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Immersive Technology-Driven Investigations on Influence Factors of Cognitive Load Incurred in Construction Site Hazard Recognition, Analysis and Decision Making

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Abstract

Digital technologies such as Virtual Reality (VR) are gaining momentum in its use to implement and deepen construction health and safety education. In this study, researchers first developed a VR-driven immersive system incorporating real construction site hazard scenarios. Immersive experiments were then conducted by recruiting 40 individuals in construction-related disciplines. Experimental data were collected to evaluate the effects of tasking mode and time pressure on individuals' cognitive load in performing virtual site tasks. The self-evaluation method and task performance-based data were adopted as the complementary ways to measure individuals' cognitive load in completing given tasks. Compared to the single tasking mode of solely focusing on site hazard recognition, analysis, and reaction, the added secondary task was found significantly increasing individuals' cognitive load and lowering task performance. Time pressure could be a double-edged effect depending on the task feature. Recommendations were provided for real site safety management in balancing employees' wellbeing and site productivity. The current study extends prior research on enhancing construction health and safety where the main focus has been on hazard detection but now incorporates also hazard analysis and reaction. It also leads to more future research such as measuring individuals' cognitive load in a real site environment.

Keywords: construction safety; cognitive load; safety hazard; virtual reality; immersive technologies; safety education

1. Introduction

Safety education plays a key role in promoting safety and health in the construction industry (Laukkanen, 1999; Pedro et al., 2016), which is one of the most risky industries measured by injuries and safety accidents (Sunindijo and Zou, 2012). Technological development has enabled alternative ways of construction safety education (Nnaji and Karakhan, 2020). For example, digital or computer vision-featured technologies have demonstrated their positive impacts on construction safety and health monitoring (Seo et al., 2015), such as eye-tracking technologies (Jeelani et al., 2018) in gauging construction employees' hazard detection. These digital driven approaches provide more objective measurements to evaluate individuals' safety perception towards hazards, compared to the conventional questionnaire survey methods (e.g., Chen and Jin, 2015) to measure safety perception and safety climate.

Failure to perceive critical information such as hazards can cause safety accidents and poor safety performance. In construction, employees retrieve information from observed site hazards. During hazard analysis and decision making process, each individual consumes internal cognitive resources to handle external information (Shaw and Shaw, 1977). Mental fatigue (Li et al., 2019) could occur if individuals' cognitive resources are over-loaded, causing lowered performance in detecting safety hazards. Cognitive load could be defined as a multidimensional construct representing the load that performing a particular task imposes on an individual learner's cognitive system (Paas & van Merriënboer, 1994a). Following the general model described by Paas and van Merriënboer (1994b), cognitive load could be assessed in various dimensions in terms of mental load, mental effort, and performance.

Construction task features including site environment (e.g., noises) could affect the outcomes of hazard detection, analysis, and reaction, and cause variations in personal cognitive demand (Hommel et al., 2012). Multiple influence factors could affect site employees' cognitive load. These influence factors and their effects on the wellbeing of construction workforce have not been sufficiently investigated. Studying these factors on real jobsite could be restricted due to safety risks of construction activities onsite. The virtual reality (VR)-based immersive experiments provide the digital approach in gauging individuals' cognitive load on treating site safety hazards. In this immersive experimental study, real site scenarios were incorporated in the virtual sites, including construction noise which represented the real site situation. Two main influence factors, namely task type and time pressure, were designed for comparative studies of individuals' cognitive load in safety hazard recognition, analysis, and decision making.

As a step from the prior investigation (Han et al., 2020b) of cognitive load of individuals in detecting safety hazards based on static site photos, the research team in this study developed the new immersive VR-based immersive experimental system to enable the dynamic and immersive site work. This study extended the work of Han et al. (2020b), which was limited to hazard detection, by moving to also analyse and react towards detected hazards. This study was designed to investigate the effects of tasking mode and time pressure on task performance and the cognitive load of individuals from construction-related disciplines. Studying the effects of these two influence factors was important based on facts that: 1) prior studies such as Dzeng et al. (2015) and Albert et al., 2017 revealed the effects of internal attributes (e.g., individuals' prior experience) and external attributes (e.g., hazard category or feature) on individuals' safety performance. There has been a need to further investigate from a practical view, such as how safety performance would be impacted when individuals face tight project schedule and multi-tasking. Studying these two influence factors for individuals with similar internal and external attributes would extend these prior studies and address this practical need; 2) Prior studies (e.g., Smith and Carter, 2006; Khanzode et al., 2012) showed that cognitive resources spent on recognizing surrounding environment (e.g., safety hazards) would help workers avoid construction site risks. But tasking mode and time pressure due to the dynamic site conditions and project scheduling requirements could change the cognitive resources demanded. Ryu and Torres (2018) found that the change of cognitive load could significantly alter task performance in terms of accuracy and time management. Crossley et al. (2018) and Bi et al. (2019) further verified the effects of cognitive load on individuals' task performance. However, these prior studies were largely limited to 2-dimensional image-based static site scenarios, which could not fully capture the more complicated, interactive, and dynamic real site environment that individuals face. By recruiting virtual site scenarios, VR-based immersive technologies could improve the interactions between individuals in the experimental tests and site conditions. By capturing individuals' recognition, analysis, and reactions towards virtually-simulated site conditions, especially under different tasking modes and time pressure, this study offered a new education approach of training construction employees' safety awareness, perception, and behavior. As one of the latest studies adopting digital-driven immersive research, the results also offered insights on professional construction safety management and provided suggestions on how to properly balance construction employees' wellbeing and project progress.

2. Background

2.1. Construction safety hazard recognition

Employees' safety hazard perceptions form part of safety climate (Han et al., 2019), which is considered a proactive measure in construction safety management (Chen and Jin, 2013). The longitudinal study of Albert et al. (2014) on safety hazard detection revealed that workforce could only identify and communicate lower than 40% of hazards onsite, and early-stage intervention could significantly improve the hazard recognition performance. There have been different approaches in evaluating and enhancing employees' hazard recognition capabilities, such as hazard recognition methods following the principles of cognitive mnemonics (Albert et al., 2014), and cognitive method assisted by visualisation devices to improve hazard identification accuracy (Sun et al., 2018). The hazard recognition of employees could be evaluated by their search patterns, which are affected by demographic factors of individuals such as experience and risk tolerance as identified by Zhang et al. (2020). Dzeng et al. (2015)found that experienced workers were more likely to identify hazards and tended to firstly assess high-risk targets (e.g., working at heights) as compared to novice workers. These different targets of hazard, or hazard types/categories, were studied further by Albert et al. (2017) through applying the experimental intervention. It was found that compared to certain types of hazards including gravity, mechanical, and electrical hazards, other types such as temperature, chemical, radiation, and biological hazards were the least recognised hazards even after the intervention (Albert et al., 2017). These empirical studies had identified the underlying factors affecting construction employees' hazard recognition, such as employees' prior experience, and types of hazards. However, there is a further need to move a step forward to investigate how other ongoing site factors such as task types or multi-tasking would impact safety recognition and further decision making of employees, who have similar prior experience and face the same types of hazards.

Traditional measurements of workers' safety hazard perceptions such as questionnaire survey (Han et al., 2019) might not be able to provide the most accurate evaluation, due to the lack of engagement in site scenarios when participants are filling the questionnaire. With the emerging digital and visualisation technologies, a variety of evaluation methods have been applied in testing individuals' hazard recognition capabilities. For example, Sun and Liao (2019) combined questionnaires (experience and risk tolerance), eye-tracking devices (eye movement), and near-infrared spectroscopy to assess hazard recognition ability involving microvascular function in the brain. This new and comprehensive approach of Sun and Liao (2019) could be adopted for onboard assessment by reducing undetected occupational hazards.

2.2.Digitalisation-based experimental studies in built environment

Feng et al. (2020) applied the Immersive VR and games to train individuals for earthquake emergency evacuation in a given indoor environment. Customised education framework was developed and showed promising opportunities for future research in adopting Immersive VR approach for not only natural disaster reaction training, but also man-made hazards (Feng et al., 2020). Also based on a VR laboratory environment, Shi et al. (2020) implemented a cognition-driven personalised training to provide early warning and estimate of individuals' construction task performance, and found that stressful training had a strong impact on task performance. Similar virtual or computer vision platforms (e.g., Zuluaga and Albert, 2018; Shi et al., 2019) are also gaining momentum to assist construction safety research, including the VR-driven eye-tracking applications in gauging individuals' safety hazard detection or recognition. For example, adopting wearable eye-tracking devices, Li et al. (2019) found significant correlations between individuals' mental state and ability to detect hazards in operating heavy construction equipment. Also with eye-tracking technologies, Xu et al. (2019) found that those who successfully recognised hazards tended to follow consistent search patterns and concentrate on specific hazardous areas.

These prior studies (e.g., Li et al., 2019; Xu et al., 2019) indicated the internal correlations between employees' mental effort, hazard search methods, and safety performance. Extending from these existing studies, this research aims to fulfil the future directions as proposed by Guo et al. (2017), including: a generalised visual-interactive-cooperative educational approach for customisation of different scenarios; extraction of safety knowledge from on-site visual safety data for future safety management. It is common practice for construction safety educational studies to recruit university students from construction-related disciplines as study samples, for example, Bhoir et al.(2015), Hasanzadeh et al. (2016), and Jeelani et al. (2017). As evaluated by Han et al. (2019), students from the similar background and experience level could minimise the effects of individuals' traits on task performance, when the research was targeting on other non-personal-trait factors (e.g., external site environment).

2.3.Theoretical background of cognitive load

Kahneman (1973)'s book entitled *Attention and Effort*, summarised a variety of aspects of attention, including divided attention, task interference, and the role of perception. Since then researchers had finally made progress in not just understanding what attention was but also in measuring and quantifying it (Bruya and Tang, 2018). According to Kahneman (1973), pupil reactions, as an indicator of mental effort, referred to both attending to the task and the effort exerted in attending to the task. The mental effort consuming attention resources have been considered as a measurement of cognitive load in multiple studies (e.g., Tabbers et al., 2000; Paas et al., 2003; Gabaude et al., 2012). Folkman (1984) and Bartolomeo (2014) stated that an individual person is with limited cognitive resources to complete a given task, and higher consumption of cognitive resources (e.g., complex tasks) could exceed the load limit and further undermine the task performance. Cognitive Load Theory has highlighted instructional methods to decrease extraneous cognitive load in order to assign the limited or available cognitive resources for learning (Van Merrienboer et al., 2005).

The multiple resource theory proposed by Wickens (2002) in accounting for differences in dual task interference was based on a four-dimensional multiple resources model. According to this model, two tasks would posit greater interference between them to the extent that they share stages (perceptual/cognitive versus response), sensory modalities (auditory versus visual), codes (visual versus spatial), and channels of visual information (focal vs ambient). It is further indicated from Wickens (2002) that double or multiple tasks simultaneously occupying the "channels" would cause reallocation of cognitive resources and potentially increase the cognitive load. Interacting elements (e.g., extra tasks) processed together would increase the working memory load, and independent measurements of cognitive load have been a valuable addition to cognitive load theory (Sweller, 2017). According to the Adaptive Decision maker theory of Payne et al. (2013), decision makers balance effort and accuracy performance and predict which strategy individuals would use in a given situation. When under time pressure, individuals with limited cognitive resources would consider how to balance the demanded cognitive resources to complete given tasks, and the accuracy-related task performance (Payne et al., 2013). High cognitive demand is caused from complex, time and safety-critical tasks, and cognitive load variation could also be caused by the types of tasks (Chen et al., 2013). Li (2010) found that complex task and time pressure had significant influences on human cognitive load during human-machine interaction. These theories and findings evaluating mental effort, cognitive load, and task performance provide background for designing this research focusing on how task types and pressure would affect individuals' cognitive load and task performance in given construction site scenarios.

3. Methodology

3.1.Research design of cognitive load measurements

Measurements of cognitive load include questionnaire-based subjective approach, task performance outcome-based, and biological methods. In this study, the former two methods were adopted based on the rationale that: 1) two methods could validate each other to ensure the reliability of measurement outcomes; 2) the process of safety hazard recognition, analysis, and reaction is highly dependent on individuals' own recall and feeling. Subjective measurements (e.g., self-evaluation through questionnaire) met the needs of the study; and 3) objective measurements based on task performance outcomes (e.g., time taken to complete, accuracy rates) could complement the subjective measurements in reflecting individuals' cognitive load. The workflow of this VR-driven immersive experimental study is described in Fig.1.

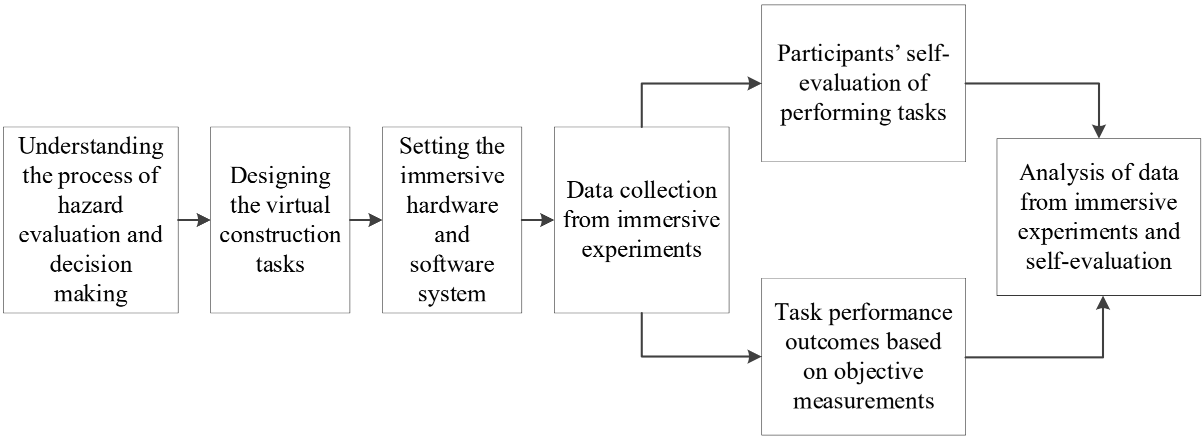


Fig.1. Illustration of the immersive experimental workflow

According to Fig.1, the study started from understanding the process of individuals' process of safety hazard analysis and decision making, followed by designing the construction tasks from real site scenarios. The existing laboratory facility (i.e., immersive hardware and software system) of the research team enabled the virtual site scenario setup and immersive experiment. Through data collection upon the completion of individual participants' immersive tasks, the two aforementioned measurements (i.e., self-evaluation and task performance outcomes) allowed the data analysis of how the task type and time pressure would affect cognitive load.

3.1.1. **Setup of the experimental platform**

Examples of the virtual sites are demonstrated in Fig.2 based on the immersive tasks to be undertaken by individual participants. The VR-based immersive tasks allowed the two major independent variables (e.g, task type and time pressure) to be embedded for comparative studies.

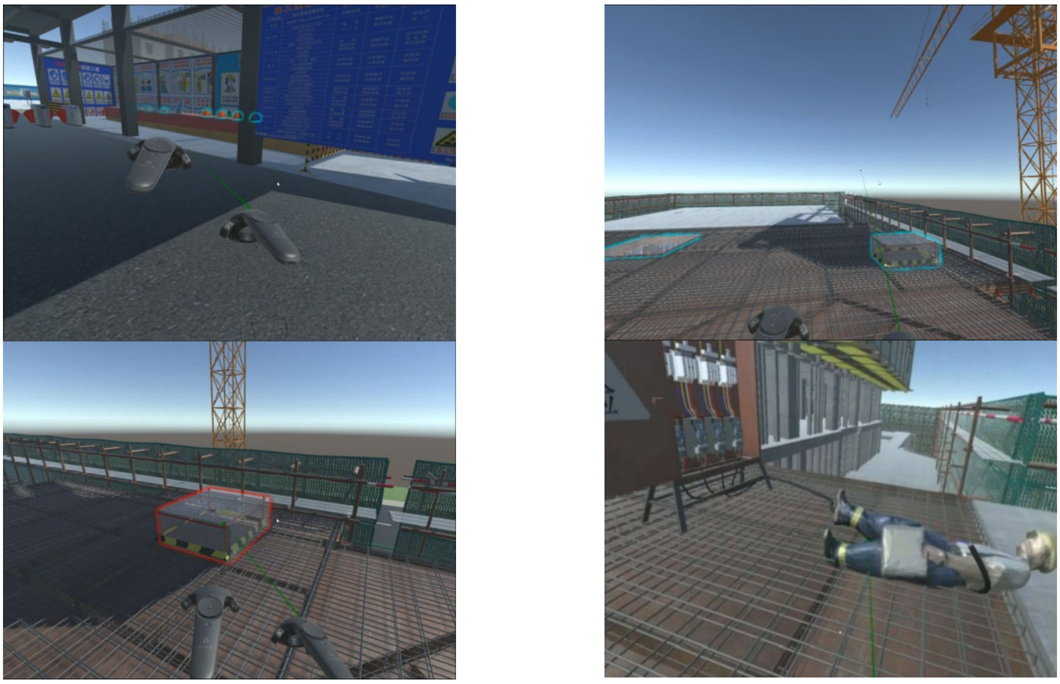


Fig.2. Demonstration of VR-based immersive platform

The site safety hazard scenes incorporated in the immersive experiments were based on the empirical safety accident data in China. According to the accident data released by Department of Housing and Urban-Rural Construction in China (2019), six major categories of safety accidents could be identified as: fall from height, structural collapse, struck-by, electrocution, injuries by heavy equipment, and injuries by manual handling or lifting. The typical safety hazards causing these six categories of accidents were adopted on designing the virtual site scenarios for the immersive experiments. Typical safety hazard scenes were considered in setting the virtual scenes. For example, in a standard floor of reinforced concrete construction site, multiple hazards exist before pouring concrete as seen in Fig.3. In this scenario, uncovered hole and unstable temporary wood platform were safety hazards. Other hazards considered on the virtual sites included weakly supported scaffolding, electrical wiring/sockets, and tower crane nearby the structural floors, etc.

a) Real-site scene from site photos b) Virtual site generated from real site

Fig.3. Site scene set-up

The virtual site also included the whole surrounding environment (e.g., roads, temporary accommodation of workforce, etc.) allowing zooming in and zooming out for immersive walkthrough as captured in Fig.4. Individual participants of this study were provided with the fully contextualised real site experience, with background noises also collected from real sites during the immersive site tour. Fig.5 displays an example of how the immersive site of scaffolding was established from a real construction site.

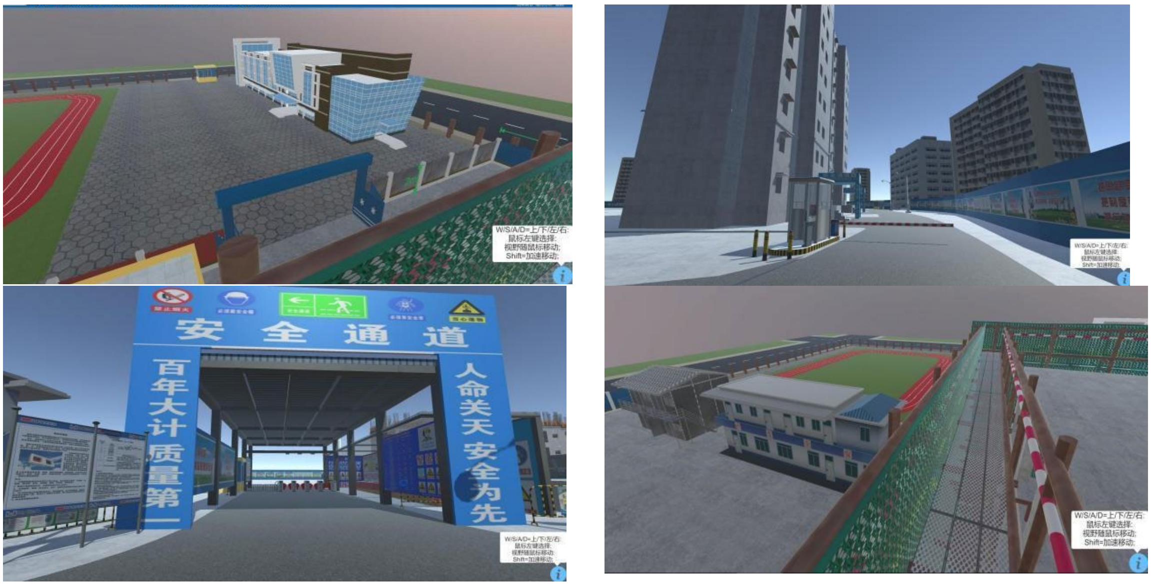
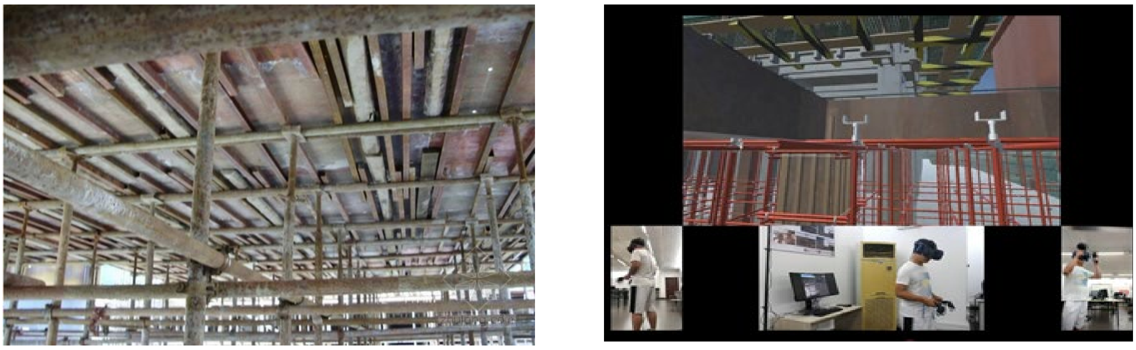


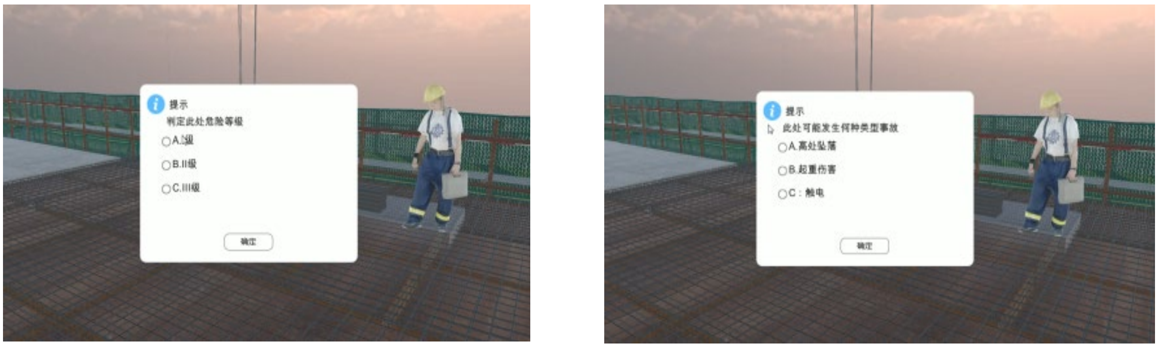
Fig.4. Examples of virtual sites for immersive experimental set-up



a) Real-site scene of safety hazards of scaffolding b) Immersive experience generated from real sites

Fig.5. Immersive experimental set-up on safety hazards related to scaffolding

Each virtual site experienced by an individual participant may have multiple safety hazards. Each hazard was designed with a task for hazard recognition, analysis, and decision making. Once a potential hazard was detected by the individual participant, he or she would be asked to confirm whether or not it was a hazard. Then the individual would be asked to select the type of accident that could be triggered from the detected hazard, for example, fall, struck-by, or caught in-between, etc. Further the individual would be asked to make a decision of how to respond to the hazard with a multi-option question as seen in Fig.6.



判定此处危险等级
○A.I级
○B.II级
○C.III级

此处可能发生何种类型事故
○A.高处坠落
○B.起重伤害
○C：触电

Fig.6. Showcase of experimental task design during the immersive site tour

3.1.2. **Measurement methods of individuals' cognitive load**

Two main measurement methods were adopted in this study as previously mentioned, namely self-evaluation of performance based on a questionnaire which is subjective, and the objective outcomes (i.e., time taken to complete tasks, and accuracy rate).

3.1.2.1. Questionnaire for self-evaluation of cognitive load

There were several existing questionnaire types for self-measurement of cognitive load, including the multi-dimensional rating-scales (Paas and van Merriënboer, 1994b), Subjective Workload Assessment Technique (SWAT) introduced by Reid and Nygren (1988), and NASA Task load Index (NASA-TLX) guided by Hart (1986).

The multi-dimensional rating tool adopted by Paas and van Merriënboer (1994b) incorporated mental efforts and performance of individuals in completing given tasks, but needed more process-based measures. SWAT is also a multidimensional scale, with three discrete levels namely dimensions of time load, mental effort load, and psychological stress load (Luximon and Goonetilleke. 2001). When using the SWAT scale, an individual is required to perform a card sorting procedure and to rank 27 SWAT cards which are yielded from the combinations of the three discrete dimensions at three discrete levels (Reid and Nygren, 1988). Adopting SWAT could be time-consuming and insensitive to low cognitive load.

NASA-TLX is a multidimensional scale for which the overall cognitive load is a function of mental demand, physical demand, temporal demand, performance, effort, and frustration dimensions (Hart, 1986). Both SWAT and NASA-TLX resulted in significantly different ratings, but NASA-TLX was sensitive to some mental workload differences not discriminated by SWAT (Battiste and Bortolussi, 1988). NASA-NASA-TLX shows a high correlation with performance, and the correlations with performance were lower for SWAT (Rubio et al., 2004). In this study, NASA-TLX was adopted as the multi-dimensional measurement method due to its proper level of sensitivity and complexity, as well as its widely proven reliability in measuring individuals' cognitive load.

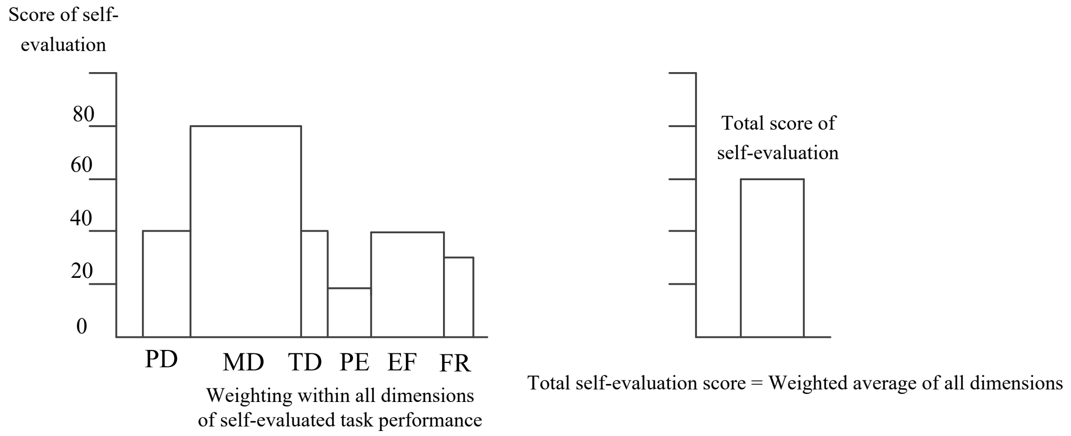
*3.1.2.2.*Measurements of individuals' cognitive load in this study

In this study, safety hazard analysis and reactions are key stages for each experimental participant to undergo the workflow of hazard recognition, evaluation, recalling, reasoning, and decision making or reaction. Detailed measurement indicators include the NASA-TLX-based self-evaluation and the objective measures. Table 1 provides the definitions of six indicators following NASA-TLX principles (Hart, 1986), namely mental demand, physical demand, time demand, effort level, performance evaluation, and frustration level.

Table 1. NASA-TLX-based measurement indicators for individuals' cognitive load

Measurement indicator	**Definition**
Mental demand	The mental resources spent by construction employees to search and identify site hazards, and to properly react towards hazards
Physical demand	Physical work required for construction employees to find safety hazards and to properly handle them
Time demand	Time pressure that employees feel in finding and properly handling safety hazards
Effort level	The effort level that employees experience to find and to properly handle safety hazards
Performance evaluation	Self-evaluation of employees of their own performance in finding safety hazards and making proper decisions towards them
Frustration level	Degree of frustration (e.g., anxiety, disappointment, worry, etc.) that construction employees experience in finding and properly handling site safety hazards

Fig.7 shows the mechanism of how NASA-TLX was applied to obtain the total cognitive load-based score, which was based on the comparison between each pair of indicators defined in Table 1. There would be a total of *15* pairs' comparisons, for example, the comparison between physical demand and mental demand reveals that the former indicator scores *60* as compared to the later one with *70*. The relative weighing of one indicator to another would be quantified. Each indicator would be finally quantified with its overall weighted score, contributing to the total cognitive load score.



(Note: PD is physical demand; MD stands for mental demand; TD represents time demand；PE denotes performance evaluation；EF means effort level；FR stands for frustration level)

Fig.7. NASA-TLX weighting method for cognitive load calculation

The principles and weighting method were incorporated into this study for measuring individual participants' cognitive load of performing immersive tasks. The NASA-TLX questionnaire for self-evaluation of the six measurement indicators is displayed in Table 2. Each indicator is based on a scaled rating. The final cognitive load score is weighted and obtained ranging from 0 to 100.

Table 2. NASA-TLX questionnaire for self-evaluation of cognitive load

Cognitive load measurement in safety hazard recognition, analysis, and reaction	
NASA-TLX self-evaluation of cognitive load	
1. Mental demand In your immersive virtual site work, how would you score the mental demand (i.e., search, analysis, judge, and decision making) for you to complete the safety hazard detection, analysis of hazard category, and reaction towards identified hazards? (0 means extremely easy and simple, and 100 refers to most difficult and complicated)	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high
2. Physical demand In your immersive experiment, how would you score the physical demand (i.e., operation, muscle control, fatigue, etc.) for you to complete the safety hazard detection, analysis of hazard category, and reaction towards identified hazards?	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high
3. Time demand In your immersive site work, for you to complete the safety hazard detection, analysis of hazard category, and reaction towards identified hazards, how would you score the pace of work? 0 means extremely low time pressure and slow pace, 100 refers to most fast-paced causing difficulties and panic.	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high
4. Effort level In your immersive site work, how would you score the effort required for you to complete the safety hazard detection, analysis of hazard category, and reaction towards identified hazards?	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high
5. Performance evaluation In your immersive site work, how would you score your own performance in completing the safety hazard detection, analysis of hazard category, and reaction towards identified hazards?	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high
6. Frustration level In your immersive site work, how would you score your frustration level (i.e., stress, anxiety, disappointment, worry) in completing the safety hazard detection, analysis of hazard category, and reaction towards identified	0 Extremely low (Score from 0 to 100 to self-measure the given task performance dimension) 100 Extremely high

hazards?	

The objective measurements are defined in Table 3, based on time demand and accuracy rate of answering questions related to safety hazards on virtual sites or other construction related questions. Table 3 shows the two different stages of undertaking tasks, i.e., hazard analysis and decision making.

Table 3. Objective measurement indicators of cognitive load occurring in performing safety hazard related tasks

Task	**Process-based measurement items**	**Outcome-based measurement items**	**Description of cognitive load**
Hazard analysis	Time spent on answering questions related to hazard analysis (time for information treatment)	Correction rate of answering questions	Less time spent on answering questions, and higher accuracy rate of answers, are considered lower cognitive resources demanded for participants, and hence a lower cognitive load.
	Time spent on performing secondary task	Correction rate of performing secondary tasks	
Decision making	Time spent on answering questions related to hazard reaction (time for information treatment)	Correction rate of answering questions	
	Time spent on performing secondary task	Correction rate of performing secondary tasks	

Time spent to complete tasks was measured differently between performing primary and secondary tasks. Time spent for information treatment in the primary task was automatically recorded in the developed immersive system, such as the time period from a question proposed to the participant's completion of answering it. For time spent in completing a secondary task, researchers used an electronic millisecond timer to measure the time taken between the question being asked and the answer being provided. The average time spent for each group of participants in a given task mode was measured consistently following the measurement procedure described in Li et al. (2020) in adopting task performance for evaluating cognitive loads.

3.1.3. Linking task performance into cognitive load

Task performance is considered objective measurements, including outcomes and time-related measurements, such as those outcome-based measurement items listed in Table 3. The outcomes can be referred to accuracy rate, and the time-related measurements can be identified as time taken to react or make decisions. It is common practice to have double tasking mode for measuring cognitive load, such as in the study of Brunken et al. (2003). In the double tasking mode, accuracy rate and time demand to perform the secondary task could reflect the overall cognitive load and the cognitive demand to perform the primary task. Depending on the primary task nature, the time taken to perform each secondary task may vary from 300ms to 1s (Brünken et al., 2003). The cognitive load can be measured based on the objective outcomes such as accuracy rate. Accuracy rates rely on the information receiving, analysis, and retreating, which is highly linked to the cognitive load. Generally, a higher accuracy rate would indicate lower cognitive load to retreat information. Therefore, accuracy rate has been recognised as a measurement for cognitive load such as in Brünken et al. (2002). Besides the accuracy rate, time consumed completing a given task is also considered as an objective measurement of cognitive load (DeLeeuw et al., 2008; Chevalier et al., 2009). The time demand for project completion also includes the time taken to treat and analyse information received. According to Barrouillet et al. (2004), the tasks which continuously consume the attention resources of an individual would cause a higher cognitive load, and the time demanded to analyse and retreat information is positively proportionate to the individual cognitive load. The reaction time refers to the period of time from an individual receiving the stimulus to the decision or reaction being made. A lower reaction time could reflect the lower cognitive load as evidenced by research from other fields such as traffic (Guo et al., 2017), who adopted the reaction time as an indicator to measure vehicle drivers' cognitive load. Using time of reaction as a measurement of cognitive load can be found in other studies (Harms and Patten, 2003; Patten et al., 2004) in the fields of telecommunication and traffic. Other fields such as online shopping (Chen, 2015) and higher education (Li et al., 2017) had also engaged reaction time in evaluating cognitive load.

3.1.4. **Pilot experimental study**

The pilot experimental study was conducted before the formal study to gain the data of time needed to complete immersive tasks, such as the average time and standard deviation. The pilot data acquired would then be used to determine the time pressure control in formal experiments. The two task modes (i.e., double tasking and single tasking) underwent the pilot study to gain the data of time demands. Following the procedure of Wickens (2002), under each task mode, the average time needed for completion lessened by one standard deviation would be considered high time pressure for experimental participants; the average time plus one standard deviation would be adopted as low time pressure for individuals. Time pressure control was determined accordingly. The pilot study also allowed the correction of any potential flaws during the immersive experimental process and verified the data of time pressure. Initially a total of 20 undergraduate and graduate students from the subjects of civil engineering and construction management were recruited as individual participants for the pilot study, with the results summarised in Table 4.

Table 4. Statistical summary of pilot experimental study

Group	Sample size	Average time to complete tasks	Standard deviation
Single task	10	153.06 s	74.96 s
Double task	10	265.73 s	88.58 s

The pilot study results are shown in Table 4. The average and standard deviation of individuals performing single task are both lower compared to those performing double tasks. The results indicated that double tasking was likely to increase the time spent for participants to complete as compared to single tasking.

The other purpose of conducting the pilot study was to ensure these pre-set hazards from common site hazards (e.g., working at height) could be correctly recognised provided that: 1) the entry point of participants in the virtual site was located where hazard zones could be identified; 2) participants had construction site knowledge learned from lectures; and 3) participants had adapted the VR hardware system well to undergo the immersive walkthrough.

It was indeed found that pre-set hazards were not identified by few participants who had problems using the wearable headset or not having the basic knowledge of site safety. These exceptions were fully noticed by the research team and therefore taken care of during the follow-up formal immersive experiments.

3.1.5. **Formal immersive experiments**

The formal experimental study was designed to incorporate two main independent variables, namely task mode and time pressure. The VR-based immersive experiment was based on construction employees' cognitive learning process, consisting of safety hazard recognition, analysis, and reaction. Corresponding tasks were embedded during the immersive site work (e.g., Fig.2) testing individual participants' performance. The time of completion and accuracy rates were recorded by the VR immersive system or the researchers. The self-evaluation was completed following the completion of immersive tasks with each individual participant filling the questionnaire shown in Table 2. The detailed task mode and time setting are described below:

3.1.5.1.Task mode setting

Each individual participant under the single tasking mode was asked to only perform the hazard detection, analysis, and decision making during the immersive site tour. Individuals under double tasking mode were asked to perform a secondary task to verbally answer a construction related question during the immersive site tour. In the double tasking mode, each individual was required to answer the question in a shortest time period, for example, "What are the main failure modes of oblique section in reinforced-concrete structure?" The challenge level of questions to be asked under the double tasking mode was validated during the pilot study stage. Each individual to undertake double tasks was made aware of the themes and potential topics for their secondary task.

3.1.5.2.Time pressure setting

The pilot study provided the guide for time setting in the formal study. The time settings for double tasking were determined to be 177.5s for high time pressure, and 354.3s for low time pressure. Under single tasking mode, 78.11s was determined as high time pressure, and 228.02s was considered low time pressure. Each individual assigned with time pressure would be reminded of the time limit. For example, before the start of double-tasking immersive work, the individual would be told "You are asked to complete the work of hazard detection, accident category analysis, and decision making within 228.02s". Similar instruction would also be given for single tasking individuals with time pressure.

3.2. Experimental procedure and data collection

3.2.1. Experimental participants

Individuals participating in the formal experiment were divided into four groups. They were different from the pilot study participant sample. Each of them was only allowed to be in one of the four groups. None of them was allowed to know the immersive site scenario or any safety hazard related information before the experiment. Individuals to participant in the immersive experiments were expected to have background knowledge or skills in construction, and also with similar professional knowledge or experience level in order to exclude the effects of individuals' own experience or knowledge on task performance. Following the sampling guide for construction-related experimental study as described in Han et al. (2020b), a total of *43* participants were recruited in the formal immersive experiment. They were undergraduate or graduate students from the subjects of civil engineering or construction management.

3.2.2. Experimental procedure

The immersive study procedure was comprised of the following standardized steps:

1) As seen in Fig.8, the researcher explained to each individual participant before the start, including the tasks to be performed, the experimental steps, and the operation of VR-based immersive hardware (e.g., the right way to operate the VR handle and headset).

The task would be explained according to the task mode that the individual was assigned to.

2) Each individual would then follow the experimental workflow to properly wear the VR headset and other hardware to be ready for the immersive site tour. Once the immersive work started, the individual would then begin searching potential site safety hazards, and would then make the judgement, analysis, and the decision.
3) Once the tasks were completed, each individual would be asked to fill the NASA-TLX questionnaire to self-evaluate the performance. Researchers would also hold a short interview with the individual regarding the immersive experience. Afterwards, the collected data would be stored for follow-up statistical analysis. Fig.9 depicts the workflow of the immersive experimental study.

a)User interface of entering the immersive system　　b) Individuals receiving guides before starting

Fig.8. Start-up of the immersive experiment

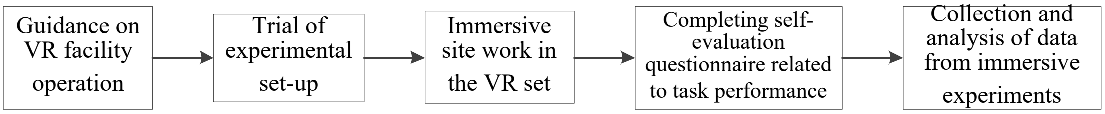


Fig.9. Workflow of formal immersive experiment

4. Results from immersive experiments

Initial analysis of the collected data was performed to exclude outliers such as incomplete dataset of individuals, improper operations of immersive experiments, and extremely long time taken to complete tasks, etc. Finally, a total of 40 participants' data were included for the follow-up comparative study.

4.1.Comparisons based on self-evaluation of cognitive load

The two main independent variables related to task mode and time pressure were adopted in the significance tests of group performance according to self-evaluation following Table 2. Before conducting the variance analysis, researchers performed the normality test and the test for homogeneity of variance. It was found that the data samples had normal distribution. Therefore, the parametric-based analysis of variance (ANOVA) was suitable for comparative analysis. It was also found that variations between samples were significantly different. According to the Jiang and Zhao (2016), *t*-test for two separate samples was recommended when the two samples are with the same sample size but non-homogeneous variances. Adopting inferential statistics (e.g., ANOVA in this study) for analysing participants' performance could be found in other studies conducting VR-based immersive experiments, such as Shi et al. (2020). The null hypothesis was that two groups of participants did not have significant differences in performance. Based on the *5%* level of significance, a corresponding *p* value lower than *0.05* would reject the null hypothesis and suggest the alternative hypothesis that the two studied groups are with significantly different performance. Table 5 displays the time spent in completing the immersive tasks for double-tasking groups.

Table 5. Statistical comparison of time expenditure for double task groups between those under time pressure and those without time pressure

	Group	N	Average (s)	Standard deviation (s)	*F* value	*p* value
Time pressure	With time pressure	10	279.5	73.4	4.489	.048
	Without time pressure	10	403.3	132.2		

The *p* value lower than *0.05* indicates significant differences of time spent on completing tasks. Basically, those under time pressure finished the tasks faster than their counterparts without time pressure. For those without time pressure, the time needed to complete tasks also varied more significantly among individuals. For those under time pressure, the comparison between single and double tasking groups based on self-evaluated task performance is summarised in Table 6.

Table 6. Statistical comparison of performance evaluation under time pressure between single and double task groups

	Group	N	Average	Standard deviation	*F* value	*p* value
Task mode	Single task	10	42.42	22.50	4.622	.045
	Double task	10	51.34	11.53		

The *p* value also below *0.05* indicates significant differences between single and double tasking groups. Under time pressure, double tasking significantly increased the cognitive resource demand. The other comparison for those without time pressure is summarised in Table 7.

Table 7. Statistical comparison of performance evaluation without time pressure between single and double task groups

	Group	N	Average	Standard deviation	*F* value	*p* value
Task mode	Single task	10	37.88	10.17	4.250	.048
	Double task	10	45.21	14.33		

Similar to the comparison for groups under time pressure, double tasking was also found significantly increasing the cognitive load for those without time pressure. A further comparison for double tasking groups regarding time pressure is summarised in Table 8.

Table 8. Statistical comparison of performance evaluation for double-tasking groups between those under time pressure and those without time pressure

	Group	N	Average	Standard deviation	*F* value	*p* value
Time pressure	Without time pressure	10	45.21	14.33	4.544	.041
	With time pressure	10	51.34	11.53		

The *p* value below *0.05* indicates that under double tasking mode, time pressure significantly increased the cognitive demand, with lower variation of performance among individuals. Similarly, it is seen from Table 9 that time pressure also increases the cognitive load for single-tasking individuals.

Table 9. Statistical comparison of performance evaluation for single task groups between those under time pressure and those without time pressure

	Group	N	Average	Standard deviation	*F* value	*p* value
Time pressure	With time pressure	10	42.42	22.50	6.371	.021
	Without time pressure	10	37.88	10.17		

The overall comparisons among the groups' NASA-TLX-based self-evaluation are displayed in Fig.10. It is seen that single tasking group without time pressure had the lowest cognitive load, followed by the other single tasking group under time pressure. Double tasking group with time pressure had the highest cognitive load. The standard deviation, which measured the individual variation of performance within each group, was found highest in the single tasking group with time pressure, and lowest in the single tasking group without time pressure. The variations between the two double tasking groups were not significant. It was inferred that individuals had more unpredictable cognitive load when adding time pressure into single tasking. In comparison, when under the highest cognitive load (i.e., double tasking with time pressure) and lowest cognitive load (i.e., single tasking without time pressure), individuals tended to have lower variations in cognitive resource demand.

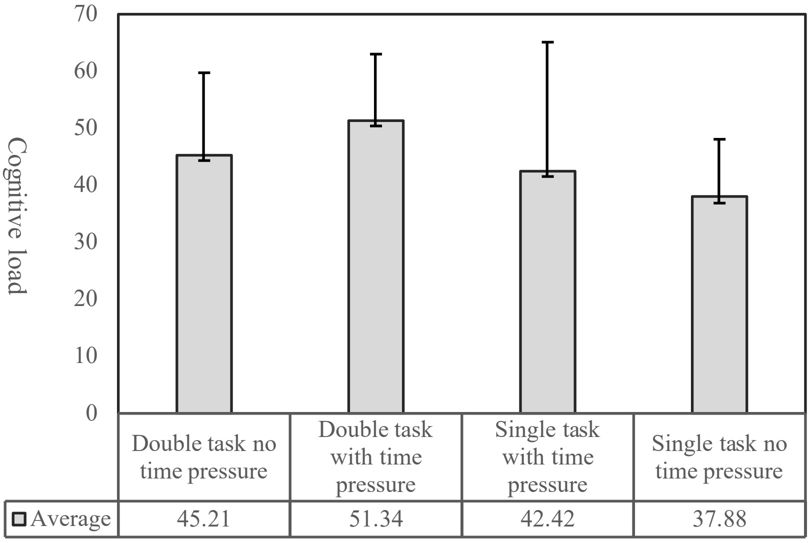


Fig.10. Statistical summary of evaluation performance among different groups

4.2.Experimental results of task performance

The accuracy rate of performing tasks is considered the objective measurement. The accuracy rates of performing primary tasks are compared among the four groups as illustrated in Fig.11.

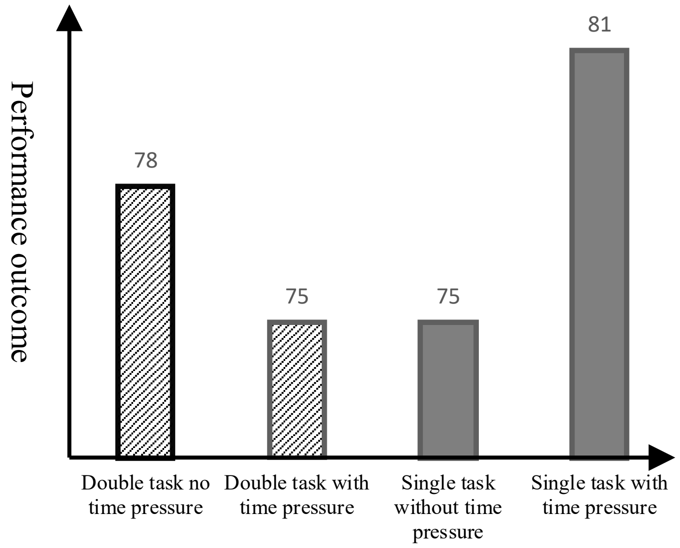


Fig.11. Average score of different groups performing the primary task

As seen in Fig.11, the groups of single task with time pressure and double task without time pressure achieved higher primary task performance as compared to two other groups. Double-tasking individuals performed the secondary task by answering construction-related professional questions whilst working on their primary task immersively. Table 10 compares the accuracy rate of performing secondary task between the two double-tasking groups. The reaction time to the secondary task is compared as summarised in Table 11.

Table 10. Accuracy rate of performing secondary task

Group	Double task without time pressure	Double task with time pressure
Accuracy (%)	80	60

Table 11. Reaction time to secondary task

Group	Average reaction time (ms)	Standard deviation (ms)
Double task without time pressure	279.5	73.4
Double task with time pressure	403.3	132.2

Time pressure was found decreasing the accuracy rate of performing the secondary task, with the rate reduced from *80%* to *60%*. It also largely increased the time demanded to perform the secondary task. The time variation was higher for those under time pressure, indicating that time pressure does not only undermine task performance, but also create higher uncertainty of individual performance.

4. 3. Experimental results between NASA-TLX self-evaluated cognitive load and task performance

The comparisons of outcomes between NASA-TLX self-evaluated cognitive load and objective measurements of task performance revealed consistent findings:

1) Under the single tasking mode of only performing hazard analysis and reaction, adding time pressure would increase cognitive load, while also enhancing the accuracy rates of hazard analysis and reaction. It was hence inferred that proper time pressure exerted into a certain concentrated work mode could improve task performance;
2) Under the double tasking mode of simultaneously performing primary tasks (i.e., hazard analysis and decision making) and secondary tasks (i.e., thinking of other construction-related questions), adding time pressure would increase the cognitive load. Nevertheless, the performance of working on both tasks would downgrade. In real sitework, it is commonplace that workers multi-task. Adding extra time pressure (e.g., pushing for reducing task duration and speeding work) would increase employees' cognitive load and undermine performance. It is indicated that adding more time pressure under multi-tasking would not only increase safety risks but also lower work performance;
3) Under time pressure, higher cognitive load would occur under double tasking mode compared to that under single tasking mode, and the task performance would be lower under double tasking mode. Extra task could exert disturbance to the primary work, distracting the cognitive resources of employees from performing the primary task;
4) When no time pressure was added, although cognitive load would still be higher in double tasking mode compared to that in single task mode, the performance of undertaking double

task is higher compared to that of those in single tasking mode. It is inferred that primary task and secondary task could be organised by employees effectively without lowering the performance. It is therefore not recommended to overemphasise time and speed in performing construction tasks.

4.4. Analysis of experimental outcomes

4.4.1. Self-evaluation of cognitive load

The self-evaluation of cognitive load is a subjective measurement. The comparisons from self-evaluation are illustrated in Fig.12.

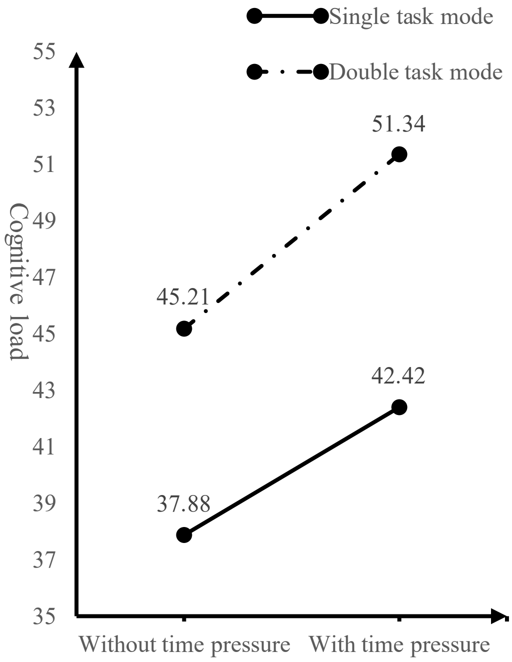


Fig.12. Comparisons of cognitive load among different groups

It is seen from Fig.12 that adding time pressure increased cognitive load under both single and double tasking modes. The double tasking mode demands high cognitive loads regardless of time pressure. It is clear that cognitive load is increased by either adding time pressure or the secondary task. Time pressure increases the cognitive load by raising the density of mental resource in a shorter time period. Double or multitasking divides the total cognitive resource which is allocated between various tasks. The comparisons of cognitive load among the four different groups according to self-evaluation revealed consistent outcomes as what was found out from the comparisons of task performance.

4.4.2. Data analysis of task performance outcomes

4.4.2.1. Evaluation of primary task performance

The evaluation of primary task performance was based on the VR-based immersive experimental results in terms of accuracy rates (%) of participants' safety hazard recognition, analysis, and reaction. Fig.13 illustrates the comparisons between single and double task modes, as well as groups with and without time pressure.

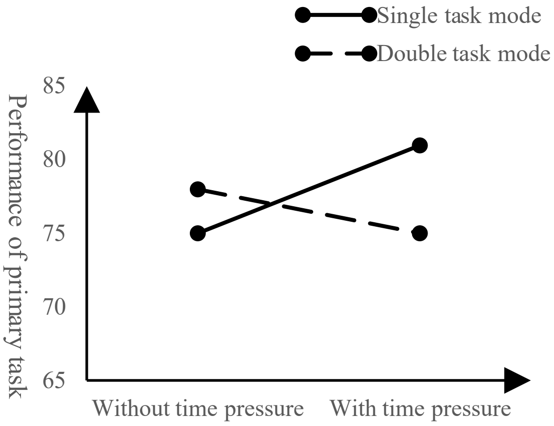


Fig.13. Evaluation performance comparisons of performing primary tasks

As seen in Fig.13, under the single tasking mode, a higher accurate rate was achieved with time pressure (81% versus 75%). It was inferred that proper time pressure exerted to controllable tasks (e.g., single primary task) could improve task performance. However, under double tasking mode when the secondary task was added, time pressure was found undermining the primary task performance. Under single tasking mode, an individual is more likely to be distracted by other non-relevant information and less likely to complete the given task in a seamless and efficient manner. Adding time pressure could motivate individuals to concentrate on the task and to complete it with a greater performance. However, when multitasking, two or more tasks are occupying the cognitive resources of individuals. Since cognitive resources are divided under double-task mode, less resource will be assigned to perform the primary task. Individuals tend to simplify the information retreating process. When time pressure is added under double task mode, a higher cognitive load will be demanded on performing tasks. As a result, lower performance is likely to occur.

4.4.2.2. Evaluation of secondary task performance

The secondary task (i.e., answering a construction-related question) during the immersive site work only applied to the double tasking mode. It represented the site scenario of employees simultaneously working on a given construction task and another task (e.g., safety hazard assessment). The two objective measurements, namely reaction time period and accuracy rate, were used to quantify the individual cognitive load. Fig.14 compares the outcomes between the two double tasking groups.

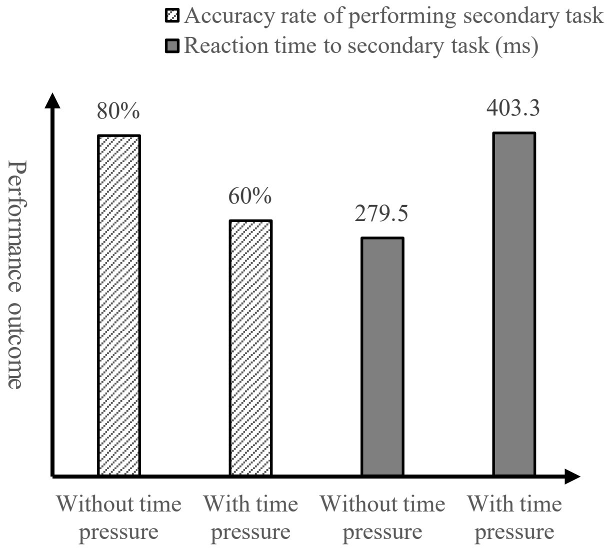


Fig.14. Performance comparisons of performing secondary tasks

As seen in Fig.14, time pressure reduced individuals’ accuracy rate of performing the secondary task and increased the reaction time to handle it. According to the theories of limited cognitive resources (Folkman, 1984; Pashler, 1994), each individual is with limited cognitive resource, and higher demands on cognitive load exceeding the limitation would turn into lower task performance. Increased time pressure would demand higher cognitive load concentration.

Double or multitasking reduces the cognitive resource allocated to primary and other tasks. When the limit of cognitive resource is not exceeded under a given time period, task performance could be maintained or even enhanced. However, adding time pressure and an extra task is more likely to exceed the resource limit. To make up for the increasing cognitive load, individuals may either demand more time of decision making due to extra tasks, or undermine the task performance.

5. Discussion

5.1.Effects of time pressure on cognitive load involved in hazard analysis and decision making

5.1.1. Impacts of time pressure on cognitive load

Time pressure increases the cognitive load demand involved in hazard analysis and decision making. As indicated by the Adaptive Decision Maker theory (Payne et al., 1993), under limited cognitive resources, individuals may spend less resource on retreating the information and speed the decision making process. As a result, the task performance could be compromised. The experimental data showed that individuals under time pressure had a higher cognitive load compared to their counterparts without time pressure. Under double tasking mode, time pressure increased the time needed for individuals to respond to the secondary task, with lower accuracy rate. Time pressure is likely to change the allocation of cognitive resources on given tasks.

A high time pressure could cause stresses of construction employees. In construction site work, a proper schedule of activities would be important to prevent over-stressing of employees. It is further inferred that a tight construction schedule could increase employees’ stress with higher cognitive load. Employees’ capability to analyse and react properly to given tasks may be undermined. Construction contracting or subcontracting in many developing markets (e.g., China) is lump-sum-based, meaning that the total payment is solely based on the total amount of work completed regardless of time input. To pursue the highest income in shortest time, construction employees are motivated to simplify the analysis and decision making process, such as ignoring safety risks. External time pressure, such as the demands from clients or line manager to reduce project duration, would further increase the cognitive load of employees in handling tasks. It is hence not suggested to only exert time pressure as the way to achieve higher site productivity. Instead, a more balanced measure could be taken for the wellbeing of employees, such as incentive for safety behaviour (Han et al., 2020a).

5.1.2. Impacts of time pressure on task performance

Some previous theoretical models (e.g., Hsiao et al., 2017; Yi et al., 2018) indicated that time pressure could positively contribute to enhanced task performance. Existing studies (e.g., Chong et al., 2011; Li et al., 2015) claimed that time pressure could also serve as a double-edged sword towards task performance. It could either enhance work performance positively or reduce it. Li et al. (2015) proposed the Attentional Focus model, which described the effects of time pressure on individuals' attention resources spent on given tasks and the surrounding environment. Higher time pressure would make an individual highly focus on the given task. Insufficient or excessive time pressure would both backfire on task performance as indicated by Li et al. (2015). This goes to show that an optimal level of time pressure that properly allocates the cognitive resources to given tasks would enhance performance. Due to the double-edged effect of time pressure, the key point is how to ensure proper level of time pressure for employees. In construction work, employees should be considered by the features of their individual tasks assigned. In a relatively simple tasking mode, such as single tasking mode, time pressure could be added to achieve better performance. In a more complex task scenario however, the work breakdown could be considered by looking to divide the work package into individual sub-tasks, with time pressure assigned accordingly to broken-down single sub-tasks.

5.2.Mutual effects between tasks and their impacts on cognitive load

As indicated by Pashler (1994) and Bartolomeo (2014), an individual has limited cognitive resources to perform any assigned task, and reaching the limit of cognitive resource would undermine the performance due to overloading of resources. Any task, such as analysing safety hazards with corresponding reactions in this study, costs cognitive resources. Recalling past working scenarios and applying safety knowledge (Han et al., 2019) will occupy the working memories of individuals in participating in this immersive study, costing cognitive resources. More expenditure of resources causes higher cognitive load. Double or multiple tasks being performed simultaneously would distract the cognitive resource from being solely allocated to the primary task. It is not uncommon that site employees work simultaneously on a given primary task while also distracted by other non-relevant task or information. There would be mutual effects between the primary task and other tasks or distractions, resulting in reallocation of cognitive resources. To prevent overloading of cognitive resources, it is recommended to break down tasks, if possible, into sub-tasks with specialised resources and with proper coordination and collaboration between individuals.

6. Conclusion

Two cross-comparison scenes were designed in this immersive study, namely double tasking mode versus single tasking, and also with time pressure versus without it. The primary task under the single tasking mode was safety hazard detection, analysis, and decision making in the immersive site work. The secondary task added into the double tasking mode was answering a construction-related question. Experimental outcomes revealed that double tasking mode increased individuals' cognitive load and lowered the task performance. The findings of this study provide recommendations for real construction site management in that:

1) Task complexity, number of tasks, and time pressure would affect site employees' cognitive load in hazard recognition, analysis, and decision making. Therefore, the three

factors should be properly assigned and managed to not affect performance or employees' mental wellbeing;

2) Time pressure tends to be more applicable under single tasking mode, in which cognitive load could be increased for employees to concentrate on the task and to enhance performance of safety hazard analysis and reaction;

3) Several measures are recommended to reduce safety risks and maintain proper level of cognitive loads of employees, including proper construction scheduling, phased and broken-down tasks, team coordination in joint completion of assigned tasks, and allocation of specialised resources to clearly defined sub-tasks;

This study recruited students as the sample for immersive experiments. It was designed to remove the bias of data analysis caused by the extra variables (i.e., participants' experience level or safety knowledge), and to focus on task mode and time pressure as the two independent variables. The sample could be considered entry-level site employees who were with basic safety knowledge but limited site experience. The current study has not considered other demographic factors' effects on individual's safety recognition performance, for instance, prior site experience. More future work could focus on the effects of personal traits (e.g., safety knowledge) on safety hazard recognition, analysis, and decision making by continuing the immersive approach.

VR-based immersive safety education allows behavioural trials in the virtual environment for individuals to handle safety hazards, which would be too costly or risky on real construction sites. Currently, the level of details of real sites simulated in the immersive and virtual environments could be further enhanced. Individuals' specific safety education needs should also be considered when adopting the immersive approach. Not every experimental participant in this study was comfortable wearing the VR-based devices when performing virtual tasks. Those who felt unable to complete the immersive site walkthrough were excluded from the data analysis. The current VR-driven immersive study was limited to single player approach in a laboratory condition. It is not able to capture completely the dynamic real-site working environment, such as peer interruption. Future research could adopt more real-site tasks besides the current virtual scenarios from this study to test individuals' safety hazard detection, recognition, and reaction. A variety of digital tools could be adopted to enrich data collection and analytics. For instance, wearable glasses in real site tour followed by eye-tracking data analytics could be adopted to evaluate individuals' biological status in relation to task performance and cognitive load. Future work could also adapt the multi-player approach with two or more experimental participants interacting with each other in the immersive virtual site work.

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