The Impact of Engineering Information Complexity on Working Memory Development of Construction Workers: An Eye-Tracking Investigation

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ABSTRACT

Owing to the increasing complexity of construction tasks and operations performed in confined workplaces, workers rely progressively on working memory, i.e., the short-term and temporary storage of information pertaining to near future events, to ensure the seamless execution of construction tasks. Although literature has discovered a strong relationship between engineering information formats and the quality of working memory, there is still a clear theoretical disagreement on the implications of the complexity of engineering information in the development of working memory. This study addresses the knowledge gap with a human-subject experiment (n=60). Participants were required to review one of the two instructions for a pipe maintenance task: a simple 2D isometric drawing with bulletins (2D-simple) and a complex 2D isometric drawing with rich text (2D-complex). After the review session, the participants were asked to perform the pipe maintenance task in a virtual reality (VR) environment. Collected data include participants' task performance (accuracy and time), pupillary dilations, and gaze movements. The results show that the 2D-simple group outperformed the 2D-complex group in terms of both accuracy and time. An attention pattern analysis using approximate entropy (ApEn) of gaze movements suggests that a higher ApEn in the vertical axis, i.e., a more irregular and complex gaze movement between instructions, may result in a more efficient use of working memory and thus contributes to a better performance. This study provides preliminary evidence regarding the impact of engineering information complexity on the working memory development of construction workers.

INTRODUCTION

Working memory, i.e. the short-term and temporary storage of information pertaining to near-future events or tasks (Baddeley 1992), plays a critical role in construction operations (Hou and Wang 2013). Although real-time access to engineering information is possible during operations, due to the growing complexity of construction tasks, many field workers still need to understand and memorize large quantities of engineering information, such as spatial configurations and operational sequences, prior to operations in order to ensure a seamless execution of the tasks (Shi et al. 2019). This reliance on working memory is especially prominent in confined workplace, where real-time access to necessary information is not guaranteed due to physical constraints (OSHA 1999). As construction projects are growing rapidly in both scale and complexity, it is critical to gain a deeper insight into the mechanisms of working memory development and retention in the context of complex construction operations. Literature has well documented that exposure to various formats of information may lead to different levels of working memory development and ultimately, task performance (Engström et al. 2010). Recent evidence also indicates that the complexity of information can affect the development and use of memory in a series of human-computer interaction experiments (Bacim et al. 2013; Ragan et al. 2015). Yet the fundamental causes and mechanisms remain unclear, as they can be related to multiple cognitive processes that are currently under-explored.

The objective of the study is to test the hypothesis that information complexity influences attention patterns during information review, which further drives the development of working memory. To achieve the research objective, a human-subject experiment (n=60) was conducted in a Virtual Reality (VR) environment with gaze movement analysis as an indicator of attention patterns. The testing group consisted of 60 participants who were randomly divided into two groups, with each half given two levels of instruction complexity. The pupillary changes and gaze movements were then compared between the two groups to explore the causes of different levels of working memory development. The remainder of this paper introduces the background and experiment results.

RELATED WORKS

Information Processing, Cognitive Load and Working Memory

Literature has provided compelling evidence supporting the relationship between information complexity and working memory development (Kirschner et al. 2011; Parmenter et al. 2007). Classical theories tend to explain it from the cognitive load perspective. The Multimedia Learning theory found that increased information complexity burdened sensory information processing and affected the efficiency of working memory development (Mayer 2002). The Cognitive Load theory further suggested that an excessive amount or complexity of information can significantly increase intrinsic cognitive load (related to the task difficulty) and extraneous cognitive load (related to how information is presented) (Sweller 1994). The increased cognitive load pertaining to the processing of complex information ultimately results in worse working memory and performance. Bacim et al. (2013) discovered that higher visual complexity resulted in slower performance of spatial inspection tasks. The study of Ragan et al. (2015) evaluated the performance of a visual scanning task with varying visual complexity. The results found that a higher visual complexity resulted in decreased performance. According to Mayer and Moreno (2003), humans usually have only a limited cognitive capacity to process information, thus unnecessary cognitive loads should be reduced to avoid overloading in multimedia instruction design. However, our data indicated that cognitive load is not the only cause of varying qualities of working memory development. In this study, we proposed to explain the information complexity – working memory relationship from the information digestion perspective, i.e. attention patterns (analyzed with gaze movement data) that affect how efficiently the information is encoded in the memory system.

Eye-tracking and Attention Study

With promising efficacy and growing industry awareness, eye tracking techniques have gained popularity in the contemporary research field. Eye trackers records the user's eye movement to be analyzed retrospectively (Jacob and Karn 2003). In the Human-Computer Interaction (HCI) research field, the eye tracking technique is widely utilized in usability research including improving user interface (Goldberg and Kotval 1999), data visualization (Conati et al. 2015), 3D interaction (Lee et al. 2010), and website review (Wang et al. 2014). An advantage of using eye-tracking is that the integration of eye-tracking technique and psychological theory can assist researchers in investigating people's perceptual and cognitive processes (Monty and Senders 2017). With these promising benefits of implementing the eye-tracking techniques, researchers have started to use eye-tracking techniques to investigate construction problems. For instance, Hasanzadeh et al. (2018) used a mobile eye tracker to investigate the relationship between construction workers' visual attention and their situation awareness under hazardous conditions on the construction job site. The results of the study found that the workers' visual attention to the hazardous areas is modulated by their level of situational awareness.

EXPERIMENT

Overview

To investigate the impact of information complexity on construction workers' working memory, a complex pipe maintenance task including 10 pre-start-up steps was designed. Test subjects included 60 participants who were randomly divided into two groups, given two levels of instruction complexity (see Fig. 1). The sequence was adapted from the instruction manual of Alfa Laval plate heat exchangers (AlfaLaval 2016). An interactive VR system was developed for participants to implement the task. Pupillary changes and gaze movements were recorded to evaluate cognitive load differences and attention patterns.

VR system with eye-tracking function

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). The two eye trackers used in the experiment were Tobii Pro X3-120 eye tracker and Tobii Pro VR as they could obtain precise and high-resolution pupil data (see Fig. 2). During the review session, the Tobii Pro X3-120 was mounted to the monitor screen to record participants' gaze positions at the frequency of 120 Hz. The accuracy of the Tobii Pro X3-120 is 0.4 degree on the monitor with an operating distance of 50 cm to 90 cm (Tobii 2019). At the end of the review session, a TSV file recording all raw eye-tracking data was automatically generated.

To achieve the eye-tracking and visualization functions in the virtual environment, several C# scripts were developed based on the Tobii Pro software developer's kit (SDK) (Tobii 2019) and the application programming interface (API) in Unity. In the virtual environment, participants' gaze movement data were collected by the system with a frequency of 90 Hz. After each VR experiment trial, the developed VR system automatically generated a CSV file with all the raw data. The VR HMD we used in the study is HTC VIVE PRO (HTC 2018). The Field of View (FOV) is 110 degrees with the resolution of 1400 x 1600 pixels per eye for the dual displays (HTC 2018). The VR system used in the experiment was developed with the Unity 3D-

5.6.3f1 version and the pipes were developed based on the heat exchanger model developed in SketchUp. The VR system is supported by a workstation using the Intel Xeon CPU at 2.60GHz with a 64GB of RAM. The graphic card of the workstation is NVIDIA GTX 1080.

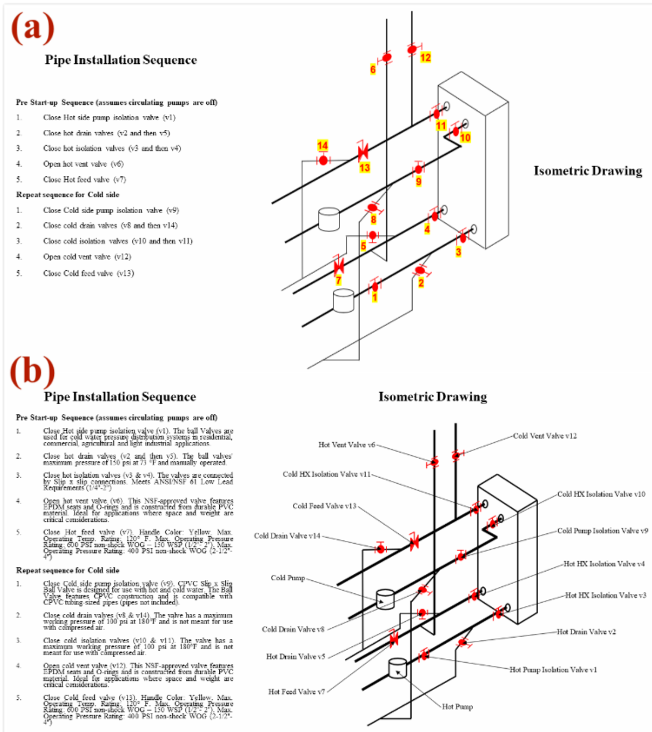

Figure 1. Two levels of information complexity (a) 2D-simple; (b) 2D-complex

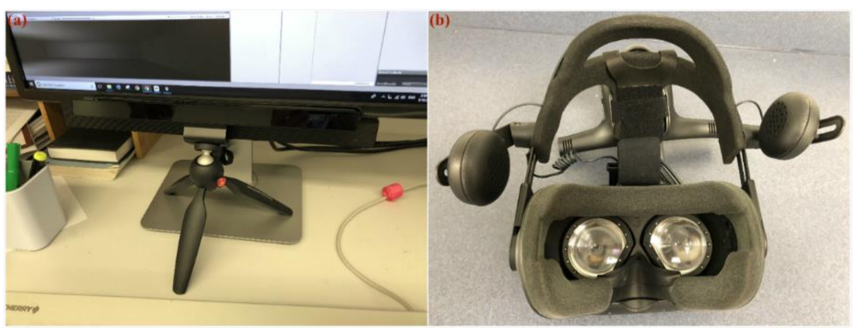

Figure 2. The Eye trackers used in this study (a) Tobii Pro X3-120 eye tracker; (b)Tobii Pro VR Integration eye tracker

Experiment Procedure

Participants were required to memorize the right sequence and spatial configuration of a 10-step pipe maintenance task within 5 minutes on a monitor screen, and then to perform the task in the VR environment based on their working memory. As a motivation to achieve better performance, participants were informed that their performance would be compared with others and the amount of experimental compensation would depend on their performance. The experiment procedures included 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.

Firstly, a pre-questionnaire session of 5-10 minutes was conducted. The participants filled in a background questionnaire that included demographical information (age, gender, major, degree level, previous game and VR experience, and knowledge of HVAC system). Secondly, participants were required to complete the spatial and memory tests developed by the Educational Testing Service (ETS) (Sweany et al. 2016) to set a baseline for their task performance (10-20 minutes). Then a 5-minute training session was executed to help participants familiarize with the VR environment, including learning how to use the two controllers to manipulate virtual valves in the VR environment. After the training session, participants were given 5 minutes to review the instructions on a monitor screen and to memorize the task sequence. To further complicate the task, participants were required to do another shape memory test during the retention period, as a way to interfere the working memory development and trigger a higher cognitive load. Then, participants were required to perform the pipe maintenance task in the VR environment. No time limit was given, as completion time was an important indicator of working memory development level and the performance. Lastly, post-questionnaire was conducted to collect feedback and comments. The whole procedure lasted for about 60 to 90 minutes (Fig. 3). Each participant received a 10-dollar gift card after the whole experiment.

Figure 3. Participants in review and operation sessions (a, b) 2D-simple group; (c, d) 2D-complex group

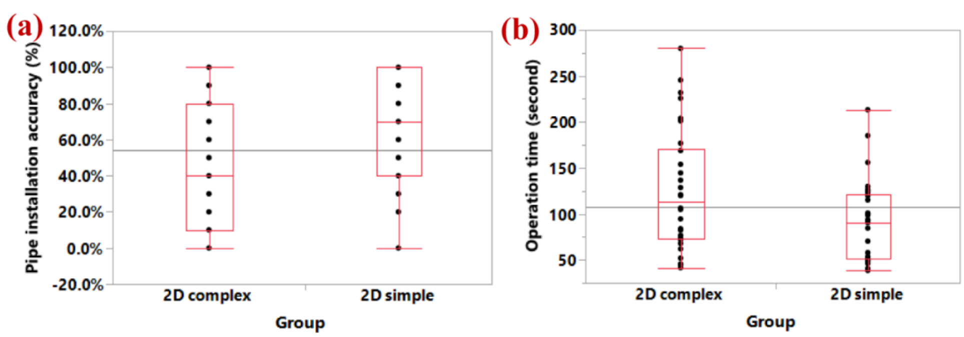

Figure 4. Participants' task performance (a) accuracy; (b) time

RESULTS

Overview

The experiment recruited 60 participants via the university email. Among them, 37 participants were males while 23 were females. The ages of participants ranged from 18 to 45 with a median of 23. In the background questionnaire, the previous game and VR experience were surveyed as it would affect their task performance in the VR environment (Enochsson et al.

2004). The 10-point Likert scale survey (1-no experience, 10-a lot of experience) showed an average game experience of 5.80 and an average VR experience of 3.16. It indicated that most participants had very limited VR experiences. The survey regarding construction knowledge and HVAC systems was also performed on the 10-point Likert scale. The results showed that most participants had limited knowledge or experience in HVAC system with an average rate of 2.30. Due to the limitation of recruitment method, it is not practical to recruit sufficient participants with much VR experience or good HVAC knowledge. However, the survey suggested that there was no need to perform individual adjustment as most participants showed similar levels of familiarity with the task and the VR system.

Task Performance

To evaluate task performance, two indicators, pipe installation accuracy (%) and operation time (second) were used. To uniformly evaluate pipe installation accuracy, only touching the right valve with the correct sequence would be considered as correct action. The outliers were removed by Mahalanobis distances analysis. A Kruskal-Wallis non-parametric test was adopted for both accuracy and operation time comparison as the data did not conform to normal distribution. From Fig. 4(a), a certain difference regarding installation accuracy can be observed (p=0.0164) between two groups. The difference of operation time can be detected as well from Fig. 4(b) (p=0.0445). The differences indicate that the performance of the 2D-simple group is better, as the participants in the 2D-simple group used less time and achieved higher accuracy.

Cognitive Load and Attention Pattern Comparisons

Working memory literature tends to attribute the decreased performance to the increased cognitive load in the processing of complex information (Kirschner et al. 2011; Parmenter et al. 2007). As a result, we performed a pupillary size analysis to evaluate the cognitive load differences between the two groups. Literature shows that the pupillary dilation is a strong indicator of increased cognitive load, which has been widely used in real-time cognitive load assessments (Recarte and Nunes 2000; Schwalm et al. 2008). Cumulative evidence also shows that pupillary dilation significantly correlates with results of questionnaire-based psychometric methods, such NASA Task Load Index (TLX) (Krejtz et al. 2018). The pupillary analysis, however, shows no difference between the two groups, suggesting a similar cognitive load level (p=0.4909, Fig.5(a)). Similarly, pupillary dilations in the performance session did not show any differences between the two groups either using the VR-embedded eye tracker (p=0.9429). Therefore, we further investigated the gaze movements as an indicator of attention patterns, using the Approximate Entropy (ApEn) method. ApEn is a statistical method to quantify the regularity complexity of noisy time-series data (Pincus 1995). The method is widely used in physiological time series analysis, including heart rate (Lake et al. 2002) and Electro-Encephalo-Gram (EEG) (Bruhn et al. 2000; Srinivasan et al. 2007). The application of ApEn in eye-tracking is helpful to evaluate the regularity and unpredictability of fluctuations of gaze movement data. McKinley et al. (2011) applied ApEn to eye position data and discovered that the low level of ApEn, i.e. the low irregularity of gaze movement, is related to decreased performance of fatigue pilots during flight tasks.

In this study, ApEn was calculated for the participants' gaze movement separately for X axis and Y axis by approximate Entropy in a MATLAB toolbox (MathWorks 2019). Fig. 5(b)(c) shows the ApEn results in X axis and Y axis of the two groups. As the results were not normally distributed, the Kruskal-Wallis non-parametric test was used to compare the results. For the results in X axis (Fig. 5(b)), there is no difference between the ApEn of two groups (p=0.7363). However, there is a clear difference in Y axis (p<0.0001). As shown in Fig. 5(c), the 2D-simple group has a higher ApEn than the 2D-complex group in Y axis. A higher value of ApEn indicates a more frequent gaze movements in the Y direction when reviewing the instructions. In other words, test subjects in the 2D-simple group tended to scan information more quickly and repeatedly across different task steps.

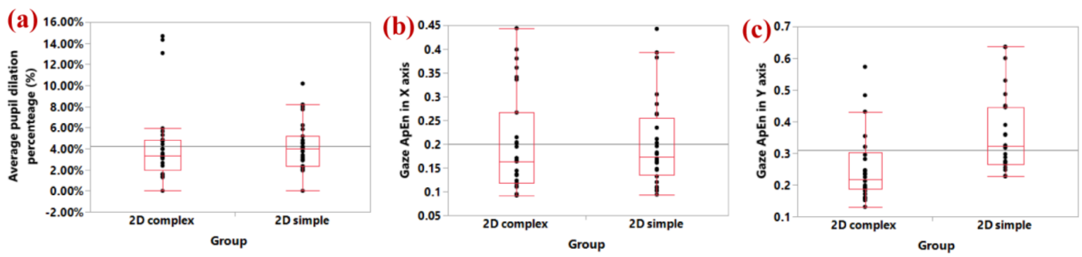

Figure 5. (a) Pupil dilation (%) (b) Gaze ApEn in X axis (c) Gaze ApEn in Y axis

The results indicate that the participants' horizontal eye movement had similar irregularity. It may result from a similar attention pattern when reading a single text instruction and switching between text information and image information. In terms of the irregularity and complexity of vertical eye movement, the differences between the two groups may be related to the varying levels of working memory development. The higher ApEn in Y axis of the 2D-simple group indicates a more irregular and complex vertical gaze movement between the 10 steps in text instruction. When participants reviewed the semantic instructions, participants tended to memorize the sequence by repeating switching their attention across different steps to enhance memory process. As the instruction is short for the 2D-simple group, we suppose that the participants had a higher repetition of information reviews, which reinforced their working memory development. As for the 2D-complex group, the rich texts tended to cost participants more effort understanding the sequence. Meanwhile, according to McKinley et al. (2011)'s study, a low ApEn of gaze movement is related to fatigue-induced poor performance. Thus, the lower value of ApEn of 2D-complex group may indicate fatigue or attention distraction of participants during the review session. It resulted in a low review efficiency and a poor working memory development of the 2D-complex group.

CONCLUSIONS

This study investigates how the complexity of engineering information affects the working memory development of construction workers. We conducted a human-subject experiment (n=60) in the VR environment and measured pupillary dilations and gaze movement. Participants were asked to memorize instructions of different complexities and performed a pipe maintenance task. The results showed that the participants given the instruction with bulletins (2D-simple) outperformed the participants given the instruction with rich texts (2D-complex). While the pupillary analysis shows no difference between the two groups, suggesting a similar level of cognitive load, the analysis of gaze movement indicates different attention patterns between the two groups. The higher gaze ApEn in vertical axis of the 2D-simple group indicates a higher complexity and frequency of gaze movement, resulting in a higher review repetition and reinforced working memory. The lower ApEn of the 2D-complex group may imply fatigue and attention distraction. The findings suggest that attention patterns during information review drive working memory development and further affect task performance.

A potential limitation of the study is that the experiment only focused on two levels of information complexity. A more sophisticated experiment design with more levels of complexity could help identify is a nonlinear relationship between information complexity and working memory exists. The future research also includes collecting other sources of data to study the causes and mechanisms of the relationship, such as neuroimaging data in order to study the level of brain activation.

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REFERENCES

AlfaLaval (2016). "Instruction Manual - Plate Heat Exchangers."

Bacim, F., Ragan, E., Scerbo, S., Polys, N. F., Setareh, M., and Jones, B. D. "The effects of display fidelity, visual complexity, and task scope on spatial understanding of 3D graphs." *Proc., Proceedings of Graphics Interface 2013*, Canadian Information Processing Society, 25-32.

Baddeley, A. (1992). "Working memory." *Science*, 255(5044), 556-559.

Bruhn, J., Röpcke, H., and Hoeft, A. (2000). "Approximate entropy as an electroencephalographic measure of anesthetic drug effect during desflurane anesthesia." *Anesthesiology: The Journal of the American Society of Anesthesiologists*, 92(3), 715-726.

Conati, C., Carenini, G., Toker, D., and Lallé, S. "Towards user-adaptive information visualization." *Proc., Twenty-Ninth AAAI Conference on Artificial Intelligence*.

Du, J., Shi, Y., Zou, Z., and Zhao, D. (2017). "CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users." *Journal of Construction Engineering and Management*, 144(2), 04017109.

Du, J., Zou, Z., Shi, Y., and Zhao, D. (2018). "Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making." *Automation in Construction*, 85, 51-64.

Engström, J., Aust, M. L., and Viström, M. (2010). "Effects of working memory load and repeated scenario exposure on emergency braking performance." *Human factors*, 52(5), 551-559.

Enochsson, L., Isaksson, B., Tour, R., Kjellin, A., Hedman, L., Wredmark, T., and Tsai-Felländer, L. (2004). "Visuospatial skills and computer game experience influence the performance of virtual endoscopy." *Journal of gastrointestinal surgery*, 8(7), 874-880.

Goldberg, J. H., and Kotval, X. P. (1999). "Computer interface evaluation using eye movements: methods and constructs." *International Journal of Industrial Ergonomics*, 24(6), 631-645.

Hasanzadeh, S., Esmaeili, B., and Dodd, M. D. (2018). "Examining the Relationship between Construction Workers' Visual Attention and Situation Awareness under Fall and Tripping Hazard Conditions: Using Mobile Eye Tracking." *Journal of Construction Engineering and Management*, 144(7), 04018060.

Hou, L., and Wang, X. (2013). "A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender." *Automation in Construction*, 32, 38-45.

HTC (2018). "HTC VIVE PRO." <https://www.vive.com/us/product/vive-pro/>. (June 6th, 2019).

Jacob, R. J., and Karn, K. S. (2003). "Eye tracking in human-computer interaction and usability research: Ready to deliver the promises." *The mind's eye*, Elsevier, 573-605.

Kirschner, F., Paas, F., and Kirschner, P. A. (2011). "Task complexity as a driver for collaborative learning efficiency: The collective working-memory effect." *Applied Cognitive Psychology*, 25(4), 615-624.

Krejtz, K., Duchowski, A. T., Niedzielska, A., Biele, C., and Krejtz, I. (2018). "Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze." *PloS one*, 13(9), e0203629.

Lake, D. E., Richman, J. S., Griffin, M. P., and Moorman, J. R. (2002). "Sample entropy analysis of neonatal heart rate variability." *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 283(3), R789-R797.

Lee, E. C., Woo, J. C., Kim, J. H., Whang, M., and Park, K. R. (2010). "A brain–computer interface method combined with eye tracking for 3D interaction." *Journal of neuroscience methods*, 190(2), 289-298.

MathWorks (2019). "MATLAB and Predictive Maintenance Toolbox R2019a." < (https://www.mathworks.com/help/predmaint/ref/approximateentropy.html).>. (July 30, 2019).

Mayer, R. E. (2002). "Multimedia learning." *Psychology of learning and motivation*, Elsevier, 85-139.

Mayer, R. E., and Moreno, R. (2003). "Nine ways to reduce cognitive load in multimedia learning." *Educational psychologist*, 38(1), 43-52.

McKinley, R. A., McIntire, L. K., Schmidt, R., Repperger, D. W., and Caldwell, J. A. (2011). "Evaluation of eye metrics as a detector of fatigue." *Human factors*, 53(4), 403-414.

Monty, R. A., and Senders, J. W. (2017). *Eye movements and psychological processes*, Routledge.

OSHA (1999). "PAPERWORK REDUCTION ACT 1995 SUBMISSION SUPPORTING STATEMENT FOR PERMIT-REQUIRED CONFINED SPACES." <https://www.osha.gov/Reduction_Act/CON-SPA3.html>. (May 28th, 2019).

Parmenter, B. A., Shucard, J. L., and Shucard, D. W. (2007). "Information processing deficits in multiple sclerosis: A matter of complexity." *Journal of the International Neuropsychological Society*, 13(3), 417-423.

Pincus, S. (1995). "Approximate entropy (ApEn) as a complexity measure." *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 5(1), 110-117.

Ragan, E. D., Bowman, D. A., Kopper, R., Stinson, C., Scerbo, S., and McMahan, R. P. (2015). "Effects of field of view and visual complexity on virtual reality training effectiveness for a visual scanning task." *IEEE transactions on visualization and computer graphics*, 21(7), 794-807.

Recarte, M. A., and Nunes, L. M. (2000). "Effects of verbal and spatial-imagery tasks on eye fixations while driving." *Journal of experimental psychology: Applied*, 6(1), 31.

Schwalm, M., Keinath, A., and Zimmer, H. D. (2008). "Pupillometry as a method for measuring mental workload within a simulated driving task." *Human Factors for assistance and automation*(1986), 1-13.

Shi, Y., Du, J., Ahn, C. R., and Ragan, E. (2019). "Impact assessment of reinforced learning methods on construction workers' fall risk behavior using virtual reality." *Automation in*

Construction, 104, 197-214.
Shi, Y., Du, J., Lavy, S., and Zhao, D. (2016). "A Multiuser Shared Virtual Environment for Facility Management." *Procedia Engineering*, 145, 120-127.
Srinivasan, V., Eswaran, C., and Sriraam, N. (2007). "Approximate entropy-based epileptic EEG detection using artificial neural networks." *IEEE Transactions on information Technology in Biomedicine*, 11(3), 288-295.
Sweany, J., Goodrum, P., and Miller, J. (2016). "Analysis of empirical data on the effects of the format of engineering deliverables on craft performance." *Automation in Construction*, 69, 59-67.
Sweller, J. (1994). "Cognitive load theory, learning difficulty, and instructional design." *Learning and instruction*, 4(4), 295-312.
Tobii (2019). "Tobii Pro SDK." <https://www.tobiipro.com/product-listing/tobii-pro-sdk/>. (June 6th, 2019).
Tobii (2019). "Tobii Pro X3-120." <https://www.tobiipro.com/product-listing/tobii-pro-x3-120/>. (June 5th, 2019).
Wang, Q., Yang, S., Liu, M., Cao, Z., and Ma, Q. (2014). "An eye-tracking study of website complexity from cognitive load perspective." *Decision support systems*, 62, 1-10.