Paradox of Time Pressure: Cognitive and Task Performance during Time-Sensitive and Challenging Teleoperation

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Abstract: A heavy machinery operators' ability to adhere to schedules is crucial for the success of construction projects. However, unforeseen delays often occur during projects, forcing operators to expedite their work. This pressure often presents challenges for teleoperators. Completing tasks remotely typically takes longer than performing the same tasks on-site due to reduced situational awareness and reliance on technology for perception and understanding in remote workplaces. These inherent aspects of teleoperation add complexity to tasks, especially under time-constrained conditions. This study explores operators' cognitive and task performance during teleoperation of challenging tasks under various time pressures. Thirty-one participants operated a virtual excavator under four different levels of time pressure during the experiments. Results show that appropriate time pressure enhances task performance in aspects of safety, productivity, and quality, whereas excessive pressure results in cognitive overload, disengagement, impaired situational awareness, increased errors, and reduced productivity. This research contributes to enhancing the understanding of teleoperation from the operator's perspective, addressing cognitive challenges to improve safety and efficiency during the remote operation of heavy machinery in construction. **DOI: 10.1061/JCEMD4.COENG-15417.** *© 2024 American Society of Civil Engineers.*

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Introduction

Construction automation has attracted interest as a means of preventing fatal accidents in workplaces by isolating humans from the hazardous environment. Despite technological advancements in recent decades, achieving full autonomy for construction robots still requires a great deal more research and development due to dynamic and complex nature of construction tasks, and unorganized and hazardous obstacles in construction workplaces (Hong et al. 2020; Hou et al. 2023). Moreover, automation in construction is typically obscured by open and changing environments, which are more challenging than controlled and structured work environments (Lee et al. 2022). For example, in the case of excavation tasks, various work types and differences in work conditions (e.g., potential hazards such as buried utility lines, site layouts, soil types) exist (Liu et al. 2023; Rodrigues et al. 2023) and vary from site to site and from time to time, which are quite different from indoor controlled work environments such as in the manufacturing or logistic industry.

Since humans are able to adapt to challenging conditions and overcome issues that cannot be addressed with the current level of automation, teleoperation has been employed for these environments in a variety of scenarios (Hong et al. 2020). It has been shown as a promising solution in hazardous construction sites as an intermediate form toward full automation (Ito et al. 2021; Lee et al. 2022). Teleoperation is the control of a slave robot via a master robot by a human operator over a remote location and it is one type of human-in-the-loop automation (Lee et al. 2022; Lee and Ham 2022b). This implies humans have a significant impact on distanced robots' movement since they make decisions and control based on their awareness and understanding of the distanced situations. Although supporting technologies for sensing the distanced work environment exist, teleoperators are known to still suffer from impaired situational awareness and limited sensory feedback compared to onboarding control. Consequently, teleoperators are required to handle more cognitive workload and information processing demands (Liang et al. 2021), which leads to spending more time than onboarding control (Hayashi and Tamura 2009).

Time pressure is a routine phenomenon in construction sites (Han et al. 2014; Lee and Ham 2024; Michalak 1997). This could worsen during teleoperation since it is more demanding than onboarding control. This pressure is influenced by a myriad of factors, such as pressure from top management, altered project deadlines, weather dependencies, sequential task interdependencies requiring swift completion of subsequent tasks, and the constraints imposed by project budgets (Lee and Ham 2024). Beyond these factors, the complexity of the urban construction environment adds another layer of time pressure on operators. In contrast to open spaces, urban environments involve various work-related elements along with safety issues that need to be taken into account, such as pedestrians, traffic, nearby workers, construction equipment, roads, structures, and buried hazards like underground utilities (Liu et al. 2023). Since several inherent challenges in the urban context need to be addressed simultaneously, devoting much time to each object becomes extremely challenging during work. In this scenario, time pressure stems not merely from external deadlines, but is inherently linked to the necessity of managing the multifaceted and complex nature of urban construction environments. At the same time, an operator must be careful and precise, considering that a single

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mistake in such operations with heavy machinery could lead to fatal, disastrous, and costly consequences. This implies that operators are tasked with executing multiple responsibilities concurrently under time constraints, requiring them to consider productivity, safety, and the quality of their work at the same time. Handling multiple task objectives simultaneously under pressure might not be a problem for operators if the task is simple and time pressure is minimal. However, construction tasks performed by heavy machinery are not always easy, for example, when excavators are operated near hazards such as underground utilities as opposed to those without obstacles nearby. Moreover, time pressure in construction varies across different levels rather than being uniform. In order to conduct complex construction tasks, operators are often required to perform with a high level of cognitive workload. In such stressful cases, human performance may deviate from the expected norms under normal conditions (Nnaji and Gambatese 2016). Further exploration is imperative to understand comprehensively how operators react, behave, and perform in various situations, including normal to challenging ones, with time pressure.

This paper aims to investigate how time-sensitive teleoperations, from no to extreme time pressured conditions, affect human operators' cognitive workload and task performance regarding safety, productivity, and quality aspects during conducting challenging tasks. The findings of this study will contribute significantly to the development of knowledge in the field of construction teleoperation, particularly from the viewpoint of a human operator by offering an in-depth analysis of human cognition, behavior, and task performance under diverse conditions.

Research Background

Human Cognition and Behavior under Time Pressure

Time pressure can be defined as the perceived requirement to complete a task within a designated period, which is usually shorter than the baseline period (Kern et al. 2023; Nepal et al. 2006; Zhang et al. 2023). Time pressure has been studied in various contexts including the aviation or automobile industry, and it is known to affect human cognition, emotions, behavior, and performance of their task (Cœugnet et al. 2013; Kern et al. 2023; Rendon-Velez et al. 2016; Schilbach et al. 2023; Zakay and Wooler 1984), which is also common in the construction field. The schedule pressure can be alleviated by putting more resources (e.g., workers, equipment) into the task so that the same amount of work can be accomplished in a shorter period of time. However, additional resources are not always available because these pressures are not typically anticipated, and in turn, this solution is likely met with reluctance when the contractor is facing resource constraints. Because of these reasons, construction workers often experience schedule pressures due to work demands from the top. From the managerial perspective, there is an advantage to making people busy and seeing them busy to expect the productivity to increase. However, actual human behavior and decision-making might not be the same as the management team's expectation that they would simply work faster.

A human's cognition consists of two parts: working memory known as short-term memory, which exhibits constraints in terms of both capacity and duration, and long-term memory known as unlimited capacity (Bartsch and Oberauer 2023). During the task, individuals require their cognitive workload to process information to make appropriate decisions according to Cognitive Load Theory (Sweller 2024; Sweller et al. 2011). Cognitive workload is the user's perception of mental workload, the amount of working memory resources required to accomplish a task. Proper decision-making is important for the success of the task: (1) gathering and analyzing information about the work environment and context, (2) identifying possible alternatives or plans based on an understanding of the work context, and (3) making a decision and taking action based on the alternatives. This process may take a while depending on how hard the task is. However, under time pressure, individuals are forced to make decisions more quickly, which means the process should be shortened or accelerated. Within a limited amount of time, humans may not be able to thoroughly assess the environment or situation, plan for alternatives, and make the right decision based on those alternatives. Under time pressure, the amount of information that needs to be processed is likely to increase as compared to a nontime pressure situation. According to the Adaptive Decision Maker theory, in this situation, decision-makers use heuristic methods based on their past experiences, causing suboptimal performance without fully taking all factors into account (Payne et al. 1993). This process is fast and effortlessly aids the working memory, so there is not enough time for good-quality decision-making (Luokkala and Virrantaus 2014). Although heuristics provide mental shortcuts to reduce mental workload, this decision may not always be appropriate. This may lead to incorrect understanding of the work environment as well as errors due to insufficient time allocated to the reasoning process. Additionally, time pressure is known to negatively affect human emotions by causing excessive stress, productivity demands, negative emotional reactions, anger, and aggressive performance (Cœugnet et al. 2013; Rafique et al. 2023; Szollos 2009). This would lead to risk-taking behaviors or decisions to achieve goals in time, just like a driver may not be able to pay close attention to their surroundings and neglect safety when speeding (Su et al. 2023).

Human Operator in Construction Teleoperation

Construction teleoperation gained its interest in the late 1990s to remove humans from the hazardous work environment and overcome skilled labor shortages (Liu et al. 2023; Okishiba et al. 2019). There has been substantial technology-driven research for a teleoperation system, including sensing (Kim and Chi 2020; You et al. 2023), communication (Kim et al. 2018; Nagai et al. 2024), and optimal algorithms for system architecture (Feng et al. 2023; Yao et al. 2023). However, human-centered research has not received much attention and little has been conducted in construction teleoperation (Lee et al. 2022). As teleoperators are the key component of telerobotic systems since their decisions and actions directly influence the movement of robot end effectors, research on the human side is required in order to provide a comprehensive understanding of teleoperation for system enhancement. In teleoperation, operators must use interfaces for understanding the working environment (information feedback interface) and commanding the action or movement (control interface) to manipulate the construction robot from a distance (Basañez and Suárez 2009). Although controls may be similar or the same as in onboarding (e.g., joysticks or buttons), the way of understanding the work environment is completely different. Most of the information is conveyed visually in teleoperation so teleoperators highly rely on visual interfaces to understand distanced working environment (Moniruzzaman et al. 2022), while onboarding operators utilize multiple sensory systems to comprehend their working environment including visual perception, tactile sensations, and auditory sense. In other words, teleoperators have limited information sensing and spatial awareness of the working space as compared to onboarding operations. Since excavation work also requires doing the job in a safe manner by avoiding nearby obstacles (e.g., underground utilities), teleoperators experience more cognitive workload for information processing compared to onboarding operations in order to do the job safely with impaired situational awareness that comes with teleoperation. Also, they need more time to complete the same task. Therefore, if these teleoperators are subjected to time pressure, their job would be quite demanding since they will suffer from processing information and making decisions with less time. There has been prior research into how time pressure affects construction workers' safety and hazard recognition abilities. A prior study on time pressure in construction examined the electrical line workers' impaired safety-related performance and risk-taking behavior under high cognitive demand based on the Risk Compensation Theory (Pooladvand and Hasanzadeh 2022). Another study showed construction workers had impaired hazard recognition under time constraints but improved performance with relatively easy tasks (Han et al. 2021). They also reported that work performance improved under time pressure for relatively easy tasks.

Gaps to Fill

For a successful teleoperation system, it is crucial to understand human teleoperator behavior and decision-making in various scenarios since humans directly influence robot performance. Considering the nature of the construction project, it is highly likely that human operators will face time pressure while teleoperating the task. Teleoperation demands more cognitive effort than onboard controls, causing operators to work more slowly and experience stress, especially during challenging tasks. Thus, investigating their performance under time pressure through observation and experimentation is vital for enhancing teleoperation systems and operator efficiency.

Despite previous studies on time pressure among construction workers (Han et al. 2021; Pooladvand and Hasanzadeh 2022), a gap in knowledge still exists regarding the performance of construction robot teleoperators, especially in situations with difficult tasks under time pressure. As opposed to common construction workers, they control multidegree-of-freedom robots for intricate tasks. In addition, although most of the time pressure related studies considered binary conditions, the absence versus the presence of time pressure, we considered four different levels of time pressure that are likely present in a real construction environment. Considering that human subject research involves conducting experiments in abstract simulated environments to acquire knowledge, understand, and gain insights into human behavior and performance, various levels of time pressure make it easier to mimic a real-life construction site environment than a binary environment. Thus, this study aims to investigate how different levels of time pressure affect excavator teleoperation task performance and cognitive workload when performing a challenging excavation task and interpret the results based on theoretical foundation knowledge to comprehensively understand construction teleoperation and gaps that exist for future exploration.

Virtual Simulation Model of Realistic and Time-Critical Excavator Teleoperation

Site Modeling

Our scope for the construction robot in this study is an excavator, which is one of the most widely used construction robots in the field. For the scope of the challenging construction task, excavation near underground utilities was considered since underground utility strikes are known to result in fatal accidents and significant compensation costs during excavation (Lee et al. 2024; Liu et al. 2022, 2023; Tanoli et al. 2019). For time-sensitive settings, different levels of time pressure were modeled to examine various states and performance of teleoperators. An overview of the key elements in this study is displayed in Fig. 1.

To improve the fidelity of human subject research, this study developed a virtual model that matched real-world conditions as closely as possible. Our virtual simulation includes key features such as a physics engine to simulate soil dynamics as well as realistic excavation tasks. In the virtual environment, daylight illumination, soil compaction variability, adverse weather scenarios, and communication delays were modeled. We visited several construction sites in College Station, Texas for site modeling. During our site visits, four operators and safety managers reviewed and confirmed our experiment environment design as a challenging excavation task [Fig. 2(a)]. Two concrete pipes were placed for the task design. Compared to digging without pipes or digging with a single pipe, this task is a lot more challenging since participants need to control the excavator delicately to avoid colliding with pipes [Fig. 2(b)]. In the experimental scenario, participants were asked to dig soil between two buried pipes by manipulating the bucket while avoiding colliding with the pipes, then place the soil on the landfill on the left side of the excavator five times [Fig. 2(c)]. The excavator used was a 21-t

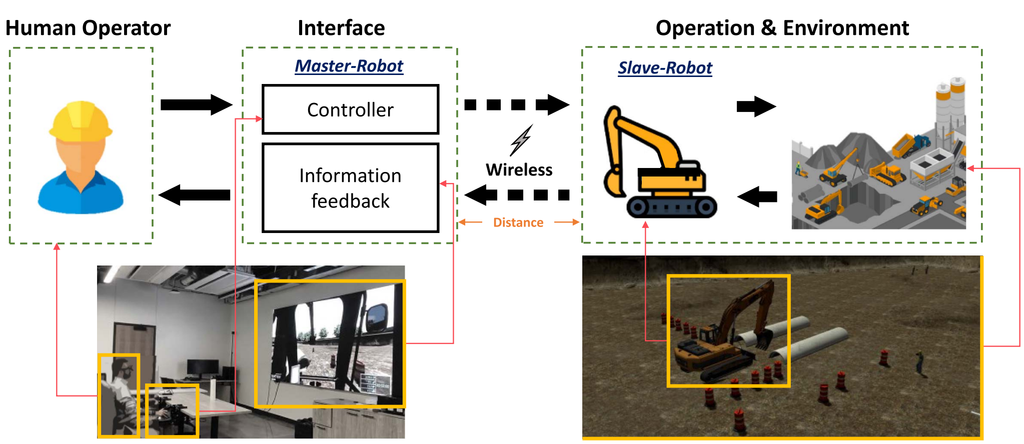

Fig. 1. Virtual teleoperation environment in construction.

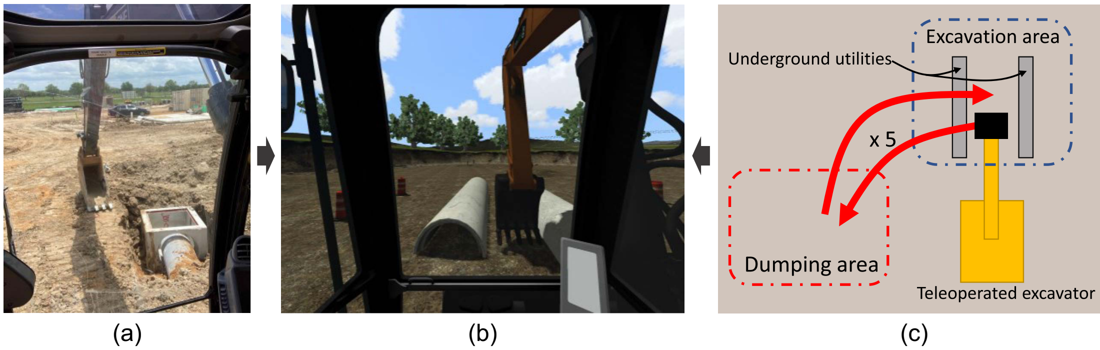

Fig. 2. Excavation site design and task: (a) real excavation site; (b) virtual excavation site referencing real site; and (c) excavation task for the experiment.

hydraulic excavator (Figs. 1 and 2). The joysticks were configured according to ISO standards. Six excavator operators evaluated our virtual model. They found that soil dynamics, characterized by realistic soil particle movement, as well as hydraulic movements of the excavator's components closely resembled those experienced at an actual excavation site.

Time Pressure Modeling

The time pressure and experiment procedure were built upon previous studies (Han et al. 2021; Kocher and Sutter 2006; Rendon-Velez et al. 2016; Zakay and Wooler 1984). In most cases, time pressure methods have been pretested through pilot studies and consist of subtracting a certain amount of time from the baseline time (Han et al. 2021; Pooladvand and Hasanzadeh 2022; Zakay and Wooler 1984), subtracting time with a ratio (Koldijk et al. 2014; Rendon-Velez et al. 2016), or alarming at certain intervals (Rendon-Velez et al. 2016). To mimic the real-world setting where various time pressure levels exist, the four different levels were designed by subtracting time based on a ratio from each participant's baseline time (Lee and Ham 2022a). The No time pressure (NTP) session was the first session conducted by all participants. Each participant's NTP completion time was used as the baseline for the following three sessions: Low time pressure (LTP), Medium time pressure (MTP), and High time pressure (HTP). During LTP, participants are required to finish tasks within 90% of baseline, in MTP, participants are required to finish tasks within 80% of baseline, and during HTP, participants are required to complete tasks within 70% of baseline. For example, if a participant's NTP completion time was 300 s, they were told to complete the session within 270 s for LTP, 240 s for MTP, and 210 s for HTP.

Each session consisted of five excavation cycles, which required participants to dig and dump five times each. In order to control cognitive bias due to learning effects observed during the pilot test, we implemented the below to give time pressure, and their validity was confirmed in prior studies:

1. Randomization: We randomized the order of the LTP, MTP, and HTP sessions for each participant (Fig. 4). This randomization prevents participants from developing a fixed strategy based on the sequence of the sessions, thereby reducing the potential for learning effects.
2. Sample Session: Prior to the main experiments, participants completed a sample session (Fig. 4). This sample session was designed to familiarize participants with the task without influencing their performance in the subsequent sessions. By providing this initial practice, we aimed to reduce any first-time bias and ensure that participants' performance in the main sessions reflected their response to time pressure rather than initial learning.
3. Verbal Cues: To avoid the learning effect, time information was not visually provided during time pressured sessions. Instead, verbal cues (Rendon-Velez et al. 2016) indicated if participants were behind schedule, preventing them from knowing their success intuitively and using past visual cues to predict their future performance. This method, tested in prior studies (Lee and Ham 2022a, 2024), ensured consistent time pressure and experimental validity. To minimize additional learning effects, verbal cues were kept consistent across all sessions, ensuring participants received uniform feedback throughout the experiment. Thus, every half-cycle, a manager checks whether the participant is on track in terms of the given timeline, then says, "Hurry up," "You are late," and "You are behind schedule," if the participant is behind schedule.

Apparatus and Data Collection

In the experiment, participants manipulated the excavator with two joysticks, the control interfaces of the excavator, while observing the movement of the excavator and the surrounding situation with a 135-in. screen, illustrated in Fig. 1. During the experiment, task performance data (e.g., collision frequency, completion time, and soil quantity) and physiological responses of operators were collected in real time (Fig. 3).

There are three goals for each excavation session during the experiment. (1) Avoid collisions: to measure this, the number of collisions with the buried pipes were collected. This measure shows the control accuracy and how much the participant safely and carefully dig soil without utility strikes; (2) dig a certain amount of soil: to measure this, the soil quantity on the dumping area was collected [Fig. 2(c)]. To assess the participant's productivity, it is important to measure the soil quantity when the task is done since each participant has five opportunities to dig soil between the two utility lines in each session; (3) finish the task on time: the task for all sessions is the same, but different time pressures (LTP, MTP, HTP) were assigned for each session. Thus, we measured the completion time at each task in order to determine how quickly they completed the task.

Teleoperation performance is greatly determined by the human operator's decisions and actions. However, decisions and actions taken by operators may vary depending on their physical and mental condition. Consequently, it is vital to measure the fatigue and cognitive workload of the operator since these factors can affect the control performance. To quantify the cognitive workload for each session, we build upon the NASA Task Load Index (TLX) to

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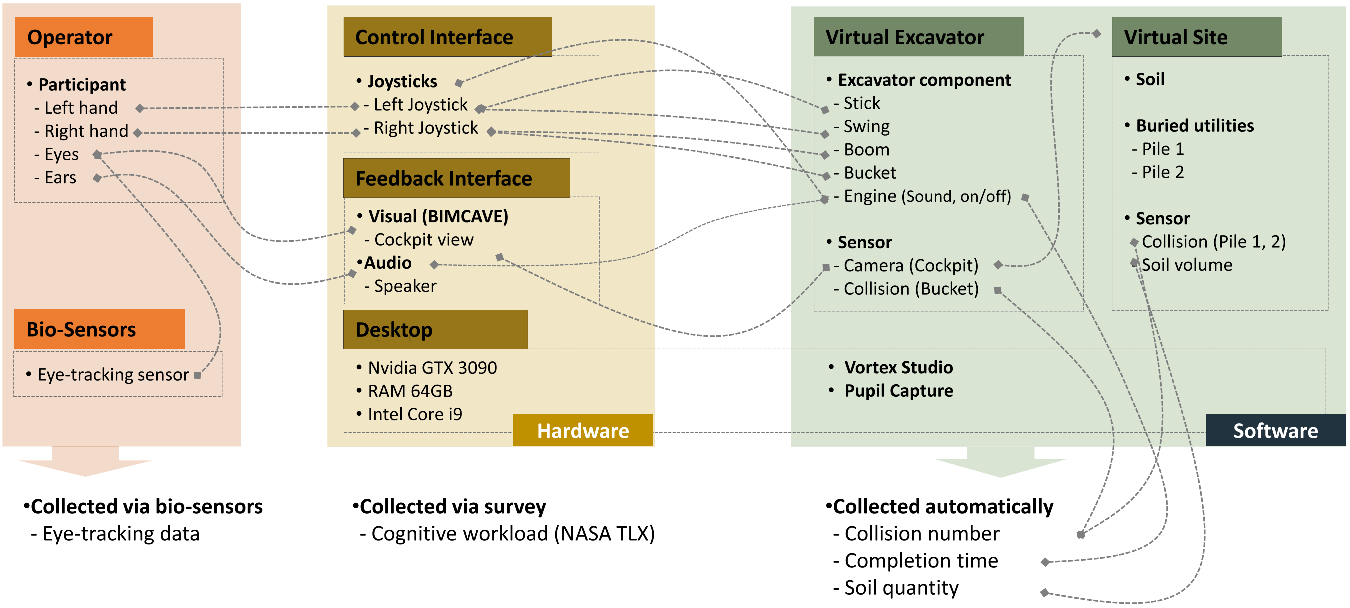

Fig. 3. Apparatus and data collection.

measure perceived workload in a subjective and multidimensional manner (Hart 1986). After each session, participants were asked to rate the NASA TLX questionnaire on a scale of 0 to 10 in six aspects (mental demand, physical demand, temporal demand, self-rated performance, effort, and frustration level). Based on the ratings provided by participants, six aspects of cognitive workload in each session with different levels of time pressure were assessed. Meanwhile, eye-tracking sensors have been used for monitoring human cognitive workload in real time (Merat et al. 2014; Shahini et al. 2022), such as for driving and flight simulations (Park and Zahabi 2022; Shahini et al. 2022; Zheng et al. 2022). Among various pupillometry measures, this study focused on pupil size variations. Changing pupil dilation indicates that the locus coeruleus norepinephrine (LCNE) system is strongly associated with psychological flow, which influences decisions regarding whether to engage or disengage in the activity the human is involved in Lu et al. (2023). Pupil size usually increases when task difficulty increases (Bailey and Iqbal 2008; Park and Zahabi 2022). Prior studies have verified that pupil size can be used as a near-real-time indicator of cognitive workload (Chen and Epps 2014; Lohani et al. 2019). Specifically, this study used the percentage change in pupil size (PCPS) to measure physiological responses rather than using absolute changes in pupil size as a measure. Due to the significant variances in baseline pupil sizes among individuals, this method provides a precise and personalized assessment of pupillary reactions to stimuli, offering an accurate reflection of physiological responses.

Experiments

Participants

Students at Texas A&M University with Architecture, Engineering, and Construction (AEC) majors (e.g., Construction Science, Architecture, Civil Engineering) or who have experience in the AEC industry were invited because they have domain knowledge and understanding of the construction work environment. Before the main experiment, there was a demonstration for each participant. Participants were required to flawlessly execute 15 consecutive excavator control movements, including arm out/in, swing left/right, boom down/up, curl/uncurl bucket, using two joysticks within 10 attempts, to demonstrate the basic skills expected of novice excavator operators. Thirty-one participants (28 males, 3 females; $M_{\mathrm{age}} = 24.5$, $SD_{\mathrm{age}} = 3.81$) who were able to demonstrate their controls successfully were able to conduct the main experiment in our study. The sample size was determined based on employing G $*$ Power, with a significance level (α) of 0.05, a desired power (1-β) of 0.8 and based on Cohen's moderate effect size of 0.25

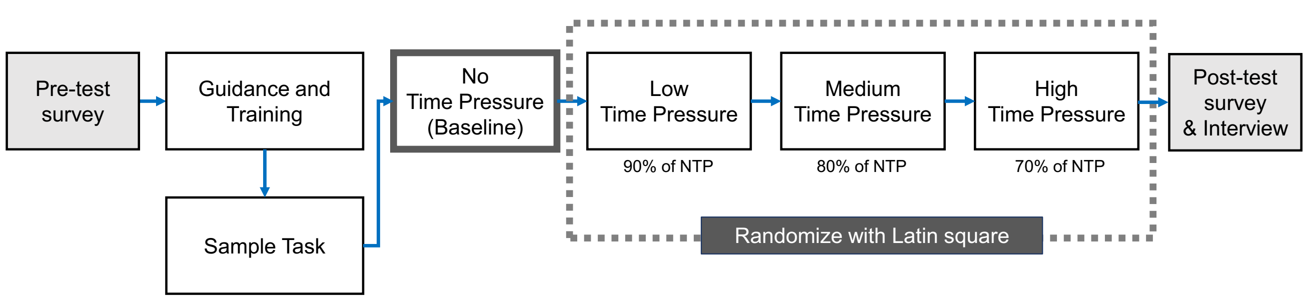

Fig. 4. Experimental procedure.

(Faul et al. 2007). Fig. 4 illustrates the procedures of the experiment for each participant.

Procedure

Step 1: Pretest questionnaires [gender, age, three-dimensional (3D) game experience, and work experience in the AEC industry] were provided to the participant before the experiments began.

Step 2: Participants were trained not to hit the utility lines during excavation. Sometimes, the participants find it hard to engage or focus on the task during simulation studies because it is not a real environment. To make them perform like an actual operator, two methods were used to increase their engagement and involvement: perspective-taking (Herrera et al. 2018) and additional compensation (Pater et al. 2021). During perspective-taking (i.e., where participants are asked to imagine themselves in specific circumstances), they were told that they are real excavator teleoperators who earn income by operating the excavator. They were also told that they would receive an additional compensation based on their overall performance during the main experiment.

Step 3: To mitigate biases associated with the learning curve and the heightened cognitive load and frustration often encountered when performing a challenging task for the first time, participants were initially exposed to sample tasks without any time constraints. This preliminary phase was designed to acquaint them with the task environment, thereby easing the typical stress and anxiety experienced during initial attempts at complex tasks.

Step 4: In the experimental task, we had participants excavate the soil between two utility pipes and dump the soil by swinging the excavator body to the left, repeating a total of five times. At first, all participants performed excavation in the absence of time pressure. The time measured with NTP was used as the reference time when applying the time pressure. Participants were asked to finish the task at 90% of NTP time for the LTP task, 80% of NTP time for the MTP task, and 70% of NTP time for the HTP task. During the experiments with time pressure, we tried to reduce the learning effect bias by randomizing the orders of time pressure levels for each participant. After each task, the NASA TLX questionnaire was used to measure the cognitive workload depending on the time pressure levels (Hart 1986).

Step 5: To get insights from the participants beyond the objective results, we conducted post-experiment interviews.

Statistical Analysis

The statistical significance was determined using an analysis of variance (ANOVA) with significance reported at $\alpha = 0.05$. An ANOVA is a statistically significant method used to compare the means of multiple groups in order to determine whether the differences are statistically significant, which can be used to determine whether performance varies significantly under the different time pressures. Other statistical techniques included t-tests, which are useful for comparing the means of two groups, and regression analysis, which models the relationship between a dependent variable and one or more independent variables. However, these methods are less suitable for our study since t-tests do not adequately handle multiple group comparisons, whereas regression analysis is more complex and better suited to different types of data. Post hoc analysis was conducted with Bonferroni corrections to account for multiple comparisons. Levene's test was used to check the equality of variances to ensure the assumptions of ANOVA were met. When the distribution of data did not meet the assumption of the normal distribution, the Games-Howell correction was performed to make multiple comparisons for that set of data at an $\alpha = 0.05$. In the figures, error bars represent standard errors, and asterisks (*) represent significant differences between groups identified through post hoc analysis (*: <0.05; **: <0.01; ***: <0.001). These statistical tests were chosen because they are robust methods for analyzing the effects of different time pressures and controlling for Type I errors in multiple comparisons, ensuring the reliability and validity of our findings.

Results

Task Performance

Completion Time

Completion time represents the amount of time spent by the participant on completing the task at each session, which could be interpreted as the speed at which the participant completed the task. An ANOVA was conducted to determine the effect of time pressure on completion time as shown in Fig. 5. The result indicates that time pressure had a significant impact on completion time $[F(3,116) = 24.44,\ p < 0.001,\ p < 0.001,\ \eta 2 = 0.39]$. Post hoc comparisons were performed to examine pairwise differences of completion time between the time pressure conditions. The result indicates that the NTP ($M_{CT\_\mathrm{NTP}} = 348.47$, $SD = 62.62$) had a significantly longer completion time (all $p < 0.001$) than other time-pressed sessions (LTP, MTP, HTP). Although the result showed a difference from the LTP ($M_{CT\_\mathrm{LTP}} = 264.93$, $SD = 47.90$), the MTP ($M_{CT\_\mathrm{MTP}} = 257.53$, $SD = 45.49$), and the HTP ($M_{CT\_\mathrm{HTP}} = 247.10$, $SD = 48.53$) and the completion time is shorter when participants are given a greater time pressure, no statistical significance was reached for any of these differences (all $p > 0.05$).

Considering that participants were required to complete a task within a set of time limits, it is critical to determine whether they were able to complete the task. Based on the data collected, it appears that the success rate of completing the task within the time limits decreased as the time pressure increased. In the LTP session, almost all participants were able to reach the goal (96.7%, 29 out of 30 participants), while in the MTP session, slightly over two-thirds of participants were successful (70%, 21 out of 30 participants). However, in the HTP session, more than half of the participants were not able to meet the time goal (40%, 12 out of 30 participants).

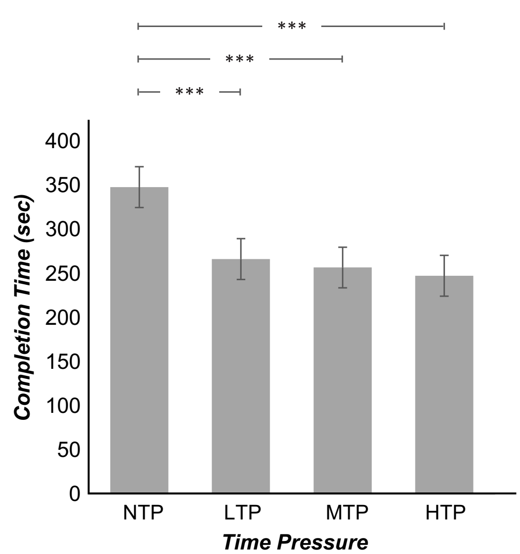

Fig. 5. Effect of time pressure on completion time.

Collision Number

The collision number presents how accurately and delicately the operator controlled the excavator bucket by using two joysticks during the soil excavation task between two pipes without collision errors. The number of collisions in this study is defined as the total number of collisions between the excavator bucket and the two pipes during the session. Collisions are detected automatically when the bucket and a pipe either to the left or right make contact. Prior to the experiment, participants were specifically instructed on the importance of avoiding underground utilities, using real-life examples to illustrate the dangers of contacting buried pipes. This safety training was not only a precaution but also a critical element in assessing participants' behavior during the experiment. By integrating safety education directly into the experimental protocol, like safety meetings at the construction job site, we tried to enhance awareness and prevent potential accidents during the experiments. The result of the collision numbers during the different levels of time pressure is shown in Fig. 6.

A one-way ANOVA revealed a significant effect of time pressure on the collision number $[F(3,62.83) = 8.73,\ p < 0.001,\ \eta 2 = 0.12]$. Post hoc comparisons were used to examine the pairwise differences in collision numbers between the time pressure conditions. According to the post hoc analysis, there were significantly fewer collisions in the LTP ($M_{\mathrm{COL\_LTP}} = 3.16$, $SD = 3.73$) than in the NTP ($p = 0.022$), the MTP ($p = 0.001$), and the HTP ($p < 0.001$). No statistically significant difference was found among the NTP, MTP, and HTP on collision number. However, there was a trend indicating that collision numbers ($M_{\mathrm{COL\_HTP}} = 10.47$, $SD = 8.45$) were higher in the high time pressure session, compared to NTP ($M_{\mathrm{COL\_NTP}} = 6.43$, $SD = 4.73$) and MTP ($M_{\mathrm{COL\_MTP}} = 8.33$, $SD = 6.05$).

Soil Quantity

All participants have a total of five opportunities to dig soil in each session of NTP, LTP, MTP, and HTP. Participants were preinstructed to dig at least 8 t of soil per session, so they needed to dig 1.6 t of soil per scoop on average. At most, 2.3 t of soil can be loaded per scoop in our experiment setting. Thus, the maximum amount of soil that can be excavated with five scoops, meaning each session, is 11.5 t.

According to the analysis results of variance for the effect of time pressure on soil quantity, the level of time pressure had a significant impact on the amount of soil dug during the experiment $[F(3,116) = 3.67,\ p = 0.014,\ \eta 2 = 0.09]$. Post hoc analysis shows that the soil quantity in the LTP ($M_{SQ\_\mathrm{LTP}} = 9.54$, $SD = 1.26$) was significantly higher ($p = 0.008$) than the HTP ($M_{SQ\_\mathrm{HTP}} = 8.27$, $SD = 1.73$) and no other significant differences were found across other conditions. But with trends with the mean soil quantity, the LTP session showed the highest soil quantity, followed by the NTP ($M_{SQ\_\mathrm{NTP}} = 9.07$, $SD = 1.28$), the MTP ($M_{SQ\_\mathrm{MTP}} = 8.88$, $SD = 1.72$), and the HTP as shown in Fig. 7. Considering that participants were required to dig and dump at least 8 t of soil by the end of each session, it is important to determine whether they were able to dump at least 8 t in the designated area within 5 scoops in each session. In the NTP session, the success rate was 83.3%, which means 25 out of 30 participants were able to reach the goal for soil quantity. The LTP session had a success rate of 86.7%, which means 26 out of 30 participants were successful. The success rate for MTP session was 73.3%, which means 22 of 30 participants achieved the goal. In HTP session, the success rate was 63.3%, which means 19 out of 30 participants reached their goals. The highest success rate was observed at LTP, not NTP, and the lowest success rate was found at HTP, where excessive time pressure was provided.

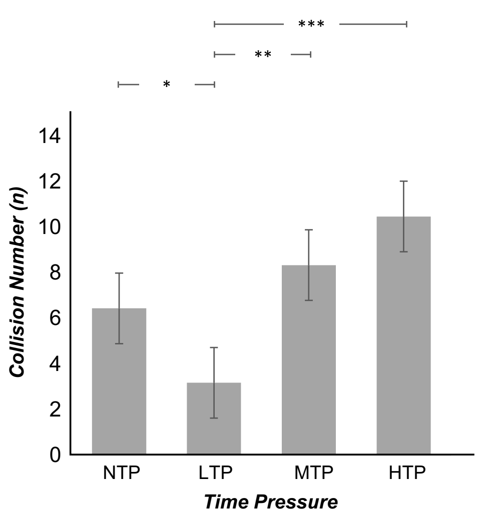

Fig. 6. Effect of time pressure on collision number.

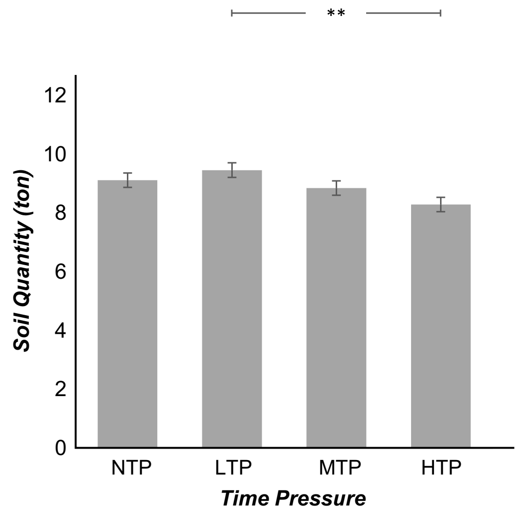

Fig. 7. Effect of time pressure on soil quantity.

Cognitive Workload with the Subjective Response

Mental Demand

The statistical analysis with ANOVA shows that time pressure significantly affects the mental demand (MD) of the participants $[F(3,116) = 11.55,\ p < 0.001,\ \eta 2 = 0.23]$. The average shows that the mental demand during the LTP ($M_{MD\_\mathrm{LTP}} = 3.20$, $SD = 1.75$) was the lowest, highest during the HTP ($M_{MD\_\mathrm{HTP}} = 5.63$, $SD = 1.96$), and the significant difference was found between them with post hoc ($p < 0.001$). The LTP was also significantly lower than the MTP ($M_{MD\_\mathrm{MTP}} = 4.60$, $SD = 2.01$) in the post hoc ($p = 0.012$). No difference was found between the LTP and NTP ($M_{MD\_\mathrm{NTP}} = 3.37$, $SD = 1.96$). The NTP had only significant difference with the HTP ($p < 0.001$).

Physical Demand

The ANOVA result indicates that time pressure significantly affects the physical demand (PD) among participants $[F(3,116) = 4.11,\ p = 0.008,\ \eta 2 = 0.10]$. Post hoc analysis reveals that only one

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significant difference was found between the NTP and HTP ($p = 0.012$). The physical demand at the HTP ($M_{MD\_\mathrm{HTP}} = 3.63$, $SD = 2.24$) was higher than the NTP ($M_{PD\_\mathrm{NTP}} = 2.20$, $SD = 2.13$). Even though there was no statistically significant difference between the remaining sessions, physical demand increased gradually for the NTP, ($M_{MD\_\mathrm{LTP}} = 2.53$, $SD = 1.63$), MTP ($M_{MD\_\mathrm{MTP}} = 3.27$, $SD = 1.72$) and HTP as shown in Fig. 8.

Temporal Demand

Temporal demand (TD) is a measure that tells how much time pressure participants felt in each session. Therefore, this can also be used to determine whether the time pressure is appropriately applied to each of the LTP, MTP, and HTP sessions during the experiment. The ANOVA result shows that participants' temporal demands were significantly affected by time pressure $[F(3{,}116) = 72.76,\ p < 0.001,\ \eta2 = 0.65]$. A significant increase in temporal demand across the sessions was seen with the order being the NTP session ($M_{TD\_\mathrm{NTP}} = 0.93$, $SD = 1.53$), followed by the LTP session ($M_{TD\_\mathrm{LTP}} = 2.57$, $SD = 1.61$), MTP session ($M_{TD\_\mathrm{MTP}} = 4.93$, $SD = 1.87$), and HTP session ($M_{TD\_\mathrm{HTP}} = 6.80$, $SD = 1.68$). Between the NTP and LTP, the p-value was 0.001, and between the NTP-MTP, NTP-HTP, LTP-MTP, LTP-HTP, and MTP-HTP, the p-value was less than 0.001. The results infer that the participants experienced a significant difference of temporal demand in the different levels of time pressures.

Self-Rated Performance

The results of the statistical analysis with ANOVA indicate that time pressure significantly impacted the participant's rating of their own performance (SP) $[F(3{,}116) = 8.43,\ p < 0.001,\ \eta2 = 0.18]$. Post hoc comparisons revealed that the highest performance rated by themselves was observed in the LTP ($M_{SP\_\mathrm{LTP}} = 8.43$, $SD = 1.36$), and significant differences were found compared to the NTP ($M_{SP\_\mathrm{NTP}} = 7.37$, $SD = 1.33$) with a p-value of 0.042, and HTP ($M_{SP\_\mathrm{HTP}} = 6.53$, $SD = 1.75$) with a p-value less than 0.001. Participants rated their performance the lowest in the HTP session, and there was a significant difference with a p-value of 0.009 observed with the MTP ($M_{SP\_\mathrm{MTP}} = 7.80$, $SD = 1.54$), but no significance was found when comparing that with the NTP.

Effort

This metric indicates the amount of physical and mental effort (EF) required for each session. According to the statistical results, time pressure did not show a significant effect on participant's effort in completing the task $[F(3{,}116) = 2.27,\ p = 0.085,\ \eta2 = 0.06]$. It was observed that effort on the NTP ($M_{EF\_\mathrm{NTP}} = 5.43$, $SD = 2.47$) and the LTP ($M_{EF\_\mathrm{LTP}} = 5.50$, $SD = 2.78$) were relatively similar. A slight increase in effort was shown in the MTP ($M_{EF\_\mathrm{MTP}} = 6.07$, $SD = 1.93$) and a further increase was observed in the HTP ($M_{EF\_\mathrm{HTP}} = 6.77$, $SD = 1.81$).

Frustration Level

According to the statistical analysis conducted with ANOVA, the participants' frustration level (FR) is significantly affected by time pressure $[F(3{,}116) = 10.71,\ p < 0.001,\ \eta2 = 0.22]$. Post hoc analysis reveals that participants reported the highest frustration in the HTP ($M_{FR\_\mathrm{HTP}} = 4.43$, $SD = 2.16$) than the other three conditions: the NTP ($M_{FR\_\mathrm{NTP}} = 2.37$, $SD = 1.79$), LTP ($M_{FR\_\mathrm{LTP}} = 1.67$, $SD = 1.83$), and MTP ($M_{FR\_\mathrm{MTP}} = 3.00$, $SD = 2.08$) and showed significant differences across the sessions ($p < 0.001$, $p < 0.001$, $p = 0.054$).

Overall Score

As a subjective assessment of cognitive workload, the weighted NASA TLX score in this study was analyzed as presented in Fig. 9. Subscales are weighted based on the results of pairwise comparisons between subscales conducted by each participant at the beginning of the NASA TLX survey. There are six subscales in NASA TLX, which resulted in 15 pairwise comparisons. Overall weight is calculated as the sum of the raw scores of each subscale multiplied by the number of times the subscale was selected in the pairwise comparison, then divided by the sum of the weights, which is 15. The participant responded to the NASA TLX survey right after each time pressure session (NTP, LTP, MTP, HTP). The results of the ANOVA analysis indicate that time pressure significantly impacted the participant's subjective cognitive workload rating based on the NASA TLX weighted scores $[F(3{,}116) = 23.33,\ p < 0.001,\ \eta2 = 0.38]$. Post hoc analysis shows that the HTP ($M_{\mathrm{TLX\_HTP}} = 5.35$, $SD = 1.44$) had the significant highest score compared to the NTP ($p < 0.001$), LTP ($p < 0.001$), and MTP ($p = 0.011$).

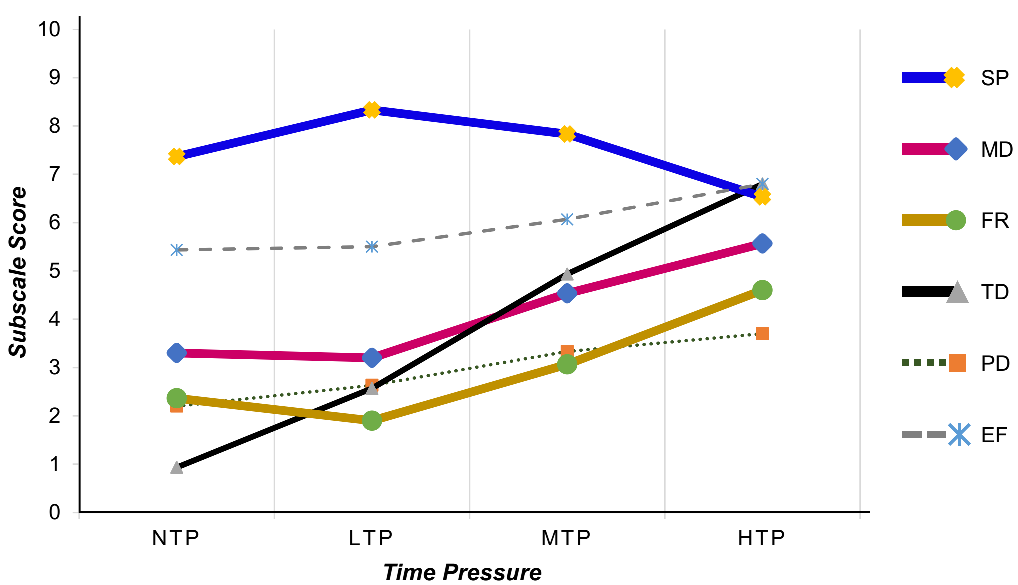

Fig. 8. Effect of time pressure on NASA TLX subscale score.

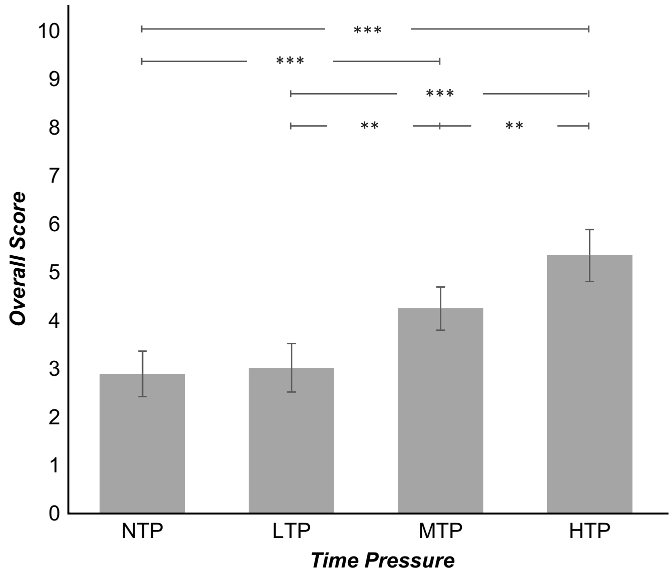

Fig. 9. Effect of time pressure on NASA TLX weighted overall score.

Next, the MTP ($M_{TLX\_MTP} = 4.25$, $SD = 1.20$) was ranked second highest, significantly higher than the NTP ($p < 0.001$) and LTP ($p = 0.002$). There was no statistical significance between the NTP ($M_{TLX\_NTP} = 2.90$, $SD = 1.26$) and LTP ($M_{TLX\_LTP} = 3.03$, $SD = 1.34$).

Cognitive Workload with Physiological Response

The physiological response was measured with pupillometry data. Prior to beginning the main experiment, the baseline pupil size was measured at the beginning of the study. Pupil size was measured in real time during the experiment. In every excavation task during each session, each participant was required to perform five digging and dumping actions. These tasks were categorized into three distinct activities: approaching the excavation site, excavating the soil, and dumping the excavated material. Given that each participant had to carry out five excavation cycles per session, this resulted in the collection of 15 average PCPS data points for each session. A two-way ANOVA was performed to analyze the effect of time pressures and excavation activity on the cognitive workload derived from the physiological response. The analysis showed a statistically significant effect of time pressure on the physiological response $[F(3,1728) = 11.59,\ p < 0.001,\ \eta2 = 0.020]$. There was also a significant main effect of excavation activity on the physiological response $[F(3,1728) = 5.84,\ p = 0.003,\ \eta2 = 0.007]$. The analysis revealed that there was no interaction effect between the time pressure and excavation activity on the cognitive workload derived from physiological response $[F(3,1728) = 0.106,\ p = 0.996,\ \eta2 = 0.000]$. There was a little increase in the PCPS from the NTP ($M_{PCPS\_NTP} = 33.77$) to LTP ($M_{PCPS\_LTP} = 35.41$). The PCPS of the MTP ($M_{PCPS\_MTP} = 43.70$) showed the highest value in comparison with others while the PCPS in the HTP ($M_{PCPS\_HTP} = 31.56$) represented the lowest value.

Discussion

Paradox of Time Pressure

In terms of time-related performance, the operators tend to complete the same task faster as time pressure increases. As the time required to complete tasks varies among individuals and under different levels of time pressure, it is essential to compare performance metrics on an apples-to-apples basis. Thus, we calculated the number of collisions per unit time and the amount of excavated soil per unit time (Fig. 10). As can be seen, both metrics demonstrate the best performance in the LTP $[F(3,64.28) = 8.22,\ p < 0.001,\ \eta2 = 0.17]$. By comparing the collision number per minute, the HTP ($M_{CPT\_HTP} = 2.55/\text{min}$) was involved in 2.3 times more collisions than the NTP ($M_{CPT\_NTP} = 1.12/\text{min}$), and 3.4 times more collisions than the LTP ($M_{CPT\_LTP} = 0.74/\text{min}$). A reasonable level of time pressure tends to improve an operator's safety during the same period of time, while a great deal of time pressure results in poor performance.

In the case of the soil productivity rate, the result reveals that different levels of time pressure affect this metric $[F(3,120) = 8.57,\ p < 0.001,\ \eta2 = 0.18]$. With post hoc analysis, no significant difference was seen among the LTP ($M_{SPT\_LTP} = 2.20$ t/min), MTP ($M_{SPT\_LTP} = 2.15$ t/min), and HTP ($M_{SPT\_LTP} = 2.08$ t/min) sessions. It must be noted, however, that the MTP and HTP required more cycles to dig the same amount of soil compared to

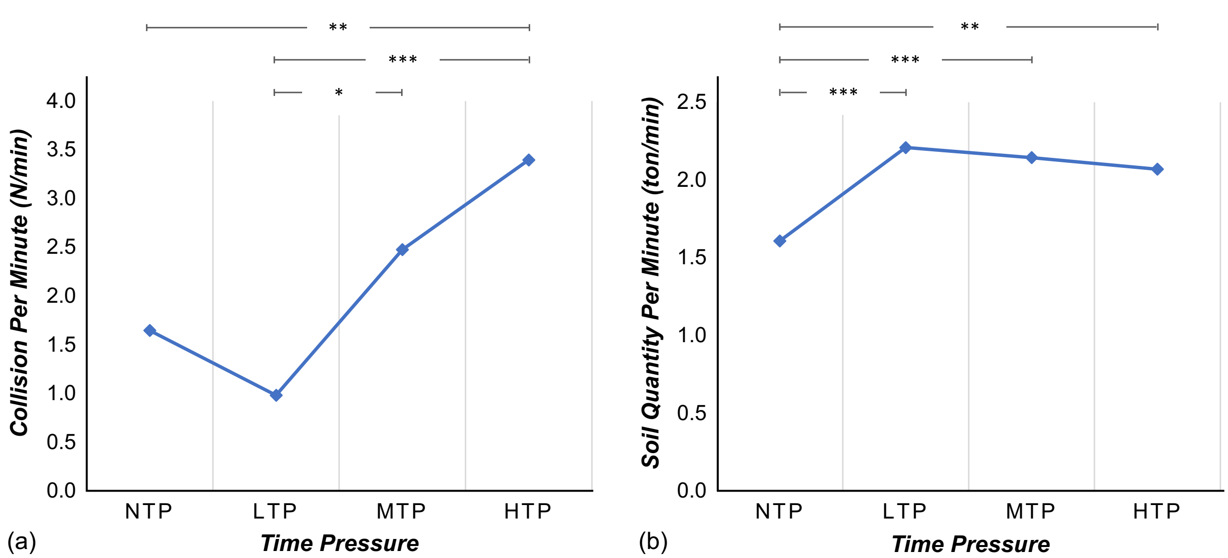

Fig. 10. Task performance per minute: (a) collision number; and (b) soil quantity.

LTP due to the average soil amount per scoop being higher in the LTP. A significant difference was found between NTP and the time pressured sessions ($p < 0.001$, $p < 0.001$, $p = 0.002$), where the NTP ($M_{SPT\_NTP} = 1.62$ t/min) had a lower rate than the LTP, MTP, and HTP. Therefore, within the same amount of time, the operator tended to dig more soil under pressure, but there was not much of a difference between LTP, MTP, and HTP.

This reveals a paradox of time pressure during excavator teleoperation. It is generally expected that increasing time pressure will lead to faster and more productive task completion, as such pressure motivates operators to work quickly. However, our findings indicate that while moderate time pressure (LTP) enhances performance by keeping operators alert and focused, excessive time pressure (HTP) leads to cognitive overload, increased errors, and decreased performance. Instead of improving efficiency, high time pressure often overwhelms operators, resulting in a degradation of the overall performance. Our results highlight the collateral effects of excessive pace in hazardous construction teleoperation work. A single utility strike could halt operations, harm workers, and incur significant costs. The 3.4 times higher collision probability under the HTP indicates increased costs and risks, which should be avoided. Conversely, moderate time pressure (LTP) should be encouraged as it improves both performance and safety by keeping operators attentive without overwhelming them. Thus, the same factor (time pressure in this study) that is expected to have a linear effect on teleoperation performance has a nonlinear effect, enhancing performance at a moderate pressure but impairing it under excessive pressure, creating a paradox in our expectation.

Cognitive Resource Allocation

The Yerkes-Dodson Law, suggesting optimal performance at an ideal arousal level, is reflected in our LTP results (Yerkes and Dodson 1908). However, it is important to investigate why performance improves when moving from NTP to LTP despite an increase in the amount of work per unit of time. Task performance is linked to working memory, which is influenced by task quantity per time unit according to Baddeley et al. (1986). However, it is noted that the level of frustration also plays a crucial role (Ashcraft and Kirk 2001). Our NASA TLX results indicate lower frustration during the LTP than in NTP. Thus, the reduced frustration levels during the LTP may outweigh the increase in the quantity of tasks per time, possibly leading to greater working memory occupation in the NTP. Furthermore, the NASA TLX subscales show that while temporal demand rises in LTP, crucial factors like mental demand and frustration level decrease, resulting in the lowest overall score. This aligns with participants' feedback of increased focus, likely due to reduced concerns and an optimal arousal level facilitating positive cognitive allocation leading optimal performance in the LTP. On the other hand, excessive time pressure caused cognitive overload. Since human abilities are not infinite, extreme pressure could result in decision-makers becoming discouraged and abandoning all efforts (Durham et al. 2000). Participants reported engaging in selective attention as a result of this intense pressure. In this context, selective attention refers to the participants' tendency to focus on immediate, task-specific goals while inadvertently neglecting or underestimating critical safety objectives. Through selective attention, people are able to focus on a specific task, reducing the burden on their limited working memory. Using selective attention, people can focus on the selected task and reduce the load on their limited working memory. Participants' interview responses matched their subjective assessment of NASA TLX and physiological responses since NASA TLX shows the highest score and PCPS shows the lowest in HTP. Since pupil size is usually correlated with cognitive load, PCPS should be the highest in HTP. However, previous experiments showed that the size of the pupil either stops or decreases when task demands exceed cognitive resources (Granholm et al. 1996; Peavler 1974; Poock 1973). Therefore, the PCPS that shows the lowest value in the HTP may support cognitive overload during the HTP. Accordingly, most of the participants were overburdened cognitively, which explains their poor safety and quality task performance.

Situational Awareness and Perception

Stress due to time pressure can impair hazard identification abilities, causing operators to focus on peripheral information rather than hazardous elements, which are critical to ensuring safety. In our study, the hazards were half-buried concrete pipes that participants could see and identify throughout all sessions without any extra effort. Participants were trained on the risks of utility strikes, their impacts on construction delays and costs, and they were explicitly warned against hitting utilities. Despite this effort, we observed a notable shift in behavior across sessions with different time pressures. In the NTP and LTP sessions, participants tended to work safely. On the other hand, collisions increased significantly under the MTP and HTP conditions. Interview responses suggest that situational awareness (SA) was notably impaired in the MTP and HTP sessions, leading to unsafe performance. While operators' ability to identify hazards (Level 1 SA) stayed the same in the MTP and HTP, some operators did not perceive utilities as hazardous as they should (Level 2 SA), while others did not consider the future impact of collisions (Level 3 SA). Under excessive time pressure, individuals may experience cognitive tunneling, which deprioritizes safety as the working memory focuses on other objectives. The lack of cognitive space for neglected safety may explain the observed impairment in SA abilities in spite of apparent hazards. In addition, the discrepancy between teleoperating and being physically onboard in a real-life setting could contribute to this issue. A task's degree of immersiveness affects the level of human engagement and performance (Mears and Cleary 1980). Since the operators in this study were required to perceive and understand the remote work environment through a screen with an egocentric view, it appears they had difficulty becoming fully immersed and focusing on the task, especially under sessions with extreme time pressure. A significant enhancement in perception and situational awareness and addressing cognitive limitations under pressure in construction teleoperation is imperative. Specifically, recognizing the differences between teleoperation and real-life scenarios is crucial for improving performance toward robust operation (Fig. 11). The development of assistive technology for impaired perception as well as the development of effective training and safety procedures for teleoperation tasks in challenging workplaces could serve as methods to achieve this goal.

Conclusion

Teleoperation is shown as an effective solution for hazardous construction sites. However, there is a still a gap in knowledge of how operators would behave and perform in various work conditions. Since time pressure is a routine phenomenon in construction, teleoperators will also face this pressure during their work. In comparison to onboarding operations, the inherent challenges of teleoperation are more apparent, such as impaired perception and reduced situational awareness. Time pressures exacerbate these challenges, creating a more complex environment in which teleoperators must simultaneously manage time constraints, ensure safety, and maintain quality. In particular, this multifaceted cognitive demand poses a significant challenge to novice teleoperators with less

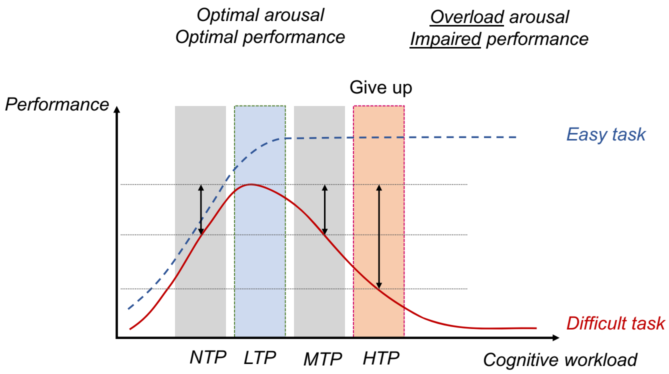

Fig. 11. Cognitive workload and performance in excavator teleoperation.

proficiency in operational aspects than experts. Hence, the objective of our study was to examine the impact of varying degrees of time constraints on both operator cognitive workload and task performance during the execution of a demanding excavation teleoperation task. Specifically, this study examines novice operators who are more likely to be involved in accidents, and excavators, the most widely used construction machines.

The results of our experiments indicate that when time pressure is applied in construction teleoperation appropriately, performance on the task is improved in all aspects, such as time, safety, and quality. Moreover, the mental demand and frustration levels were the lowest despite the existence of time constraints when low time pressure is applied. However, when excessive time pressure is applied, cognitive overload is observed, where the operators tend to disengage and give up before and during the task, resulting in adversely affecting safety, quality performance, and overall productivity. There has been a notable observation in which the operator's skill set remains unchanged, yet task performance, encompassing safety-related aspects along with quality-related outcomes, exhibits the potential for both improvement and deterioration with discernible variations in cognitive workload states under diverse levels of time pressure. This study highlights the paradox of time pressure, where moderate time constraints can enhance performance, while excessive time constraints lead to cognitive overload and decreased performance.

The expectation that operators are capable of working faster under time pressure is not always true, especially in difficult teleoperation scenarios. Comprehensive understanding of the cognitive states of human operators and their performance under time constraints is necessary for advancing teleoperation across all dimensions of time efficiency, safety assurance, and quality-related achievements. The unique finding of the study is that moderate time pressure enhances operator performance by keeping them alert and focused, whereas excessive time pressure leads to cognitive overload, increased errors, and decreased performance. These insights contribute to a broader understanding of operator task and cognitive performance during construction teleoperation in challenging working environments.

Considering that humans are an integral component of teleoperation, assisting their operational ability is crucial to the success of the system by improving impaired situational awareness and perception of distanced hazards since human decision and control directly affect the distanced robot performance in the human-in-the-loop system. However, this study also has limitations, including the focus on novice operators and a single type of construction machine, which may not fully represent all teleoperation scenarios. Therefore, in the future, methods that improve teleoperators' abilities, such as assistive technology or appropriate training programs, in enhancing situational awareness, perception, and control performance, should be developed by taking into account dynamic human mental and cognitive states and behaviors under various degrees of challenging work environments. In addition, future research should explore a broader range of operator skill levels and machine types to validate these findings and develop comprehensive training and support systems.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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