teleoperation system can be defined as the latency between the human brain at one end and the telerobotic effector and sensors at the other end [20]. A communication time delay disturbs the continuous interactions between human operators and robots, which may lead to

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degraded performance, responsiveness, and proficiency for control and adaptiveness since they require a greater mental workload by attention sustained for longer periods of time. Basically, human operators tend to be more easily overwhelmed with mental fatigue, stress, and frustrations in unfamiliar situations [6,13]. Therefore, cognitive flexibility and knowledge developed by the operators are required to improve the reliability of task performance and reduce the operator's workload in complex situations [21]. In order to manage task performance and situational awareness during teleoperation with signal transmission delay, it is critical to understand how operators perform the work and adaptively behave in such challenging conditions.

This study aims to examine the operators' performance and behaviors under the time-delayed teleoperation system, especially an excavator, that simulates the construction task on long-distance lunar terrain. In this study, we designed and modeled teleoperation tasks for lunar surface construction in virtual reality for these purposes. A simulation-based construction environment can help operators develop effective control skills, familiarize themselves with the situations, and give individual learning opportunities and adaptability to diverse types of situations [22]. We focused on the simulated model of lunar surface construction for high fidelity of spatial cognition and immersive experiences. To simulate the construction teleoperation tasks, we modeled the experimental tasks during the site preparation phase. The task scenario was conducted with different time-delay conditions (i.e., static and varying). This experimental model can provide insights into how teleoperators behave in challenging situations that are cognitively overloaded. For the evaluation, human subject experiments are designed to measure task performance and assess their behaviors in the teleoperation system. We explore how the communication time delay affects operator performance when remotely controlling an excavator on the lunar surface and how the operators change their control behaviors to adapt to such challenging conditions. This will contribute to understanding and expanding the knowledge of performance degradation and operator's strategies in extraterrestrial construction.

Moreover, in the realm of the extraterrestrial teleoperation system, previous studies on time-delayed teleoperation have primarily focused on spacecraft missions and robotic arms operations [19,23–26], as opposed to regarding teleoperated excavators in terms of the extraterrestrial construction context. This study explored the unique challenges posed by teleoperation with unstructured extraterrestrial work environments, supporting new insights into teleoperation in such conditions. In addition to general performance metrics, such as completion time, we performed an in-depth analysis of the operator's control input sequence, behaviors, and the move-and-wait strategy. By focusing on a critical task (i.e., rock pickup using an excavator control schematic) and analyzing the effects of delay conditions on operator performance, there is the potential to support future teleoperation interface design under time delay. In its exploratory phase, this study will contribute to filling the existing knowledge gap in extraterrestrial construction and the effects of latency on human performance during excavation, supported by empirical data. By offering insights into operators' behaviors and control strategies under time-delayed conditions, the findings of this research provide valuable inputs for informing the development of future teleoperation systems in extraterrestrial construction.

2. Research background

2.1. Teleoperation system between the Earth's ground and the Moon's surface

In lunar construction teleoperation, operators need to remotely control robots (e.g., from the Earth's ground workstation to the Moon's surface). Due to the long distance, communication time delay is inevitable, and the delay ranges are subject to physical distance as a major factor. In the realm of communication networks, time delays arise from processing delays (i.e., the time needed to generate and convert data into network layer format), transmission delays (i.e., the time taken to send the signal to the channel, contingent on bandwidth), and propagation delays (i.e., the time that takes for the signal to travel through the channel) [23,24]. The Earth-Moon average distance is approximately 384,400 km, which dictates a round-trip communication delay of around 2.5 s considering the speed of light limits and typically 3 s for vehicles on or near the moon [17,27]. The latency may vary based on factors such as the communication bandwidth, specifications of transmitter and receiver, computation processing/storage, and the changing distances due to the celestial bodies' rotation and revolution [16,27–30]. In the DSN system, the Tracking and Data Relay Satellites (TDRS) are involved in the signal transmission for lunar construction; TDRS is a specialized communications satellite located in geosynchronous orbit [25]. Consequently, time delays and the time-varying ranges will vary and will be influenced by complex factors, including the communication systems and operational environments of the construction tasks. In general, time delays between 100 ms and 1 s are recognizable to the operator but do not cause a significant loss of feeling or disturb the smooth operation of the system [22]. Our experimental study, focusing on teleoperation under Earth-Moon distance with communication time delay, built upon the 3-s time delay and time-varying delay (ranging from 2.5 to 3.5 s) conditions, based on insights from those prior studies and the ranges of the Earth-Moon teleoperation time delay.

2.2. Teleoperation performance in time delay

There have been studies to investigate the association between time delay and degradation in performance, along with an increase in the mental workload of operators [15,16,19,31–37]. Related to workloads, there are studies that aim to alleviate the impact of communication time delay by providing assistive sensory feedback or predictive visual information in teleoperation systems for enhancing operator capabilities and reducing mental workload [38–41]. Those studies indicate that exploring its impact on operator performance and manipulation behaviors in construction teleoperation systems with time delays is important to provide insights into designing assistive or predictive tools. For the mental workload evaluation, the NASA-TLX (Task Load Index) [34] has been utilized along with the analysis of success/failure rates, completion time, accuracy measurements, and eye-tracking data to examine the effects of the communication time delay. The multimeric measurements have enabled the comprehensive examination of work performance, control behaviors, situation awareness, and task load. The prior studies revealed that even minimal time delays could impact operator workload and overall performance, underscoring the critical aspects of delay duration on operational efficiency [19,27,42,43]. They emphasized the necessity of utilizing a range of metrics to thoroughly assess the multifaceted impacts of latency, given the inherent complexity of the tasks and systems involved. Here, the effects and extent of the performance degradation could differ depending on the task types and environment. Accordingly, there is a knowledge gap for studies in a construction work context and manipulation behaviors with long-distance remote control, such as between the Earth and the Moon, since lunar habitat construction is still undergoing a mission and has never been constructed yet. In terms of that, this study will be distinct from previous works on teleoperation with time delay by focusing on the space excavator teleoperation for lunar construction.

Operators need to obtain the necessary skills and knowledge to execute construction tasks effectively under a DSN teleoperation system. Construction robot control requires accurate and dexterous manipulation skills such as joystick functions, including control motions, directions, and speed. Appropriate performance skills and thresholds for proficiency in controlling a robot may vary depending on the task requirements and difficulties [44]. Besides, the operator's skills and proficiencies are considerably linked to actions generated in response to informative signals without conscious efforts [45,46]. The individual's mental, physical, and emotional capacity should be adequate to ensure the successful completion of tasks under time-delay conditions since individual behaviors significantly impact work performance. The Skills, Rules, and Knowledge (SRK) framework in the human performance model [21,46,47] can describe these operational behaviors during construction tasks: (a) Skill-based behaviors: These are quick, highly automated actions such as moving forward a vehicle or navigating a familiar route. They do not require conscious thought or learning for adaptation. (b) Rule-based behaviors: These involve applying learned rules to familiar situations, like devising strategies for well-known operating rules and methods. (c) Knowledge-based behaviors: These are employed in unfamiliar and unpredictable situations, requiring problem-solving and decision-making, such as navigating an unknown environment, handling unfamiliar objects, or tackling a novel issue. In this study, this SRK framework will be built upon to understand the operator's adaptive behaviors under complex and unfamiliar situations (i.e., time-delay conditions) by delving into the aspects of human factors engineering and situation awareness. We posited that operators exhibit skill-based behaviors under no-delay conditions, and they will be toward rule-based or knowledge-based behaviors during static and time-varying delay, given the unfamiliarity of the situation and the need for robust strategies to execute the given tasks successfully.

2.3. Operator behaviors in teleoperation

Teleoperation requires robust human-in-the-loop interactions, and the operator's control skills have a crucial impact on the overall task performance. Studies on the impact of communication delays in space network systems should address technological aspects and consider human factors to mitigate the challenges and enhance human-machine interfaces and, in turn, task performance effectively. Situational awareness is an essential ability to conduct tasks involving indirect viewing during teleoperation for operational decision-making within complex systems [13]. Improving operator situation awareness can support human-machine interfaces and perception of the external environment. Situational awareness has three category levels: perception, comprehension of situations, and projection of future events [48]. Perception is the first level of situational awareness. Distance and depth perception are especially challenging in teleoperation tasks and affect the ability to estimate the perspective different from the egocentric view (i.e., spatial orientation) since the visual information is transmitted through the display [49,50]. Due to the lack of spatial perception in addition to time-delay conditions, errors in situational awareness can often be linked to collisions, quality deficiencies, or safety issues in construction environments. Operators mentally simulate the outcomes of their actions, and errors often arise from human's limited mental capacity, influenced by distractions, mental fatigue, or stress [6,51]. Interruptions or distractions by time-delay conditions can significantly alter an individual's mental model, and stimulus overload may impede the prioritization of critical information during work [51,52]. Based on this knowledge, in this study, the operator behaviors are explored in terms of the manipulation of the controller and perception of visual information, focusing on skills and situational awareness.

In the realm of space teleoperation, which is a remote control in time-delay conditions, operators need to adjust their behaviors to minimize errors in navigating and controlling robots. A prior work [53] employed a servo-driven manipulator equipped with dual slave fingers to demonstrate the effects of lag between 0 s and 3.2 s in the operator's commands, scrutinizing the consequential effects on task performance. Another work [27] further highlighted how operators adapt to delays, known as the move-and-wait strategy. This strategy involves the operator executing a distinct control movement, pausing to receive feedback, and then verifying the remote manipulator's response before continuing [43,54]. This process is essentially a sequence of actions and reactions to adapt to the delay, and this cycle continues until the task is completed. The operators focused on measuring the time needed to accomplish certain tasks under these conditions, which highlighted that operators consistently employ the move-and-wait strategy, emphasizing its significance in ensuring task completion within teleoperated systems. In this paper, we delve into how operators effectively employ the move-and-wait strategy in lunar construction teleoperation.

3. Simulation modeling and experimental setup

3.1. Design of teleoperation system and challenging construction environment

For this exploratory study, we developed a virtual model to simulate the lunar surface construction task based on the site preparation scenario. The construction infrastructure on the lunar surface is essentially needed for building safe habitats and maintaining other exploration operations. In particular, conventional construction tasks are still required during the site preparation phase. For example, NASA's framework on lunar in-situ surface construction has identified the requirements for space excavators and dozers for moving the bulk of lunar regolith (i.e., fine soil) for building the habitat infrastructure [55,56]. Considering the limitations when relying on robots' autonomous capabilities on the lunar surface, the teleoperation system is critical in this mission, as it offers a human-in-the-loop system. Therefore, the human-robot interaction remains important in thoroughly demonstrating and understanding the challenges and impacts of teleoperated operations, which are unstructured and unfamiliar to operators.

To conduct the human subject experimental study, the virtual model was built on the simulated lunar surface topography and construction site landscape which are grounded in NASA's study of lunar habitats and regolith testbeds [57]. Also, we developed the effects of lunar dust on the terrain layer in the model. Lunar dust from the regolith is one of the inherent challenges during construction tasks. The fine and powdery dust from the regolith that is less than 1 mm and covers over 95 % of the lunar terrain has deleterious effects, so it can be lifted by any movement and disturb operations [1,3,58]. Besides, regolith dust is observed collecting charge on surfaces and transported by electric fields near the lunar surface [1]. For the dust effect simulation, a box collider was attached to the bucket and was determined when the collision occurred with the terrain. Whenever the excavator bucket hit the terrain and got stuck in the terrain, the dust effect triggered, and then powdery soil particles lifted near the collided area. Multiple instances of the dust effect could be triggered at the same time, and the multiple instances generated higher density and a wider range of visual disturbance from the dust particles. We simulated additional visual perception challenges considering the lunar construction environment, which has low illumination, relatively long shadows, a lack of visual landmarks, and colorless landscapes. For example, those factors increase visual ambiguity and degrade depth and distance perception during the excavator control, particularly when the operators need spatial awareness for manipulating the excavator's boom and stick [50,59]. This degraded situational awareness could increase mistakes and collisions. Therefore, we generated a virtual construction site for a moon-like simulation by focusing on challenging environmental factors such as low illumination, lunar surface terrain, and long shadows that would affect the operator's visual perception with time delay.

The model was built on a physics engine that could simulate collision detections on the terrain and other objects according to the excavator's movements. In the Unity game engine, there are three types of physics settings for objects: static (objects do not move and are unaffected by forces), kinematic (objects are controlled by code and unaffected by physics forces like gravity and collisions), and dynamic (objects are fully simulated by the physics engine, responding to forces and collisions). We built upon a kinematic rigid body setting to control the excavator movement by designing physics behaviors instead of relying on Unity's built-in physics engine. The default kinematic physics controls movement by reacting to forces and collisions following a built-in physics algorithm. Since the excavator is stationary in our experiment, we designed its movement to be unaffected by the force reactions when it hits the truck or rover. The excavator movement was blocked at the hit position to avoid a force reaction such as pushing the object or causing the bucket to bounce. This enables to conduct the task scenario consistently while maintaining the excavator's stationary position. To investigate the collision during tasks, the box colliders were attached to the excavator's elements, and we tracked the number of collisions with other objects on the lunar surface. We collected data from the box colliders against the excavator bucket by using the invoke callback function in the physics engine, triggered when colliders detect contact. We illustrate the overview of the research framework in Fig. 1 for simulation modeling, experiment setting, and evaluation.

3.2. Time delay and teleoperation system in simulation

To simulate the teleoperation task, we established three time-delay conditions of teleoperated excavator control: no-delay, 3 s-delay, and time-varying delay conditions to represent the time lag experienced at an Earth-based ground workstation as a proof of concept (Fig. 2). Time-delay conditions can be at least 3 s or longer depending on the communication systems as the signals transmit with different types of communication bandwidth, tracking and data relay satellites (TDRS), and multiple layered communication links. The varying-time delay condition was designed according to the rationale from the estimated time delay from the previous studies (Table 1). Considering the teleoperated vehicle on the Moon, we designed a range between lower bound 2.5 and upper bound 3.5 s time-varying conditions. The varying condition was randomly changed per single second between the lower and upper bounds. Time delay is programmed in the model, which simulates the latency of the excavator controls so that the model activation is delayed upon receiving the corresponding signal inputs (Fig. 3). The time delay was calculated based on the input time of the excavator movements. For instance, when a command to move the bucket was entered, the excavator's corresponding action was conducted, taking into account the designed time delay. Consequently, operators encounter time-delayed movements in the manipulation.

This time-delayed virtual environment was linked with the head-mounted display (HMD) interface representing the excavator manipulations with a rotatable view from the excavator location. In this study, the HMD was synchronized with the participant's head movements without introducing additional visual delay, providing an experience similar to a monitor display in terms of visual delay conditions but more immersive. In the model, the excavator was stationary position, and the operators were seated at a fixed table with joysticks, limiting head movements, and the HMD's maximized field of view as 110 degrees which was enough to cover the field of view of the given work environment. The HMD can enhance operators' sense of telepresence and performance compared to a desktop monitor by providing stereoscopic visualization, even if there is the potential to raise fatigue or discomfort from wearing the headset for a long time [60,61].

For excavator manipulation, we built upon joystick controllers to

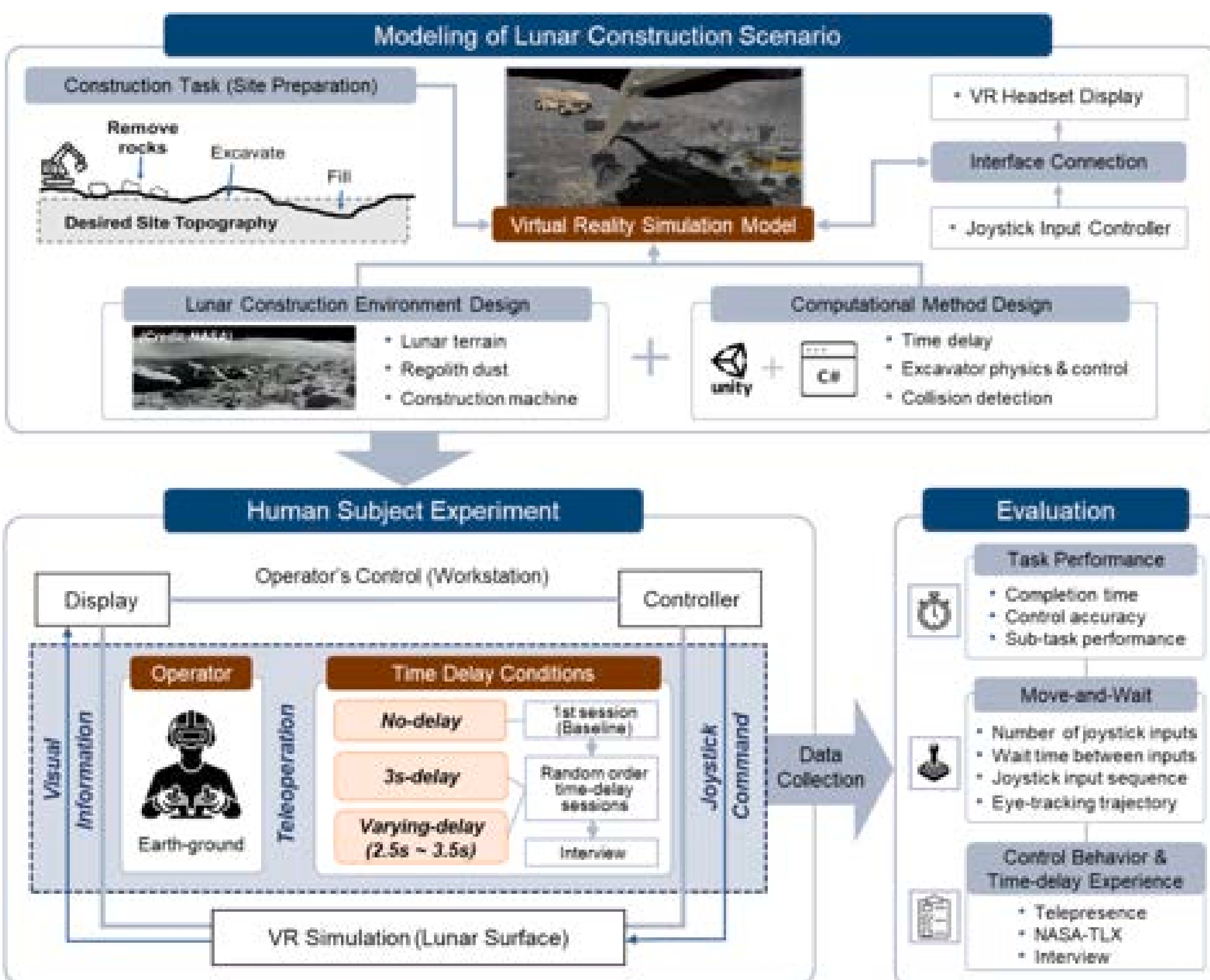

Fig. 1. Research framework.

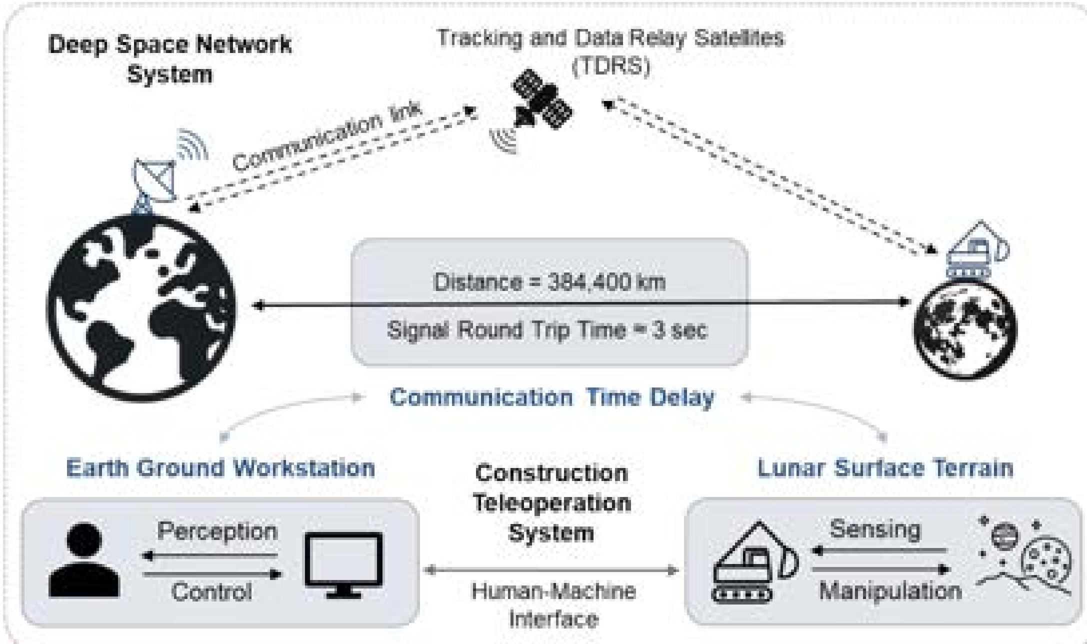

Fig. 2. Communication time delay and construction teleoperation in deep space network system.

Table 1
Time delay conditions.

Operator to machine	Description of time delay condition	Time delay (closed loop)	Reference
Earth to Moon	Speed of light limit, theoretically	2.5 s	[17]
	Vehicles on or near the Moon	3 s	[27]
Earth to on-orbiting teleoperation system	Delay range for rendezvous and docking (RVD) system teleoperation	5–7 s	[27,29]
	Delay range for virtual predictive teleoperation estimation	7.6–8.6 s	[38]

simulate the operation of NASA's Advanced Planetary Excavator (APEX). This choice has a benefit since APEX's schematic and functional design aligns well with conventional excavation systems. Such design ensures that operators can effectively understand and control the excavator, making it suitable for the construction tasks in our experimental task scenario. We used the ISO (International Organization for Standardization) operating patterns for the control mapping as the required manipulation skills in this experimental study are relative to earthworks [62]. Joystick controllers are a common interface for bilateral hand use and dexterous manipulation. The controllers offer eight distinct directional controls across two joysticks: bucket in and out, stick close and away, boom up and down, and cab left and right. The joystick inputs are recorded when a single input event is generated. For instance, joystick control allows continuous inputs, so the operators could manipulate both ways to continue or control multiple inputs depending on their skills and behaviors. Fig. 4 shows the experiments' virtual simulation environment and construction task operational setting.

3.3. Participants and experiment task

This experimental study was approved by the Institutional Review Board (IRB) of Texas A&M University on June 22, 2023 (protocol number: IRB2023-0680D). We recruited the participants via the Texas A&M University email system. A total of 36 subjects (29 males and 7 females, mean age = 24.3 ± 3.8 years) participated in this experimental study. Thirty participants were majoring in construction-related fields and six participants were majoring in other engineering fields. All participants were over 18 years old, had normal or corrected-to-normal vision, and did not have any visual, hearing, or physical impairments. Upon arrival at the experimental office, each participant was informed about the experimental procedures and completed an informed consent form. Before the main experiment began, participants filled out preliminary questionnaires that gathered data on their gender, educational background, and prior VR experiences.

The questionnaires asked participants about their VR experiences using head-mounted displays (HMD) and joystick controllers before starting the experiment. The question was (1) How would you rate your experience in any VR environment with a head-mounted display? (2) How would you rate your experience with any joystick controllers in any VR environment? (3) How would you rate your experience with excavator operation? Most participants considered their VR and joystick experiences to be between the range of slightly familiar and very

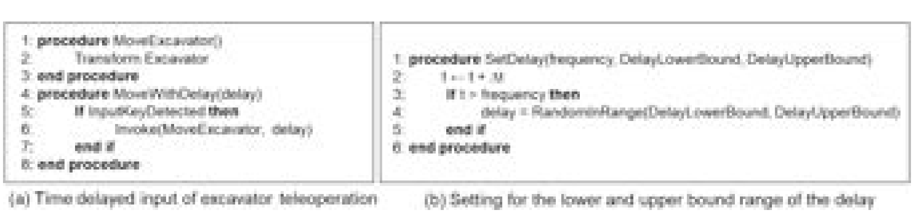

Fig. 3. Algorithm for time-delayed simulation setting.

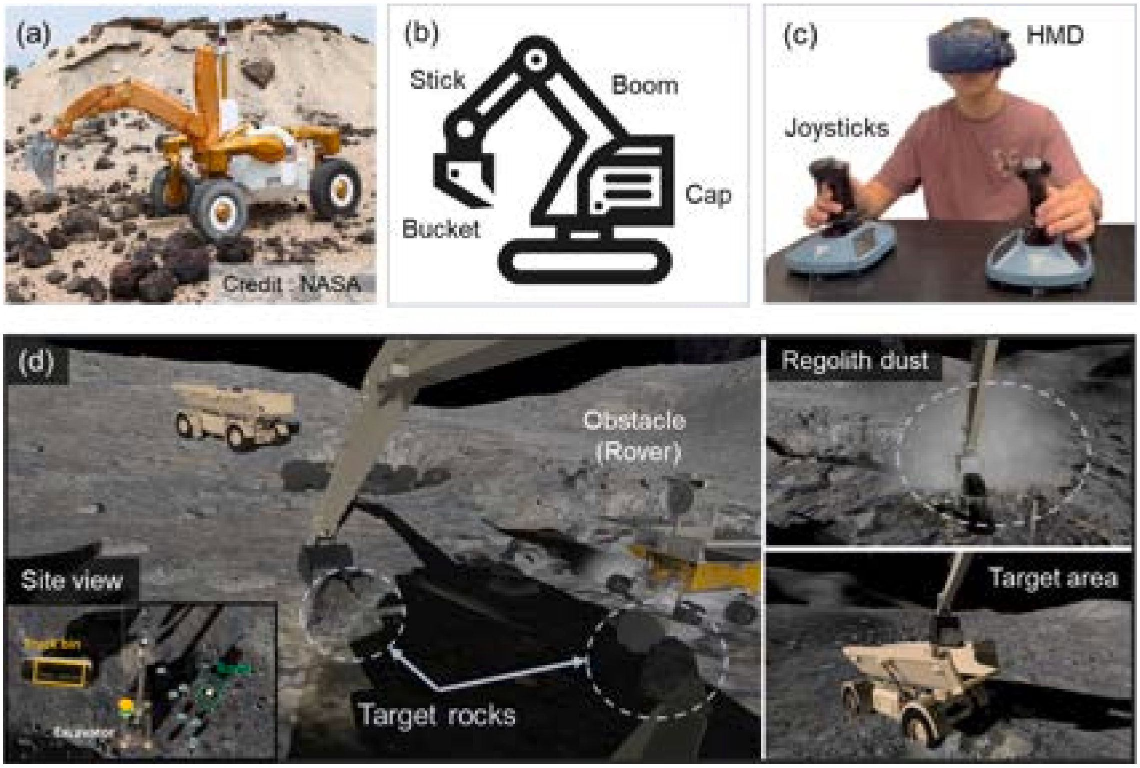

Fig. 4. Experimental setup of site preparation tasks on the lunar surface. (a) NASA's Advanced Planetary Excavator (APEX) model. (b) Excavator schematic. (c) Operator workstation setting. (d) Operator view.

familiar. Except for two participants, 34 participants (94.4 %) had VR experiences with HMDs in different extents of experience. For the controller in VR settings, 33 participants (92.7 %) had experience with joystick-type controllers before participating in this experiment (Fig. 5).

A training session was conducted within the developed simulation environment. The aim of the training session was to get familiar with joystick manipulation skills before conducting experimental tasks. The training sessions were conducted until the participants learned and familiarized themselves with the joystick control patterns and manipulations. Training sessions were conducted until the operator successfully completed at least two rock movements and conceded they had obtained the joystick manipulation skills for the given task performance. During the training, the participants were informed of the task for the experimental sessions: moving two rocks into a target area.

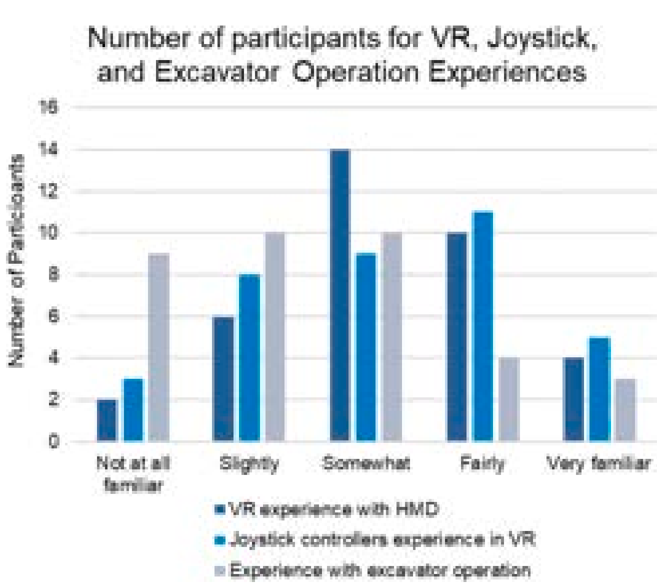

Fig. 5. Pre-questionnaires on participants' experiences with a head-mounted display (HMD), joystick control, and excavator operation.

Following the training, the operators performed the task under no-delay conditions in the first experimental session. The task design included picking up two rocks separately and dumping them out to the target area (i.e., a truck bin). Clearing a rock during the site preparation phase on the moon was built upon in the Lunar Safe Haven Seedling study [63,64]. Each session was constrained to a time duration of not more than 10 min to avoid the potential accumulation of fatigue. The timeframe was decided based on the findings and observations of our pilot studies [15]. The completion time was marked at the end of the session. In the cases in which the participants did not complete the task within 10 min, the session was terminated. The participants conducted no-delay conditions as the first session, and the other time-delay conditions (i.e., 3 s-delay and time-varying delay) were randomly ordered to minimize any effects of the performance orders. A total of 18 participants (50 %) performed 3 s-delay before the time-varying delay; the other 18 participants performed the time-varying delay first.

3.4. Evaluation and measurement

Three evaluation categories were conducted to systematically assess the effects of time delay on the construction task performance and operator behaviors. These evaluations include assessing task performance, analyzing move-and-wait strategies, and examining control behaviors and time-delay experiences. Moreover, the study delves into a detailed analysis of the groups that succeeded under the 3 s-delay condition, focusing on their operational strategies and efficiencies that set them apart from the less successful groups. Individual cases were also scrutinized based on specific evaluation metrics. Table 2 offers a summary of these evaluations and measurement indicators.

3.4.1. Evaluation of task performance

We compare three conditions, which are no-delay, 3 s-delay, and time-varying delay, in terms of task completion time and success rate. The time-varying delay conditions generated a time-delay range from 2.5 to 3.5 s that keeps changing randomly every single second, which were considered as cases of unstable signal transmission, as discussed in section 3.2. For the in-depth evaluations, we analyze and discern the differences in task execution accuracy and task performance in the 3 s-delay condition, categorizing them into two groups (i.e., success vs. failure). This study investigates the skill/knowledge-based operational behaviors and outcomes between these two groups, with a particular focus on comparing completion times, control accuracy, and the number of collisions. Thus, we examine the strategies adopted by the successful operators in the 3 s-delay, aiming to identify potentially effective manipulation with adaptation in time-delay conditions. Moreover, this study delineates three sub-tasks involved in using an excavator: bucket traveling, picking up, and dumping out, which are categorized by task characteristics and essential joystick control skills. A comprehensive evaluation of such sub-task performance is carried out by analyzing the time allocation across the sub-tasks and the associated patterns.

3.4.2. Assessment of move-and-wait behavior

The move-and-wait strategies by operators are assessed in construction teleoperation tasks under time-delay conditions. The task completion time consists of three parts, which are a sum of movement times, waiting time, and reaction times [53]. In this study, we evaluated the number of joystick inputs (NJI) and the waiting time between joystick inputs (WTJI) to examine operator behaviors in terms of move-and-wait in time-delayed manipulation Eq. (1).

$$WTJI\ (\Delta_t) = input\ time_{i+1} - input\ time_i \quad (1)$$

Understanding NJI and WTJI is crucial for analyzing operators' behaviors, as these metrics reflect the use of a move-and-wait strategy, which may vary based on the difficulty or type of the task. However, the adoption of the move-and-wait strategy is not necessarily affected by delay conditions. This means that operators would not use the move-and-wait strategy in case they can accurately anticipate movement feedback, even under time-delay conditions. Additionally, sub-task completion time (Eq. (2)) can be effectively estimated using NJI and WTJI, providing valuable insights into operational efficiency and strategy.

$$Completion\ time_{sub-task} = \sum_{i=1}^{NJI} \left(input\ time_{i+1} - input\ time_i\right) \quad (2)$$

Our study included a quantitative analysis of joystick inputs and investigated how operators' control strategies differ between no-delay and 3 s-delay conditions, focusing on their distinct movement command sequences. We also delved into the eye-tracking trajectory, which focused on coordinates of the eye gaze or fixation during tasks, to analyze move-and-wait behaviors thoroughly. This approach allowed us to explore both spatial and temporal aspects of the move-and-wait strategy. Eye movements intertwine with hand movements, forming a decisive part of the cognitive process involved in target selection and execution [65]. The data on eye movements are crucial for understanding how operators adjust their strategies to manage delays and maintain efficient task performance in teleoperation systems. Our investigation sheds light on how the operators respond differently in time-delay conditions to guide operators' attention and enhance their situational awareness. By integrating the analysis of eye-tracking trajectories along with hand movements, we aim to gain insights into operators' behaviors in the context of move-and-wait strategies.

Table 2
Evaluation metrics for the experiments.

Category	Evaluation	Measurement Indicator
Task performance	Completion time	Task time (mm: ss)
	Control accuracy	Number of collisions
	Performance of sub-tasks	Time (sec) & Ratio (%)
Move-and-wait behavior	Number of joystick input	Number of inputs
	Wait time between joystick input	Time (sec)
	Sequence of joystick input	Eight types of joystick inputs
	Eye movement	Eye-tracking trajectory
Control behaviors and time-delay experiences	Telepresence questionnaires	7-point Likert scale
	NASA-TLX (Task Load Index)	20-point scales (21 gradations)
	Open-end interview	Interpretation

3.4.3. Self-report evaluation on control behaviors and time-delay experiences

Operators interact with various interfaces during space construction teleoperation tasks, including visual displays and joystick manipulation under time-delay conditions. In terms of human-machine interfaces, individuals have varied levels of experience and behavior characteristics when conducting teleoperation tasks. Therefore, implementing self-report measurement is crucial for evaluating and understanding operators' perceptions, responses, and decision-making in the given complex construction missions. To interpret the control behaviors and task load on the impact of delay conditions, we examined how operators experience and adapt their behaviors under varied conditions. The telepresence questions for the operator's response and control experience in VR were built upon [66], and NASA-TLX (task load index) [67] were measured in terms of workload during the task performance in different time-delay conditions. The subsequent interview questions are related to the joystick control behaviors and teleoperation experiences in time-delay conditions. The questionnaires and open-ended interviews on control behaviors support the in-depth analysis of performance and operational data in teleoperation systems.

3.5. Statistical analysis for comparison between groups

We conducted a statistical analysis of performance measurements and assessment data from 36 participants to compare task performance and control behaviors. The Central Limit Theorem (CLT) states that the sampling distribution of the sample mean (μ) approaches a normal distribution as the sample size gets larger no matter the population distribution's shape [68]. This theorem is particularly applicable when sample sizes are greater than or equal to 30. The advantages of using CLT are that parametric tests provide more accurate and precise estimates with higher statistical power than nonparametric tests [68,69]. For the primary statistical analysis in this study, we conducted a paired t-test and p-value and provided the associated analysis graphs. In the test analysis, t-statistics and p-value were calculated to measure the difference and compare the mean of the no-delay and 3 s-delay conditions in terms of the standard error (null hypothesis: no difference between time-delay conditions). We leveraged a sample size which is of more than 34 per group since it would allow the detection of a moderate effect size ($d = 0.5$) on an a priori t-test at an alpha of 0.05 and with a power of 0.8 [70]. We conducted evaluations using within-subjects ANOVA (Analysis of Variance) to compare three group means according to CLT, setting $\alpha = 0.05$.

In the case of a small sample size of less than 30 for the subgroup data set, we conducted a normal distribution test with the Shapiro-Wilk test (null hypothesis: the data set is normally distributed). When the normal distribution deviation was detected in the comparison group, we analyzed additional results of nonparametric statistical tests, such as the Kruskal-Wallis test (null hypothesis: the population medians of all groups are equal) and Mann-Whitney U test (null hypothesis: the medians of the two groups are equal) at the 5 % significant level [69]. These statistical methods provided robust data analysis interpretation by allowing us to determine the significance of the delays in performance metrics and to explore the relationships between performance and behaviors.

4. Results and discussion

4.1. Task performance evaluation

For task performance evaluation, we assessed the completion time on the no-delay, 3 s-delay, and time-varying delay conditions. We also examined task accuracy, sub-task completion time, and patterns by comparing no-delay and delay conditions for an in-depth evaluation. The results showed degraded task performance, different levels of accuracy, and distinct sub-task patterns depending on the delay conditions. We elaborated on each finding in the following sections.

4.1.1. Completion time

The task completion time in delay conditions was significantly extended compared to the no-delay condition, $F(2, 105) = 214.6$, $R^2 = 0.80$, $p < .0001$ (Fig. 6). However, there were no significant differences between the 3 s and time-varying delay conditions (Table 3). In other words, the time-varying delay ranging from 2.5 to 3.5 s, even though it was under changing conditions, did not significantly affect the task performance in this experiment. We found there are no significant correlations between operators' experiences and task performance, while we observed that the experienced participants (e.g., VR and excavator operations) tended to learn quickly in a training session without confusion. To avoid and minimize the expertise effect between the subjects, we conducted prescreening questionnaires and then excluded participants who had no experience in the VR environment and operations at all. Even though other factors may still have a latent impact, such as the learning curve, various levels of control proficiency, and fatigue level during the tasks, we could reduce the expertise effect factor by VR experiences, which is a critical factor in this experiment. We posited that performance in a no-delay condition would be a type of skill-based behavior since the participants trained satisfactorily before the experimental session started. It was confirmed that all operators successfully relocated two rocks to the designated area within 10 min.

Contrastingly, in the 3 s and time-varying delay conditions, where the operators were under the knowledge-based behavior, the success rate for the given task dropped to 54 % and 47 %, respectively (Fig. 6 (b)). The time taken to move the first rock was significantly shorter in the no-delay condition compared to the 3 s-delay and time-varying delay. On average, the task completion time in 3 s-delay conditions

Table 3
Comparison of task performance in completion time. ****$p < .0001$. ns = non-significance.

Completion Time	No-delay		3 s-delay		Time-varying delay	
	1st rock	2nd rock	1st rock	2nd rock	1st rock	2nd rock
Mean (sec)	96	225	395	560	420	570
SD (sec)	51	89	177	78	164	62
(min., max.) (sec)	(40, 280)	(90, 450)	(135, 600)	(330, 600)	(160, 600)	(375, 600)
No-delay vs.	–	–	****	****	****	****
3 s-delay vs.	****	****	–	–	ns	ns
Time-varying delay vs.	****	****	ns	ns	–	–

was 9 min and 20 s. We estimate that the actual average completion time in the 3 s-delay conditions would likely be longer than 10 min in the case they perform until the task is successfully completed without the limited timeframe. We assess that the environmental scale of performing tasks and acceptable time variation range is relatively larger compared to robot arm controls or surgical teleoperation that required delicate operation in terms of precision while time-varying delays were ranged from 2.5 to 3.5 s and did not significantly affect the overall task performance. For instance, a prior study in an investigation of the time delay impact on medical robotic systems [71] used a robotic system simulated from 0 to 1000 ms time-delay range and revealed that more than 400 ms latency is perceptible for the medical robotic task and affected the surgeon's performance. Our results infer that depending on the work contexts, time-varying ranges could affect the task performance differently. We need to note that the performance degradation in time-delay conditions could possibly be even worse in real-world situations due to unexpected and unstable network conditions since our experimental setting is built upon typical delays between the Earth's ground workstation and the lunar surface. Therefore, when planning actual space missions, we should consider that the delays could be longer or subject to irregular variations, such as bandwidth, transmission processing, computation capacities, etc.

For the comparison analysis considering the limited timeframe and the failed operators' performance, we conducted the normalized data analysis on the completion time, which included all of the operators' performance. In addition, we compared the success group's completion time, excluding the failed operators' performance, with normalized data. Fig. 7 indicates the results of the performance comparison based on

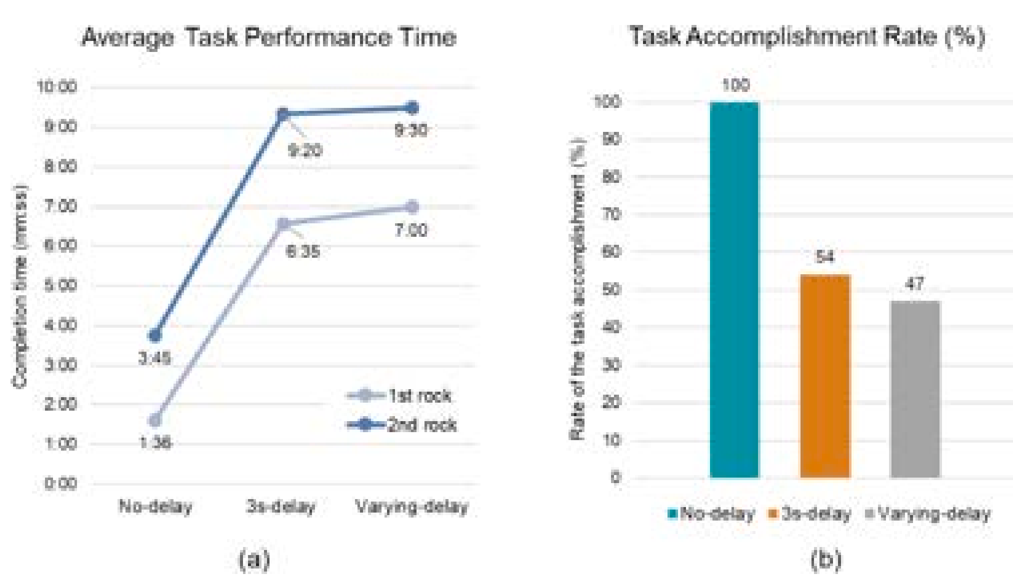

Fig. 6. Task performance in no-delay, 3 s-delay, and time-varying delay conditions ($n = 36$).

the normalized completion time to provide in-depth insights into the task performance evaluation. There is a significant difference between no-delay and time-delayed conditions for the 1st rock task ($F\,(2, 105) = 12.55$, $p < .0001$) and the 2nd rock task ($F\,(2, 105) = 37.84$, $p < .0001$). Interestingly, when we compared the success group's performance, there were significant differences for the 1st rock task ($F\,(2, 84) = 4.00$, $p = .02$). On the other hand, there was no significant difference in the success group's performance for the 2nd rock task ($F\,(2, 54) = 2.17$, $p = .12$).

Moreover, to ensure the success group's performance (Fig. 7(b)) that has a small sample size in the 3 s-delay condition ($n = 12$, mean = 56.92, median = 71.7) and in the time-varying condition ($n = 9$, mean = 48.74, median = 52.27), we conducted the Shapiro-Wilk test to determine if the samples were normally distributed. As a result of the Shapiro-Wilk test in the success group's performance for the 2nd rock task, we found that there is a significant normality deviation ($W = 0.93$, $p < .05$) in the no-delay condition. However, there was no strong evidence that data deviates significantly from a normal distribution in 3 s-delay ($W = 0.88$, $p = .10$) and varying-delay ($W = 0.96$, $p = .83$) conditions. As the sub-groups were not normally distributed in no-delay conditions and the sample size was less than 30 in time-delayed conditions, we conducted the Kruskal-Walli's test which is a nonparametric test for the comparison. The Kruskal-Wallis test result (χ^2 (2, n = 57) = 2.99, p = .22) indicated that there was no significant difference between groups in performance. Fig. 8 shows the QQ (quantile-quantile) plots for distributions with visual assessment by identifying the data points of the performance in no-delay and time-delayed conditions from both the entire participants group and the success group. Overall, the outcome implies that skilled operators, who performed the task accurately within the given timeframe, experienced less performance degradation under time-delay conditions.

4.1.2. Task performance in no-delay (SF vs. SS groups)

All participants successfully completed the given construction task in no-delay conditions. To delve into the skills and task performance, the participants were divided into two groups based on their operation skills. The first group (SF, success in no-delay, but failure in delay, $n = 9$) was defined as those who did not successfully move even one rock in the delay condition. The other group (SS, success in both no-delay and success in delay, $n = 12$) was defined as the participants who completed successfully in both conditions (Fig. 9). The comparison of the two groups aims to examine how participant behavior and performance in the no-delay condition are related to their performance in the delay condition. Specifically, we investigated how skill-based operation behavior in joystick control, varying across different skill levels, impacts performance in the delay condition, which requires knowledge-based behavior due to challenging work environments. We found that the completion time of the SS group was significantly lower than that of SF. Also, the collision frequency during the task in the SS group (e.g., inaccuracy) was significantly less than that of SF.

The task completion time comparison results (Fig. 10) showed that the operator performance of the two groups was significantly different as an independent t-test, $t\,(12.98) = 2.44$, $p < .05$. The Shapiro-Wilk test results for the SF group ($W = 0.86$, $p = .09$) and SS group ($W = 0.95$, $p = .68$) indicated that both variables were normally distributed at the 5 % significance level. Additionally, the result of a nonparametric test of the Mann-Whitney U test indicated a significant difference as well, $U = 23$, $p < .05$. Even if both groups successfully completed all tasks in the no-delay condition, a significant discrepancy was observed between them. The means of the completion times in no-delay conditions of the SF and SS groups were 287 s (SD = 102 s) and 186 s (SD = 67 s), respectively. It implies that operators with highly skilled behaviors in no-delay conditions can effectively carry over the skills to the time-delay conditions and quickly adapt to situations where knowledge-based behaviors are required. In addition, the control accuracy was examined based on collision frequencies in no-delay conditions. As a result, an independent t-test comparing the two groups yielded a significant difference, $t\,(12.17) = 2.65$, $p < .05$, indicating a higher mean collision rate in the SF group. However, the result of the Shapiro-Wilk test showed the SF group sample was normally distributed ($W = 0.94$, $p = .56$), on the other hand, the SS significantly deviated from normality ($W = 0.77$, $p < .01$). Additionally, we conducted the Mann-Whitney U test and the result (U = 20, p < .05) indicated the significant difference. The number of collisions was calculated when the end effector (i.e., excavator bucket) collided with other objects (e.g., rover or truck bin). Experimental outcomes in no-delay conditions showed that SF and SS groups make an average of 5.1 collisions ($SD = 3.6$) and 1.6 ($SD = 2.1$), respectively. This implies that joystick control skills and proficiency in no-delay conditions were related to the control accuracy under time delay. The analysis of the task performance and control accuracy between the SF and SS groups suggested that operators of the SS group who had faster and more accurate operation dexterity in no-delay were more likely to exhibit skillful control behaviors in time-delayed conditions and adapt effectively than those of SF group.

4.1.3. Sub-task pattern in delay (SF vs. SS groups)

Joystick manipulation skills are indispensable for successfully completing given tasks. A construction task using an excavator for site

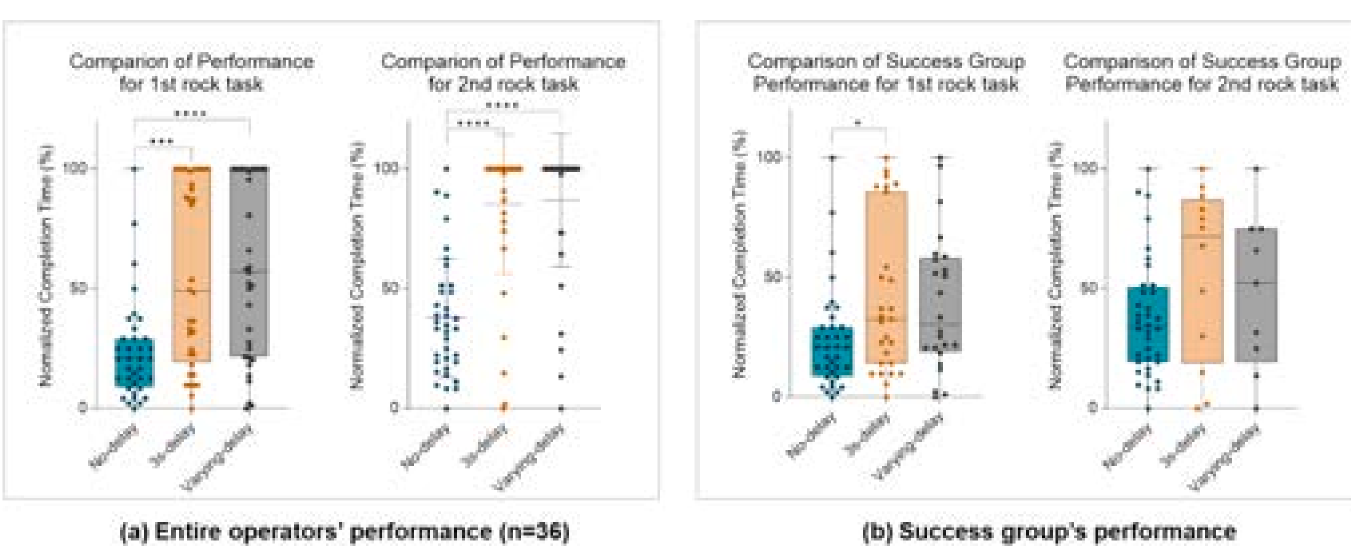

Fig. 7. Comparison of the normalized task completion time. *p < .05, ***p < .001, ****p < .0001.

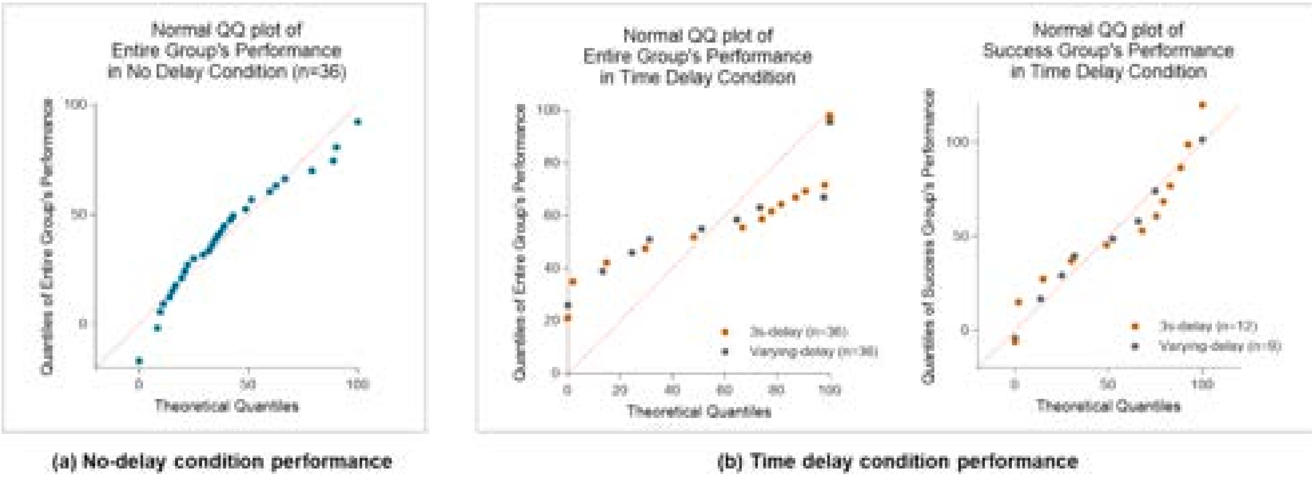

Fig. 8. Normal QQ plot for the performance.

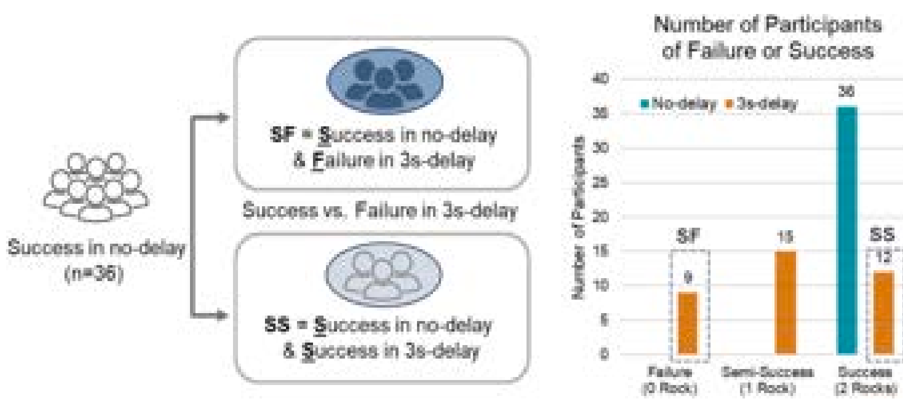

Fig. 9. Classification of SF and SS groups in delay conditions.

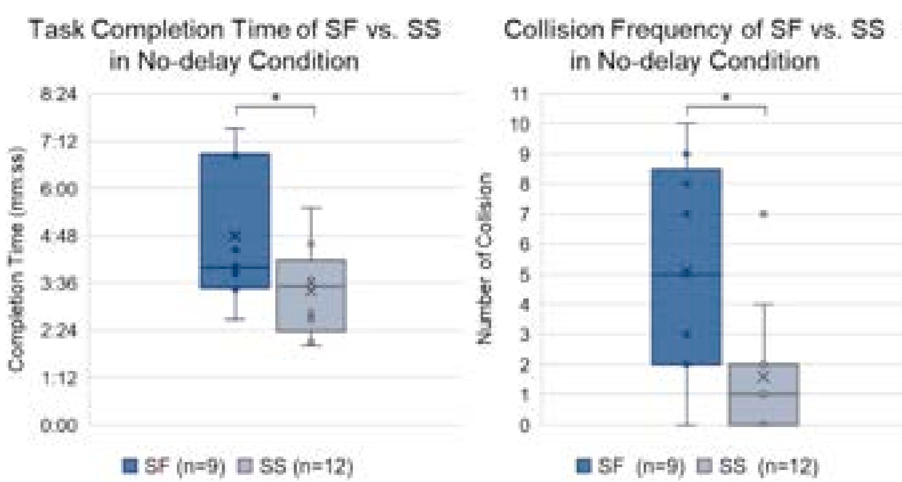

Fig. 10. Performance comparison in no-delay between SF and SS groups. $*p < .05$.

preparation comprises a series of interrelated sub-tasks. In our experiments, sub-tasks were categorized into three types: bucket traveling (T), picking up (P), and dumping out (D). The traveling tasks involve navigation, delivering rocks, and avoiding collisions before and after the picking-up and dumping-out phases (Fig. 11(a)). During the picking-up task, manipulation skills are required to situate a bucket and scoop up the specified target object. The dumping-out task requires accurately maneuvering the rocks to their intended area, the truck bin. Each requires robust joystick manipulation skills for successful completion. In the delay condition of the SS group, the time expended on each sub-task, along with its corresponding percentage of the total task duration, was as follows: for traveling, the mean of completion time was 190 s (SD = 54.7 s), accounting for 39.9 % of the total task time; for picking-up, the mean was 169 s (SD = 42.8 s), constituting 35.5 % of the total task time; and for dumping-out, the mean was 117 s (SD = 50.8 s), representing 24.6 % of the total task time (Fig. 11(b)).

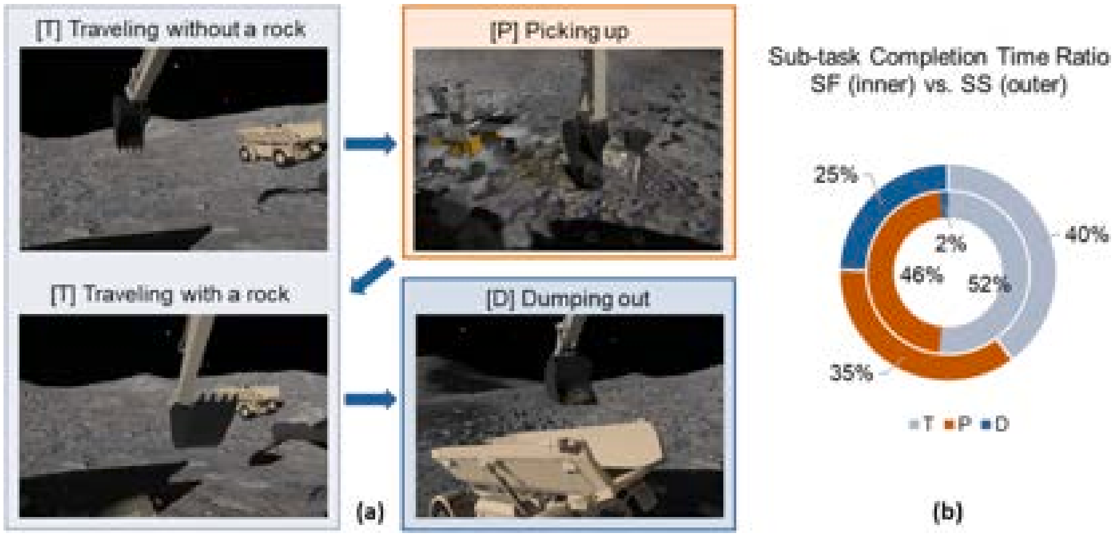

Fig. 11. (a) Construction sub-tasks. (b) Sub-task completion time ratio of SF vs. SS groups.

Within the SS group that successfully completed the tasks, eleven operators exhibited a consistent sub-task pattern in the delay conditions (Fig. 12). The observed pattern, which was TPTDTPTD, represents the shortest and most efficient sequence necessary for successful task completion, indicating that the successful participants avoided errors such as dropping the rock during transit or outside the target area. The average task completion time of the SS group in delay conditions was 7 min and 56 s, while the average of the entire participants was 9 min and 20 s. On the other hand, when it comes to the SF group who failed to pick up or dump out a rock, their completion time and patterns were distinguished from that of the SS group. The major reason for failures was falling rocks during picking-up or dumping-out tasks. One participant could not succeed in even one picking-up task within 10 min timeframe since the operator failed to adapt the operation skills in the delay condition even though the operator successfully completed the task in the no-delay condition.

As a result of our sub-task analysis, we identified the picking-up task as one of the most meticulous when remotely operating an excavator, requiring precise attention and careful movement to handle the target object accurately. The time and effort dedicated to each sub-task correlate with the operator's proficiency and mental workload, as different sub-tasks demand varying skill levels and cognitive efforts. Identifying and analyzing sub-task activities enables more efficient project planning, scheduling, and site layout analysis, contributing to enhancing performance and operations [72,73]. Identifying and investigating sub-task patterns and time spent during the sessions can inform manipulation strategies and provide information related to operator's behaviors, and further help to understand the distinguished characteristics of joystick manipulations depending on the task types (e.g., different patterns and input sequences for picking up vs. dumping out task). As such, identifying and investigating the sub-task would provide supporting data for the in-depth analysis of operators' behaviors during work.

4.2. Move-and-wait strategy in time delay

In our experiments, operators demonstrated adaptive behaviors in response to delayed movement. They often employ a move-and-wait strategy, seeking to minimize errors by observing the consequences of their actions before initiating subsequent movements. Regarding the move-and-wait strategy, we examined how operators modify and adapt their behaviors, specifically in how they manipulate controllers under time-delay conditions. This will be achieved by analyzing the waiting time before movement and the sequence of joystick inputs on a temporal

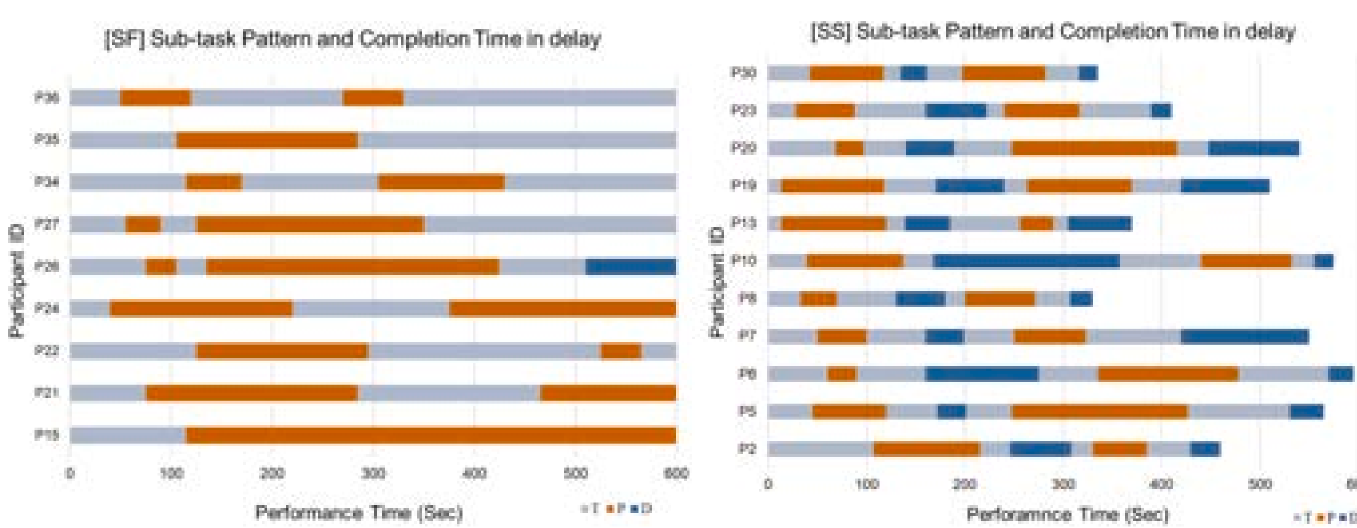

Fig. 12. Comparison of sub-task patterns and completion time in delay conditions (SF vs. SS group).

basis. To complete the given tasks, participants conducted a series of subtasks, including excavator bucket traveling, picking up a rock, and dumping out a rock into the truck bin. The total task completion time when the operator completes the task successfully can be quantified as the sum of durations for each subtask (i.e., TPTDTPTD). The task completion time involves wait times following each movement, that is, joystick inputs, actual task time, human response times, and a communication delay in the teleoperation system. To compare and assess the valid movements based on time and joystick inputs, we focused on the excavator's picking-up task and found a relationship between the number of inputs and completion time (Fig. 13). In the no-delay condition, the number of joystick inputs and the task completion time have a strong positive correlation (Pearson correlation coefficient, $r = 0.74$). This indicates that as the number of joystick inputs increases, the task completion time also increases. In time delay, the analysis result shows a moderate positive correlation ($r = 0.44$), which is weaker than the no-delay condition. This suggests that the operator who quickly finishes tasks acquires the operational skills to reduce inputs until task completion, both no-delay and delay conditions. The number of joystick inputs (NJI) and wait time between joystick inputs (WTJI) are compared between no-delay and delay conditions. Then, we analyzed the sequence of joystick inputs (SJI) for the selective cases of joystick controls. Lastly, we examined the eye-tracking trajectory during the joystick movements and the wait time to interpret the move-and-wait behaviors.

4.2.1. *Number of joystick inputs (NJI) in no-delay vs. delay*

We explored the task completion time by analyzing the average input time and the NJI during the task to examine how operators work differently in delay conditions compared to no-delay conditions. When we compared the NJI between no-delay and delay conditions in the picking-up task, the NJI had no significant difference (Fig. 14). This implies that the time delay does not significantly affect the number of manipulations of the control inputs. We can estimate that time-delay conditions are more likely to impact the response time and situation awareness process, including perception. Consequently, in our experimental setup, the completion time for the picking-up task turns out to be more influenced by the accuracy of the joystick operation than by the NJI.

4.2.2. *Wait time between joystick inputs (WTJI) in no-delay vs. delay*

To analyze behavioral changes in the delay condition, we examined the wait time between joystick inputs (WTJI) for the eight types of joystick movement, which aims to assess patterns in operational behavior during task execution. In the general operation of excavators for construction tasks, prompt joystick inputs without stopping the movement are required for continuous operation. The operators need to empirically estimate and predict an appropriate and efficient wait time between each input for smooth operation during tasks. The comparison of behavioral change along with the performance in delay conditions helps to understand the operators' response time to the unstructured situation and adaptation to the given delay conditions. The *t*-test results of WTJI for the picking-up task completion in no-delay condition ($M = 1.43$ s, $SD = 0.67$) and in delay ($M = 3.99$ s, $SD = 1.09$) showed significant differences, $t\ (33) = 12.37$, $p < .001$ (Fig. 15). We confirmed that most of the operators in delay conditions controlled the joystick more carefully while waiting longer intentionally to see the response before controlling the next movement during tasks.

4.2.3. *Sequence of joystick input (SJI)*

To examine the sequence of joystick inputs (SJI), we investigated the individual input events and sequences. An input event was defined as a single movement command, while a sequence was characterized by two or more such events. SJI is closely related to the operator's skills and proficiency and the given situation that they faced on the task. By analyzing the SJI, we can recognize the characteristics of the associated task's SJI types and their frequency. To compare the performance sequence and behaviors between no-delay and delay conditions, first of all, we analyzed all operators' SJI data. Then, we identified selective cases of joystick controls from no-delay and delay conditions. The analyzed SJI data were chosen from instances where the completion time was less than 25 s in no-delay conditions and less than 100 s in delay. After processing the *K*-means clustering for these instances, we determined the four sample cases to compare SJI from each condition. The analysis cases were circled in each condition in Fig. 16. Through the analysis of SJI during the picking-up task, we examined how each control behavior produced distinct sequences in response to the operator's varying situations.

To compare the operator's behaviors, joystick control command events or sequence types were analyzed based on the command data code (Fig. 17). A total of 34 command types were generated, which include 26 types in no-delay conditions and 15 types in delay conditions. Then, the frequency of each input command of both joystick controllers was evaluated. As a result in assessing the delay, ten events or sequence command types (67 %) were found in no-delay as well, including seven types (47 %) that had more than 3 times the frequency from both conditions. Five types (33 %) could not be seen in no-delay command sequence types. There are three not-in-use (NIU) command types (i.e., *swing left [D], swing right [A],* and *bucket cut-out [Q])* in no-delay conditions, while only one command type (i.e., [Q]) in delay. Fig. 18 represents the frequency of individual command types based on the SJI

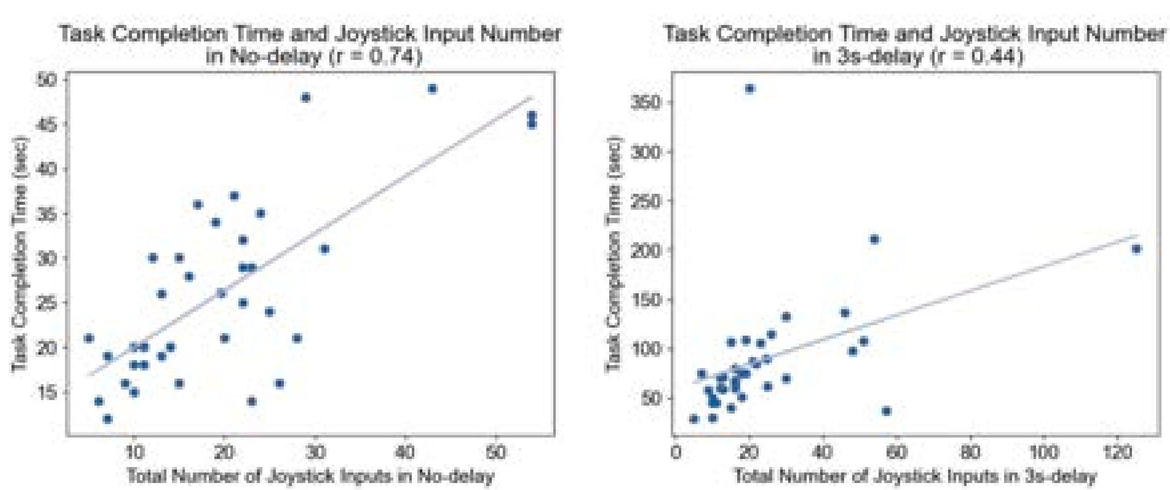

Fig. 13. Correlations between task completion time and the number of joystick inputs.

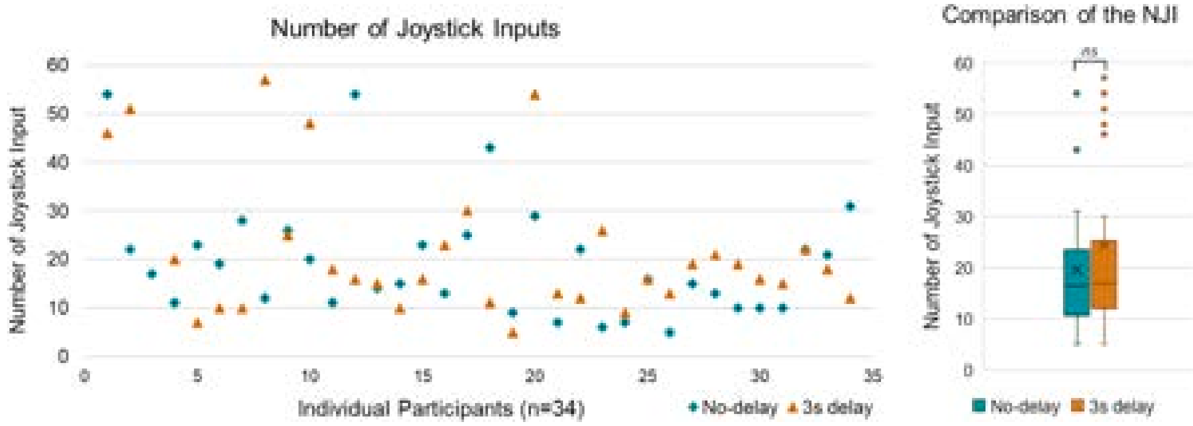

Fig. 14. Comparison of NJI during picking-up tasks. *ns*: non-significant.

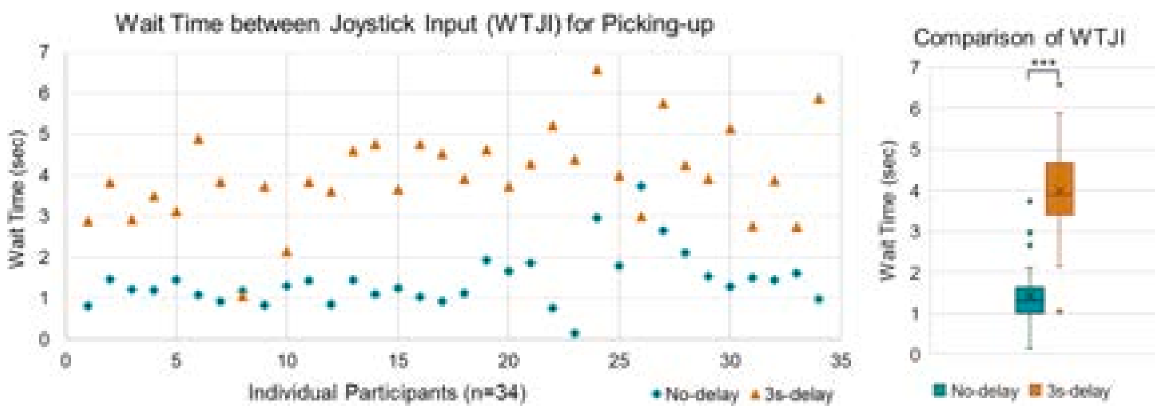

Fig. 15. Comparison of WTJI during picking-up tasks. ***$p < .001$.

analysis. Consequently, we observed that the operator's strategies in no-delay conditions tended to avoid unnecessary and inefficient inputs to save time and effort. The operators manipulated the joysticks intuitively and quickly by using only five types of input commands among eight. In contrast, the manipulations in the selected cases in delay conditions tended to be controlled carefully and deliberately by adapting one-by-one movement by fewer types of SJI.

To further evaluate the frequency of input use for eight commands, we analyzed the percentage of the operators utilizing three specific types of commands ([E], [A], [Q]), i.e., NIU commands (Fig. 19). The results showed the largest difference in joystick control behaviors, particularly regarding the use of the Q command (i.e., bucket cut-out). Unlike the selected case studies where the Q command was not employed at all (Fig. 18), when we investigated all the operators' behaviors, 66 % of operators (23 out of 35) used the Q command in no-delay conditions, and 63 % in delay conditions. Such differences can provide insights building upon empirical data into enhancing assistive interface design and joystick manipulation skills in time-delay conditions for effective control decision-making during tasks.

4.2.4. Eye-tracking trajectory during the move-and-wait strategy

The eye movements were analyzed to understand the operator's visual attention, situational awareness, and control behaviors in the move-and-wait strategy. Oculomotor behavior, including eye-tracking trajectory, can be described in the eye movement as a sequence of fixations, saccades, and smooth pursuit [65,74,75]. The immersive experience and performance can be enhanced in smooth eye-hand coordination and movement [45,76]. Hence, it is important to scrutinize the operator's eye-hand movement comprehensively. As a result of investigating the eye-tracking trajectory in no-delay conditions, we observed smooth pursuit eye movements before and after the picking-up task. Fig. 20 shows examples of eye movement in both conditions. When comparing the eye-tracking trajectory during the first 3 s for the picking-up task, there is not much difference between no-delay and delay conditions. However, the operator's attention to a target object and eye trajectory range based on the eye fixation became considerably distinguished as time went on. At the no-delay condition, the operators have a smooth and expanded range of eye-tracking trajectory on the bucket movement for 10 s before the picking-up task. On the other hand, for the operators in the delay condition, their eye-tracking trajectory was fixed and narrow range, lasting about 3 to 5 s. These eye-tracking patterns indicate that in no-delay, the operator likely prepares for their next steps more quickly and smoothly and observes the situation in advance compared to the delay conditions. Thus, the operator could generate smooth eye-hand coordination without discontinuation of their hand movements. Compared to the no-delay condition, the operators tend to wait for the next movement with delay, which demonstrates that situation awareness and response are affected by the time-delay conditions. Eye-tracking trajectory data can be useful for situational awareness and visual perception training in complex construction tasks (e.g., obstacles, unforeseeable situations, depth perception, and distance perception). Effective training is necessary (1) to assist operators in achieving and maintaining appropriate skills, (2) to develop personal mechanisms in handling situation awareness, and (3) to regain situational awareness after an unexpected event. The use of human behavior data-driven training can help enhance the operator's situational awareness at the visual perception, comprehension, and anticipation level in advance and reduce operational errors in time-delay conditions.

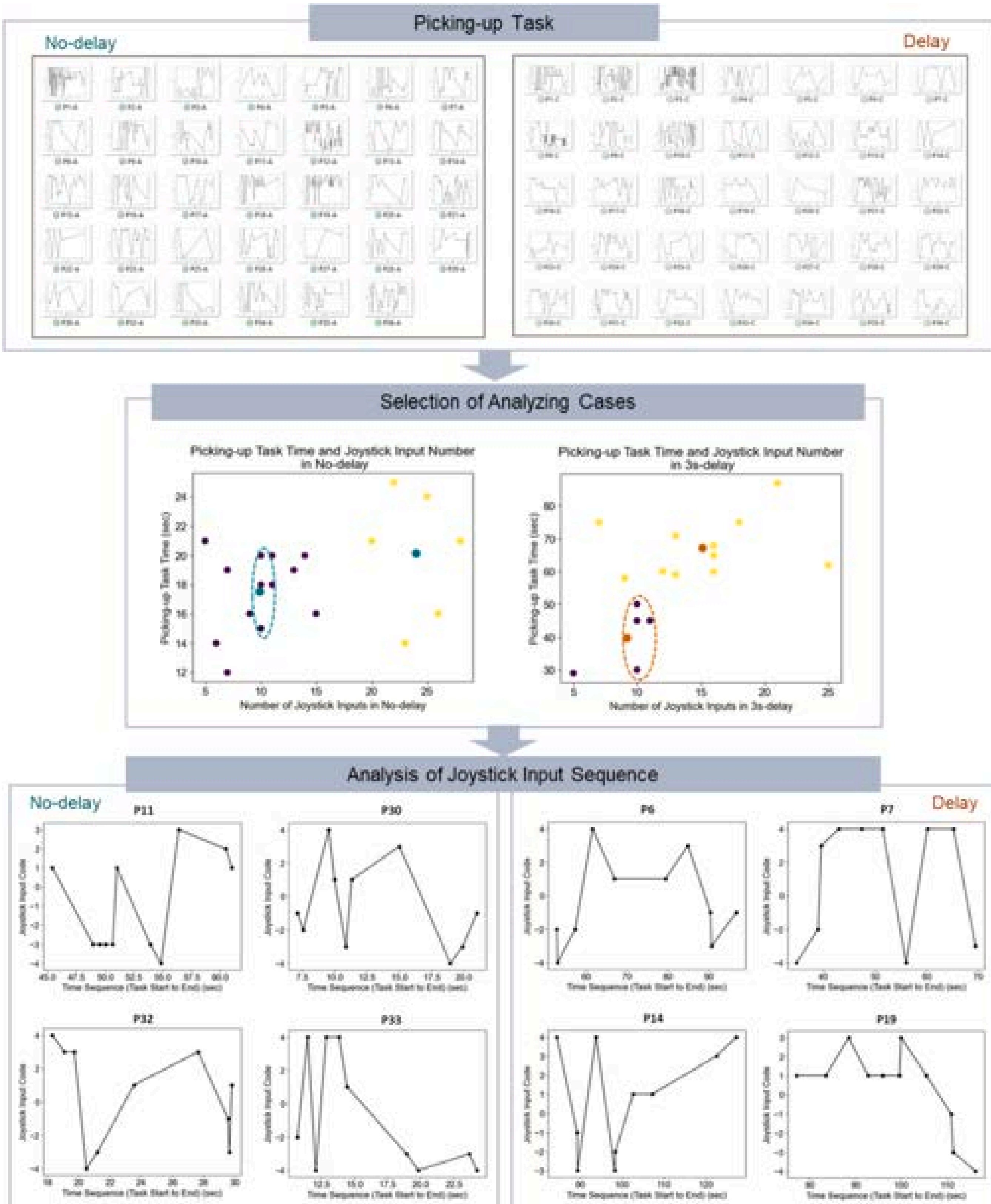

Fig. 16. Analysis of joystick input sequence (refer to the legend in Fig. 17 (a)).

4.3. Self-report on control behaviors and time-delay experiences

4.3.1. Telepresence questionnaires

More immersive telepresence experiences enhance situational awareness and the operator's ability in teleoperation task environments [76]. A control interface that supports interaction with human operators increases telepresence. To measure telepresence in the given work environment, the questionnaires were selectively adopted from [66],

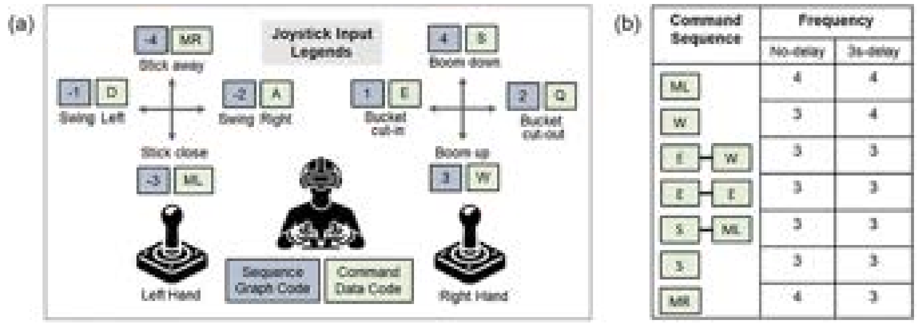

Fig. 17. Joystick inputs command and frequency. (a) Legend for sequence graph and command data. (b) Frequency of joystick input command sequence during picking-up tasks.

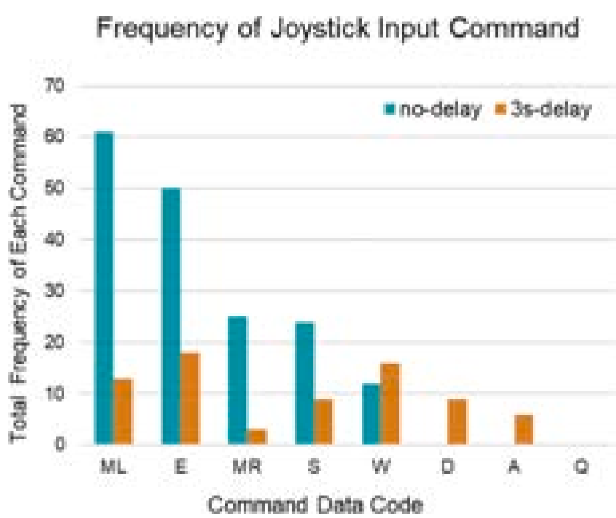

Fig. 18. Frequency of joystick input command based on the SJI analysis of picking-up tasks.

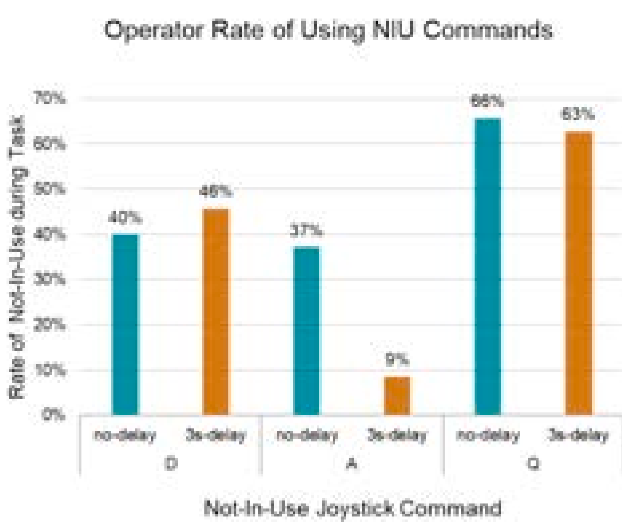

Fig. 19. Operator rate (%) of using NIU command (D: Swing left, A: Swing right, Q: bucket cut-out).

focusing on the control and interaction aspects in the lunar construction context and time-delay conditions (Table 4). As the evaluation results of the self-reported scores, we found that the answers to the eight questions in the delay conditions showed significantly different levels of experiences within the 7-point Likert scale, F (2, 864) = 283.66, $R^2 = 0.40$, $p <$ .001, with the different range of total average scores in no-delay condition ($M = 5.6$, $SD = 0.19$), 3 s-delay ($M = 3.32$, $SD = 1.4$), and varying-delay ($M = 3.15$, $SD = 1.47$) (Fig. 21). The operators' responses indicate that the greater the extent of visual and control feedback transmitted in no-delay, the stronger the ability to control the sense of the lunar construction environment. There were no significant differences between the 3 s-delay conditions and time-varying delay. This indicates that less than a 1-s variation, ranging from 2.5 s to 3.5 s, did not significantly affect the operators' telepresence experiences. Telepresence in the construction teleoperation context can be enhanced if one interacts with the environment naturally and is well-practiced in anticipating the machine's movement. To improve the presence of machine manipulation and the sense of "being there" for perception in time-delay conditions, there is a need for robust human-robot interfaces. Also, the high-fidelity simulation-based experiences in different situations will enhance the operator's knowledge and adaptability.

4.3.2. NASA-TLX (task load index)

NASA-TLX [67], which has six indexes (mental demand, physical demand, temporal demand, performance, effort, and frustration) in 0 to 20 score gradation scales, has been established for assessing the operator's workload during operating tasks. Table 5 indicates the detailed questionnaires we surveyed. As the results of the ANOVA test, total scores of the NASA-TLX indicate that the workload was significantly difference between no-delay and both 3 s-delay and time-varying delay, F (2, 105) = 24.18, $R^2 = 0.32$, $p < .0001$. However, there was no significant difference between 3 s-delay and time-varying delay in the total and each six TLX scores. The comparisons for scores corresponding to the six workload indexes are shown in Fig. 22. The TLX scores reveal that the subjective workload and task performance evaluation results, which we investigated in section 4.1, were substantially related. Our findings imply that time-varying delays within a 1-s range will not significantly affect both the operators' task load and task performance compared to constant time delay. This outcome can be useful to consider as a trade-off element when we design teleoperation interfaces.

4.3.3. Interview on control behaviors and time-delay experiences

During the post-interview, the participants replied to the open-ended question, "How did you change or adapt your behavior in time-delayed sessions?" All participants noticed the delay conditions a few seconds after starting the task. Most participants could discern the distinction between the 3 s-delay and time-varying delay conditions; some even perceived these differences substantially during the tasks. However, many operators reported that the difficulty levels of these conditions felt similar. This sense of experience is corroborated by the results of task performance, telepresence scores, and TLX scores, which indicate no significant differences between these conditions. In the cases that the operators performed for the first time under time-delay conditions, a few participants felt it was like the malfunction of the joystick control instead of considering the delay condition in the first few seconds.

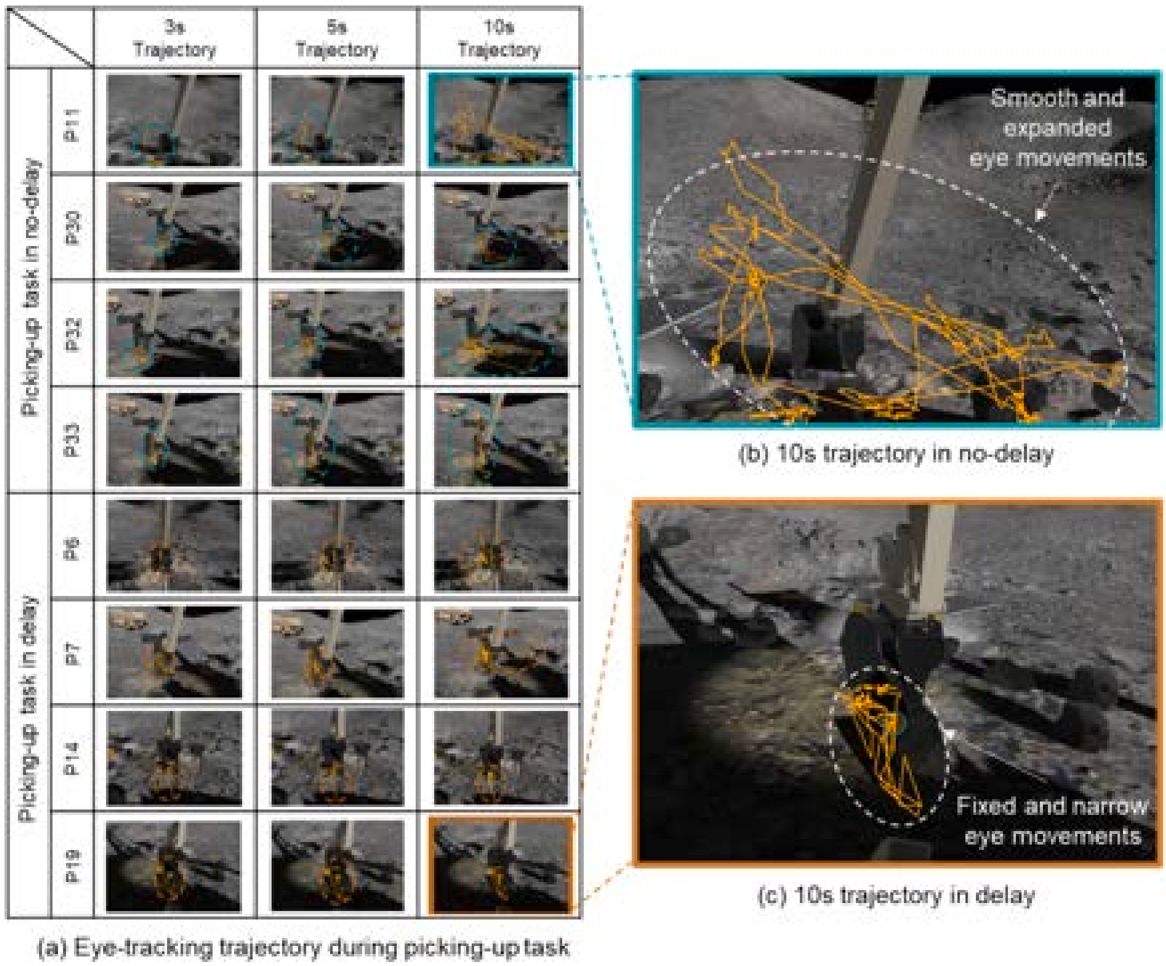

Fig. 20. Comparison of eye-tracking trajectories during picking-up tasks.

Table 4
Telepresence questionnaires.

Questionnaires	Scale 1–7
Q1. How much were you ***able to control*** events?	
Q2. How ***responsive*** was the environment to the actions that you performed?	
Q3. How natural did your ***interaction*** with the environment seem?	
Q4. How natural was the ***mechanism*** that ***controlled movemen***t through the environment?	Not at all - Completely
Q5. Were you ***able to anticipate*** what would happen next in response to the actions that you performed?	
Q6. How well could you ***move or manipulate objects*** in the virtual environments?	
Q7. How ***quickly did you adjust*** to the virtual environment experience?	Not at all- Quickly
Q8. How ***proficien***t in moving and interacting with the virtual environment did you feel at the end of the experience?	Not proficient - Very proficient

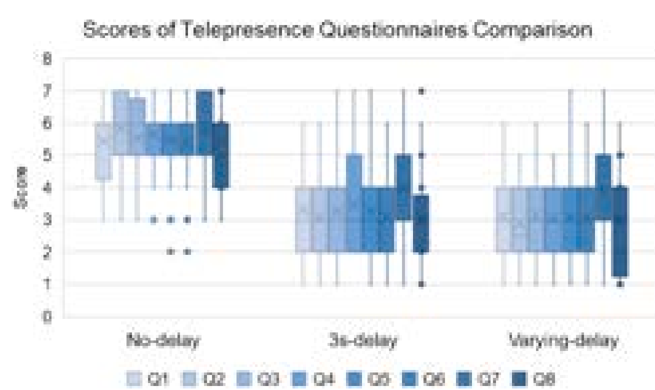

Fig. 21. Comparison of telepresence questionnaire scores.

However, they noticed the time delay situation right after seeing the delayed movement a few seconds later. The participants provided feedback on their joystick control behaviors in the time-delay conditions, including words such as "stop and wait," "slowly move," "wait and see," "calculated the delay," "see the response," and "try to move one movement at once." Without specific information on strategies and knowledge of the delayed condition, many operators could identify the move-and-wait strategies, adapting their behaviors accordingly. Some participants struggled to devise effective strategies for controller manipulation until the session ended, having experienced frustration and exhaustion due to the unsynchronized operation during experiments. Through the interview, we confirmed the level of control skills and task-related knowledge varied among individuals, leading to differing performance and behaviors in the unstructured construction tasks. Therefore, the teleoperation interface needs to provide versatile assistance tailored to human factors unique to an individual operator, their behaviors, and the specific characteristics and conditions of the task.

Table 5
NASA-Task Load Index.

Index	Questionnaires	Scale 0–20
Mental Demand	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex?	Low - High
Physical Demand	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)?	Low - High
Temporal Demand	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?	Low - High
Performance	How successful do you think you were in accomplishing the goals of the task set by the experimenter?	Good - Poor
Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?	Low - High
Frustration	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?	Low - High

5. Conclusions, limitations, and future research

5.1. Conclusions

In this paper, we examined the operators' task performance and explored their behaviors during the teleoperation of the excavator that was simulated on the lunar surface for construction tasks in time-delay conditions. As a result, we found that there was significant task performance degradation in time-delay conditions, and the operators modified their control behaviors using move-and-wait strategies. The performance and experiences in time-varying delay (ranging from 2.5 s to 3.5 s) conditions indicated that there was no significant difference with constant (3 s) time delay in the within-subject experiments. This implies that time-varying delay within the 1 s range was tolerable without significant performance degradation or workload increase for the excavator control in our experimental task setting. Our experimental study outcomes provided not only quantitative data from the measurement but also qualitative analysis of the eye-tracking data and subjective questionnaires relying on the time-delay experiences. The teleoperated human-machine interface system needs to consider the operator's performance, workload, and ergonomic requirements via the user-centered design, particularly in addressing the challenges posed by time delays in deep space network systems. With a better understanding of operators' task performance, skills, situational awareness, and behavioral strategies in time-delayed teleoperation tasks, this study shall contribute to supporting intuitive and responsive teleoperation interface designs and guidance for training.

Furthermore, broader implications for teleoperated excavators in extraterrestrial construction environments can be drawn from the findings. This study's analysis of control input data, including input sequences and not-in-use inputs, provides valuable insights for designing efficient input interfaces and predictive models by identifying the potential effective control strategies under time-delayed conditions. For training purposes, operator performance skills can be analyzed and enhanced based on various metrics, such as input count, wait time between inputs, completion time, and eye-tracking trajectories. These empirical data constitute critical indicators for assessing operator performance and can subsequently guide the improvement of interface design and the development of targeted training protocol. Moreover, data from skilled operators under different subtask types and delay conditions can be utilized to inform a machine learning model, potentially contributing to the development of semi or fully autonomous robotic systems.

5.2. Limitations and future research

In general, the studies of lunar construction have inevitable limitations due to the absence of construction experiences on the lunar surface, and the complex, harsh, and unpredictable environments remain undiscovered and unknown. Moreover, simulating real-world level physics and reflecting those into the experiments in time-delayed conditions will be a continuous challenge to solve. Communication delays basically vary based on bandwidth ranges, the distance between humans and robots, transmission processing, and computation processing, depending on the teleoperation system. Therefore, simulations under various time-delay and construction task scenarios will yield further insights into the impacts on teleoperation task performance and operator experience. Accordingly, there are some limitations in this exploratory virtual simulation study. The human subjects' performance and experience might have been influenced by unmeasured factors, such as the learning curve, task complexity, and accumulated fatigue during the tasks. Experiments that consider more compounded factors and have various conditions will be able to provide a better understanding of performance and behavior changes in time-delayed teleoperation. Also, some extreme lunar environments, including gravity, temperature, and atmosphere, were not considered in this exploratory study as those parameters are negligible in our experimental design since free-fall situations and other environmental factors do not critically influence this study's task. Our experiment primarily focused on the parameters of the time-delay conditions, visual display, and construction task performance with the teleoperated excavator.

Meanwhile, enhancing the simulation model and visual fidelity by incorporating more complex teleoperation input factors (e.g., starter, driving control, monitor control) and accurately matching the VR headset interface display to transmission delays remains to be solved. This is important for extraterrestrial construction environments where operators rely on high-fidelity interfaces to perform complex tasks in demanding and unfamiliar conditions. Future research shall focus on enhancing the display system by closely simulating visual feedback with

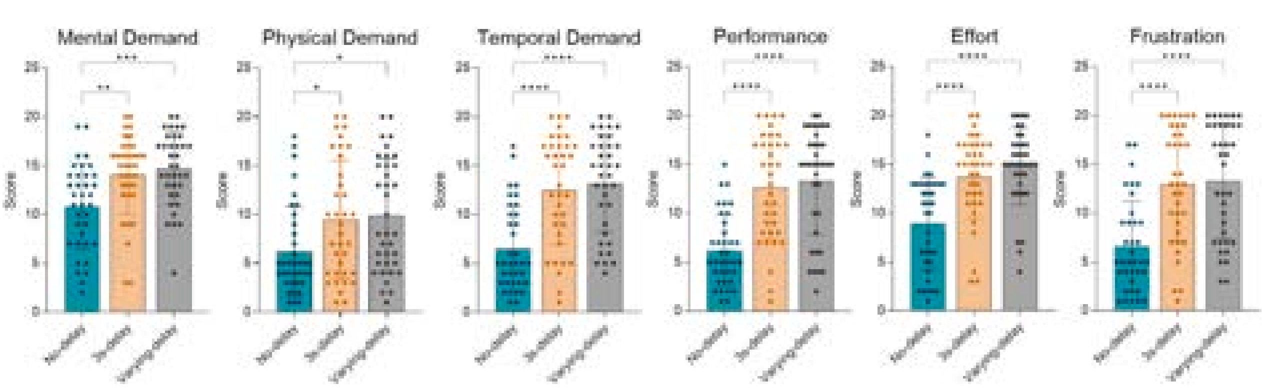

Fig. 22. Comparison of NASA-TLX scores. $^*p < .05$, $^{**}p < .01$, $^{***}p < .001$, $^{****}p < .0001$.

time-delayed conditions to further validate and extend our findings. Although this exploratory study had certain limitations, it makes a valuable contribution by addressing critical aspects of time-delayed teleoperation for lunar surface construction and excavation, an essential consideration in the early phases of space exploration.

As an ongoing study, we are investigating the impact of visual display and data quality on teleoperation performance degradation and operators' situational awareness under time-delayed construction tasks. Also, we are developing an enhanced virtual simulation modeling of the potential lunar habitat construction site (i.e., lunar south pole) and exploring how to alleviate operators' challenges in time-delay conditions. In future research, our experimental study has the potential to support an improved visual aid and force feedback interface design to enhance human-machine interaction and reduce mental workload in challenging lunar construction tasks. Our study findings will support the development of training programs for teleoperators as well. This includes training modules that simulate time-delay conditions and teach control strategies for decision support (i.e., troubleshooting and diagnostics) and situational awareness (i.e., detection of anomalous conditions) in challenging environments. Built on the findings, our ongoing and future studies will provide insights into the adaptation strategies and guidelines for teleoperation tasks in lunar surface construction.

CRediT authorship contribution statement

Miran Seo: Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Samraat Gupta:** Visualization, Software, Methodology. **Youngjib Ham:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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