The Impact of Engineering Information Formats on Workers' Cognitive Load in Working Memory Development

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ABSTRACT

Owing to the increasing dynamics and complexity of construction tasks, workers often need to memorize a big amount of engineering information prior to the operations, such as spatial orientations and operational procedures. The working memory development, as a result, is critical to the performance and safety of many construction tasks. This study investigates how the format of engineering information affects human working memory based on a human-subject Virtual Reality (VR) experiment (n=90). A VR model was created to simulate a pipe maintenance task. First, participants were asked to review the task procedures in one of the following formats, including 2D isometric drawings, 3D model, and VR model. After the review session, participants were asked to perform the pipe maintenance task in the virtual environment based on their working memory. The operation accuracy and time were used as the key performance indicators of the working memory development. The experiment results indicate that the 3D and VR groups outperformed the 2D group in both operation accuracy and time, suggesting that a more immersive instruction leads to a better working memory. A further examination finds that the 2D group presented a significantly higher level of intrinsic cognitive load and extraneous cognitive load in the working memory development compared to the 3D and VR groups, indicating that different engineering information formats can cause different levels of cognitive load in working memory development, and ultimately affect the final performance. The findings are expected to inspire the design of intelligent information systems that adapt to the cognitive load of construction workers for improved working memory development.

INTRODUCTION

Working memory, i.e., the short-term and temporary storage of information pertaining to the near future events or tasks (Baddeley 1992), plays a critical role in many construction operations (Hou and Wang 2013). Although the real-time access to engineering information is possible during operations, owing to the increasing complexity of construction tasks, many field workers still need to digest and memorize a large amount of engineering information prior to the operations, such as spatial configurations and operational sequences, to ensure a seamless execution of the tasks. Especially at confined workplaces (e.g., utility vaults and pipelines), where the real-time access to necessary information is not guaranteed due to the physical constraints, field workers often have to heavily rely on working memory in the operations (OSHA 1999; Pearce 2017). As construction projects are growing rapidly in both scale and complexity, it is critical to gain a deeper insight into the mechanism of working memory development and retention in the context of complex construction operations.

Working memory development is the result of a heterogeneous cognitive process, affected by a variety of factors (Baddeley 1992). Among all constructs, the sensory information processing is considered one of the most determinant factors, i.e., how the brain processes multiple sensory modality inputs, such as vision, auditory system, tactile and vestibular system into usable functional outputs (Stein et al. 2009). With the fast development of information and visualization technologies in the AEC industry, there is a growing interest in examining the impacts of emerging information communication methods, such as Virtual Reality (VR), on individual's working memory development (Bacim et al. 2013; Eppler and Mengis 2004; Ragan et al. 2012). Nonetheless, literature is still giving conflicting findings. For example, some scholars claimed a positive impact of more immersive information format (e.g., 3D models and VR) on spatial and working memory development (Bacim et al. 2013; Ragan et al. 2012), while others presented the opposite findings (Eppler and Mengis 2004; Richardson et al. 1999). There is an obvious knowledge gap regarding the role of information formats in working memory development in construction tasks, and the underlying mechanism that leads to different information format – working memory relationships.

To fill this knowledge gap, this study investigates how different information formats (2D isometric drawing, 3D model, and VR model) affect the development of working memory in a pipe maintenance task. We further hypothesize that the different impacts of information format are driven by the varying levels of cognitive load during the working memory development (Goldinger and Papesh 2012). We developed an interactive VR system (Ragan et al. 2012; Shi et al. 2019) to simulate a pipe maintenance task of replacing a heat exchanger. The participants' task performance (time and accuracy) was used as the indicator of working memory quality, and cognitive load questionnaires were used to evaluate the three types of cognitive load during the working memory development. The remainder of this paper introduces the point of departure of this study, the research method and the experiment, and the findings and recommendations.

RELATED WORK

Construction works at confined workplaces

Construction operations at confined workspaces is a common scenario in construction projects. Confined workspaces refer to spaces which have a limited or restricted means of entry or exit, unfavorable natural ventilation, and is not intended for continuous occupancy (Pearce 2017). Given the increasing complexity of modern projects, construction workers often have to enter the confined spaces to perform tasks such as routine maintenance, repairs, and inspections. According to the statistical data collected by the Occupational Safety and Health Administration (OSHA), there are 2.7 million permit confined spaces in United States and nearly 2.1 million workers enter permit confined spaces annually (OSHA 1999). However, with the limited space, time pressure, and unfavorable working environment, many fatal injuries were happened in confined spaces. According to a report from Bureau of Labor Statistics (BLS), the fatal occupational injuries involving confined spaces increased 15 % to 166 in 2017 from 144 in 2016 (U.S. Bureau of Labor Statistics 2018) and 52 % of the injuries happened when the workers entered the confined space to perform their work functions of routine maintenance, repairs, and inspections (Koester 2018). Given the importance of working in confined spaces, policy makers and research communities have never stopped to explore the solutions to improve the safety of workers in confined spaces. OSHA established standards and regulations such as General Industry 1910.146 and Construction 1926 Subpart AA to prevent the injuries in confined spaces. Researchers in construction filed also proposed different approaches such as improve entry permit protocol (Burlet-Vienney et al. 2015) and wireless sensors (Riaz et al. 2014) to ensure the safety of workers in confined spaces. It is worth noting that because workers have only limited time (nearly 15 minutes) to perform work in confined spaces per the safety codes (OSHA 1999), and limited access to engineering information constrained by the physical environments, most of the maintenance and repairs tasks in confined spaces require workers to rely on their working memory to retrieve the instructions and perform the tasks. Knowledge about the working memory development and retrieval is therefore important to the performance and safety to confined construction works.

Cognitive load theory

Cognition literature has well documented evidence about the proven relationship between working memory development and cognitive load (Chandler and Sweller 1991; Sweller 1988). Cognitive load is not the outcome of a homogeneous mental process; rather, the seemingly similar cognitive load is driven by various mental activities, and influences memory development in distinct ways (Repovš and Baddeley 2006). Cognitive Load Theory (CLT) (Sweller 2010) divides the overall cognitive load into three main components: Intrinsic Cognitive Load (related to the complexity of tasks), Extraneous Cognitive Load (affected by how information is presented), and Germane Cognitive Load (devoted to construction of schemas – permanent memory development). Among them, Extraneous Cognitive Load is directly related to the perception of information that can be artificially reduced (Chandler and Sweller 1991). Baddeley and colleagues investigated the internal structure of extraneous cognitive load in relation to the working memory based on the sensory information processing (Baddeley 2000). They found that there exist "dual channels" in human cognition, where different mental activities are activated when people are processing two distinct categories of information - Phonological Information (i.e., auditory verbal information or visually presented language) and Visuospatial Information (i.e., the visually presented information about objects and space). A deeper insight into the information-cognition-memory relationship is needed to set the foundation of a fine-tunable mechanism to manipulate and manage working memory development and use in important tasks via the adjustments to information visualization methods.

EXPERIMENT

Experiment task and virtual environment

Owing to the difficulty of simulating complex pipe maintenance tasks in confined spaces in the real world, an interactive VR system was developed. The system was based on our previous VR systems that have been well validated (Du et al. 2017; Du et al. 2018; Shi et al. 2019; Shi et al. 2016). In the virtual environment, participants' motion data (head, body and hands) were collected by the system with a frequency of 90 Hz for the post evaluation of task performance. After each experiment trail, the developed VR system automatically generated a CSV file with all the raw data. The HMD we used in the study is HTC VIVE PRO. The VR system used in the experiment was developed with the Unity 3D-5.6.3f1 version and the pipe model were developed based on the heat exchanger model developed in SketchUp. The participants were asked to memorize the sequences of turning or closing the heat exchanger isolation valves before they replace the plate heat exchanger. In order to examine the impacts of information formats, three types of instructions were used, including 2D isometric drawing, 3D model, and VR. 2D isometric drawing instruction was designed as the combination of bulletin instruction text with 2D isometric drawing of the plate heat exchanger displayed on the monitor as shown in Fig 1 (a). The 3D instruction was a 3D model displayed on the monitor. The participants in the 3D group could use keyboard and mouse to view the instruction texts and the 3D model as shown in Fig 1 (b). VR group used a HMD headset to review the instruction as well as a virtual plate heat exchanger model in an immersive virtual environment. The participants in VR group could also interact with the plate heat exchanger model in real time while reviewing the instruction. To simulate the confined space, participants could see the limited space boundary and they were told not to go beyond the boundary when they perform the task.

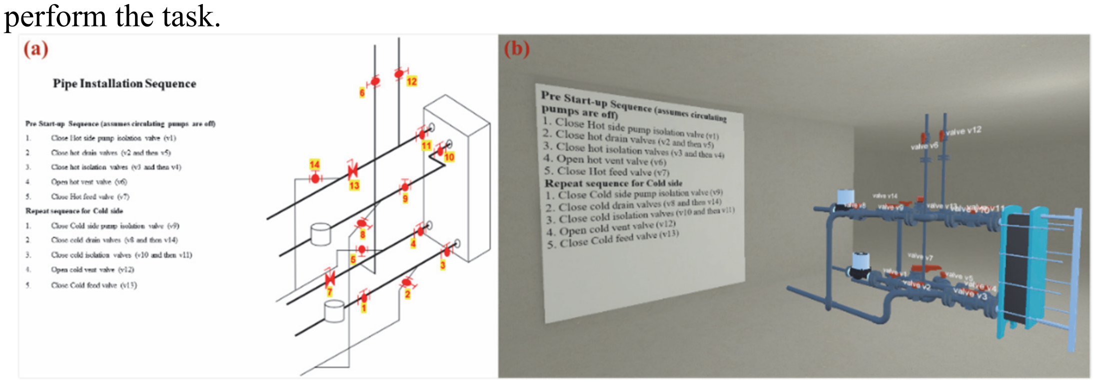

Figure 1. Three types of instruction. (a) 2D isometric drawing; (b) 3D and VR

Experiment Procedure

Participants were required to memorize the right sequence and spatial configuration of a 10-step pipe maintenance task within 5 minutes, and then to perform the task in the VR environment based on the working memory. The task steps are related to the pre start-up sequences to cut off the hot water and cold water, based on the instruction manual of Alfa Laval plate heat exchangers (AlfaLaval 2016). Participants were told that their performance would be compared with others and the amount of the experimental compensation would be decided by the task performance. The purpose was to motivate participants to memorize the pipe maintenance sequence and perform the task as accurately as possible. The experiment consisted of seven sessions: (1) pre-questionnaire, (2) spatial and memory tests, (3) training, (4) review session, (5) retention session, (6) operation session, and (7) post-questionnaire and interviews. The pre-questionnaire session (5-10 minutes) was designed to collect participants' demographical information including age, gender, major, degree level, previous game and VR experience, and knowledge level of the HVAC system. The spatial and memory tests (10-20 minutes) were used to evaluate participants' spatial cognition and spatial memory abilities and set the baseline of their task performance. We used the cube comparison test and shape memory test developed by the Educational Testing Service (ETS) in our study (Sweany et al. 2016). The training session (5 minutes) was designed for participants to familiarize with system in the VR environment. The participants were also given instructions about how to use the two controllers to interactive with the virtual valves. The review session (5 minutes) was used for participants to review and memorize the pipe maintenance sequence. The review time was limited to 5 minutes because some participants may feel sickness (nausea, headache, dizziness, and light headed) for 10 minutes or longer in the virtual environment based on our previous studies (Du et al. 2017; Mwima et al. 2017; Shi et al. 2019). In the retention session (5 minutes) the participants were given another shape memory test. The purpose is to intervene the working memory storage of the participants, and to trigger relatively high cognitive load in the following task. After the retention session, participants were asked to perform the valve maintenance task in the VR environment (no time limit). At the end, participants were also asked to fill out a post-questionnaire to provide comments and feedbacks. The post-questionnaire was developed based on the cognitive load measurement proposed by Leppink's cognitive research (Leppink et al. 2013; Leppink et al. 2014). Compared to the traditional cognitive load measurement-NASA TLX survey, this measurement can evaluate three sources of cognitive load, which are Intrinsic Cognitive Load (related to the complexity of tasks), Extraneous Cognitive Load (affected by how information is presented), and Germane Cognitive Load (devoted to construction of schemas – permanent memory development). The participants were randomly assigned to one of three groups. The experiment procedure took approximately 60 to 90 minutes for each participant. Each participant received a 10-dollar gift card after their finished the experiment. Figure 2 shows the participants in review and operation sessions.

Figure 2. Participants in review and operation sessions. (a) 2D group; (b) 3D group; (c) VR group; (d) operation session in virtual environment

RESULTS

Participants

A total of 90 participants (48 males, 42 females) took part in the study, including 38 undergraduate students and 52 graduate students. All the participants were recruited via the university email. The participants were randomly assigned into one of the three groups. Each group contained 30 participants to rule out the influences of individual differences. Participants' ages ranged from 18 to 45 with the median age of 23. Participants were from a variety of disciplines, including civil engineering, construction management, and other engineering majors. Their previous game and VR experience were surveyed since it could affect participants' VR task performance (Enochsson et al. 2004). The participants reported their previous game and VR experiences on a 10-point Likert scale (1- no experience, 10-a lot of experience). The average game experience was 5.78 and the average VR experience was 3.01. The results indicate that most participants claimed few VR experience and thus their performance could be compared on the common ground. Participants were also asked to report their previous knowledge about maintaining the HVAC system on a 10-point Likert scale (1- no experience, 10-a lot of experience). The participants' average previous knowledge about HVAC system was 1.98, indicating that participants have very limited previous knowledge about maintaining the HVAC system. According to the results of Shapiro-Wilk test, the cube test and memory test scores were found to be normally distributed, and thus the one-way ANOVA test was used. The ANOVA test found that there was no significant difference in the cube test score (p=0.3303) and memory test score (p=0.9196) across three groups, showing a similar spatial ability levels and memory ability levels among the participants in each group.

Task Performance

The outliers in the data of task performance were removed by the Mahalanobis distances analysis. Because the data was not normally distributed based on the Shapiro-Wilk test of normality, a Kruskal-Wallis non-parametric test was used to compare the operation accuracy across different groups.

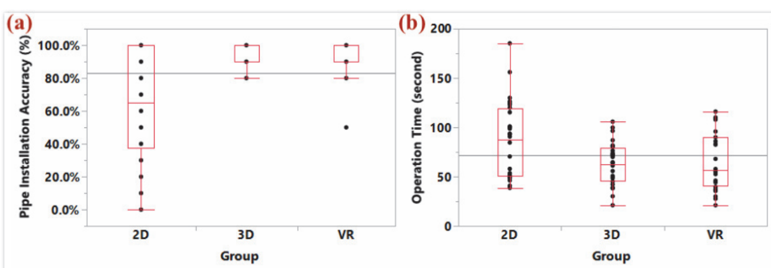

Figure 3. Participants' task performance. (a) accuracy; (b) time.

As illustrated in figure 3 (a), we found a significant difference (p<0.0001) in the accuracy among the three groups. A pairwise nonparametric comparison for each pair-Wilcoxon's test found significant differences between the 2D group and VR group (p=0.0004) and between the 2D group and 3D group (p=0.0005). We did not find significant differences between the 3D group and VR group (p=0.7159). The results reveal that the participants in the 3D and VR group had better accuracy. As for the operation time, the Kruskal-Wallis test also found a significant difference (p=0.0455) among the three groups, as illustrated in figure 3 (b). A pairwise nonparametric comparison for each pair-Wilcoxon's test found significant differences between the 2D group and VR group (p=0.0275), and between the 3D group and 2D group (p=0.0382). Again, we did not find significant differences between the 3D group and VR group (p=0.9673). The results reveal that the participants in the 2D group used more time to complete the task than the other groups.

Cognitive Load

To further investigate the cognitive load requirements in the working memory development across the three groups, we evaluated participants' cognitive load levels using Leppink's cognitive load measures (Leppink et al. 2013; Leppink et al. 2014) at the end of the experiment. The questionnaire uses a 11-point Likert scale (0-low, 10-high) to measure three types of cognitive load, including the intrinsic cognitive load (related to the perceived difficulty of the memory task), the extraneous cognitive load (related to how information is presented), and the germane cognitive load (related to the difficulty of transferring working memory into long term memory) (Leppink et al. 2013; Leppink et al. 2014). Since the survey data satisfies the normality assumption, we performed a one-way ANOVA test to compare the difference in terms of three types of cognitive load across three groups.

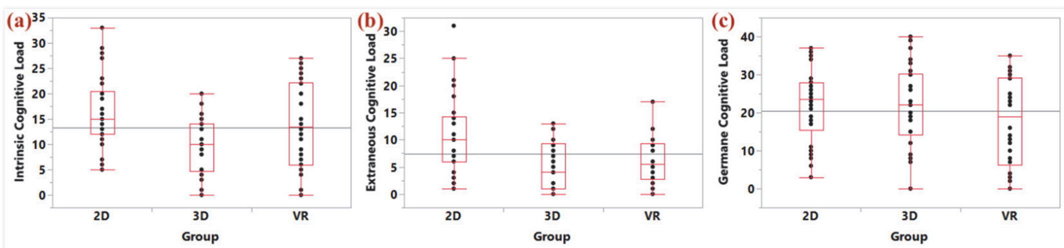

Figure 4. The results of three cognitive load. (a) intrinsic cognitive load; (b) extraneous cognitive load; (c) germane cognitive load.

Figure 4 illustrates the results of the cognitive load assessment. As for the intrinsic cognitive load, one-way ANONVA finds a significant difference across three groups (p=0.0012) as shown in figure 4 (a). The Tukey-Kramer HSD pair comparisons test finds significant differences between the 2D group and 3D group (p=0.0007). We did not find significant differences between the 3D group and VR group (p=0.1206), or between the 2D group and VR group (p=0.1681). These results indicate that participants in the 2D group demonstrated the highest intrinsic cognitive load across three groups, indicating that 2D drawings increase the perceived difficulty of working memory development. As for the extraneous cognitive load, one-way ANONVA finds significant differences between the 2D group and 3D group (p<0.0001) and between the 2D group and VR group (p=0.0004), as shown in figure 4 (b). We did not find any difference between VR group and 3D group (p=0.8272). The results indicate that the participants in the 3D and VR groups reported a lower extraneous cognitive load and the 2D group reported a higher extraneous cognitive load. Since the extraneous cognitive load is closely related to how the information is presented, it indicates that the 3D and VR display methods trigger less cognitive load related to the information processing. Finally, we did not find any significant difference (p=0.2368) in germane cognitive load among different groups, as illustrated in Fig 10 (c). Since the germane cognitive load is related to the long-term memory development, the result indicates that different engineering information formats do not affect the transition from short term working memory into the long-term permanent memory in this task. In general, the post-experiment cognitive survey reveals that 3D and VR groups tended to demonstrate lower cognitive load levels and this could have driven better performance of these two groups.

CONCLUSIONS

This study investigates how different information formats (2D, 3D, and VR) affect individual's cognitive load in working memory development. We conducted a human-subject experiment (n=90) using a VR system to perform the comparison study. The participants were asked to review instructions of a pipe maintenance task for a short period and then perform the operations in the virtual environment based on their memory. The results find that 3D and VR groups outperformed 2D group in both operation accuracy and time. The additional cognitive load analysis finds that 3D and VR groups showed lower intrinsic and extraneous cognitive load levels compared to the 2D group. The results indicate that different information formats trigger varying levels of cognitive load in working memory development phase. The 2D instruction format increases the perceived difficulty of the memory development for the participants (intrinsic cognitive load), and the information processing (extraneous cognitive load). Therefore, our research results can inspire a better design of construction training via information visualizationthat adapts to the cognitive needs. The findings are also expected to provide more evidence about information-working memory mechanism that helps resolve the current theoretical disagreement on construction literature and inspire the design of a cognition-driven information system for construction workers. The limitation of this study is that the results of participants' cognitive load level were evaluated with the cognitive load survey. Participants' subjective perspectives may contain biases. Since the cognitive load was evaluated in the post-task phase, the real-time evaluation of participants' cognitive load is need. In our future study, we will collect participants' pupil diameter changes and brain activities to obtain direct evidence about participants' cognitive statues under different information format conditions.

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