The Effectiveness of Virtual Reality in Safety Training: Measurement of Emotional Arousal with Electromyography

S. Xu[a, b], Q. Ni[c], and Q. Du[a]

[a] School of Economics and Management, Chang'an University, China
[b] National Centre of International Research on Digital Construction and Management for Transport Infrastructure along the Belt and Road Initiative, China
[c] School of Civil Engineering, Chang'an University, China
E-mail: sheng.xu@chd.edu.cn, Q.Du@163.com

Abstract –

The improvement of safety performance of construction workers heavily lies in safety training and great improvement has been achieved in training technology, training materials and training organisation. Currently, the form of training and induction based on traditional lectures and workshop studies has been innovated and enriched by digital and e-learning technologies and applications, such as immersive visualization techniques like Virtual Reality (VR), Augmented Reality (AR) and game engines. The visualization techniques allowed workers to enhance their safety capabilities by playing the safety training game in virtual scenarios. However, the validation of its effectiveness was measured with either self-reported questionnaire or the improvement in safety performance and productivity. This research proposed a framework to directly validate the effectiveness of virtual reality in safety training by measuring the degree of emotional arousal with electromyography (EMG). Specifically, the degree of inducement of fear was measured during safety trainings with pictures, videos and VR. The higher degree of fear was induced, the more effective the safety training was. In this way, this research provided a novel approach to prove the effectiveness of the immersive visualization techniques and a possible framework to further identify important personal and environmental factors of safety training process.

Keywords –

Virtual Reality; Safety Training; Emotional Arousal; Electromyography

1 Introduction

Safety training and education is an important issue in construction safety management. Because of the massive amount of new construction, large groups of new workers come into the construction industry without proper skills or enough experience. Migrant workers are common worldwide. In China, most Chinese on-site workers used to do agricultural jobs, and the number of migrant workers in the construction industry has increased by more than 1 million per year. Less than 7% of them attended vocational training programs. Senior technicians accounted for less than 0.3% of all workers, compared to 20%~40% in developed countries. The US construction sector provided 7% of all employment in the workforce but accounted for 20% of worksite fatalities [1]. According to statistics, there were more than two million Hispanic workers in the construction industry in the U.S., and those Hispanic workers also had the highest injury and fatality rates [2]. Human errors and unsafe behaviours contribute greatly to accidents [3], Garrett and Teizer [4] pointed that previous research showed human factors accounted for 90% of all accidents in complex industries with high risks. Furthermore, inexperienced workers are more likely to perform unsafe behaviour and cause accidents.

Currently, the form of training and induction based on traditional lectures and workshop studies has been innovated and enriched by digital and e-learning technologies and applications, such as accident simulations in Building Information Modelling (BIM) systems, and other immersive visualisation techniques, such as Virtual Reality (VR), Augmented Reality (AR) and game engines [5-7]. The variety of training schemes does not only transfer essential knowledge to workers, it also guarantees the attainment of certain task proficiency that is required to prepare workers for real-work task settings [8], as well as to instil a positive danger/risk-sensitive attitude and safety climate in the workplace [9, 10].

It is well recognised that VR technologies are effective in enhancing construction safety training programs, however, the amount and mechanisms of the improvement brought by VR to safety training have not been fully explored and measured with objective index other than self-reported questionnaire surveys. Therefore, this research proposed a possible explanation of the enhancement of VR safety training, and an approach to measure the effectiveness of VR safety training.

2 Literature Review

2.1 VR Applications in Construction Safety Training

The literature review identifies a variety of training approaches and techniques for construction safety. There is a long history of using classroom-based studies to upskill the construction workforce. The improvement of knowledge, attitude and self-reported practice followed by a one-hour classroom study, was evidenced by Sokas [11]. Tailored classroom training programs were also applied to 2700 training construction workers working on a railway project, which revealed positive effects, such as that workers were more likely to handle materials safely [12]. The conventional safety training takes the form of classroom teaching, and is tedious, difficult to understand and memorize, and has unsatisfying influence on performance improvement. In recent years, the form of classroom training programs has been enriched. A series of studies have made their efforts to improve safety training, for example, the peer-led training programs, which believed the interventions of co-workers could improve the learning outcomes [13]; the encouragement of verbal communications on safety between supervisors and workers [14]; the localisation of safety training materials for Hispanic workers [15] and narrative simulations, and improved toolbox training programs that are delivered by workmates or trained foremen [16]. Foremen, peers and unions help with safety performance through safety leadership and communication [17], and they improve the safety climate, which has a social influence on construction workers. It has to be noted, however, that classroom-based training was stereotyped, as its form may not be effectively conducive to motivating learners, and the uniform teaching manner may not take the learner disparity into account.

With the emergence of innovative Information Communication and Technology (ICT) applications, construction practitioners and researchers have started to shed light on technology-assisted training paradigms. To gain hands-on skills and practical experience with a shorter training turnaround, it is preferable that traineeships should be more task-oriented and available for both on and off-the-job options. Because it makes more sense to justify workers performance, potential hazards and causation factors in real-time working contexts. To facilitate a more task-oriented, context-aware and customisable training environment, innovative visualisation manners such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR) and Building Information Modelling (BIM) have been formulated and researched [18]. The rationale of VR, AR, MR and BIM is that these technologies make use of computer graphic representations (e.g., agent-based avatars, virtual/ augmented task instructions and clues, etc.) to create a virtual but immersive space where real-life scenarios can be replicated for trainees to experience and make sense of risks. Traditional safety training with texts and few graphical elements were difficult to be understood, especially by low literacy novice workers. On-the-job training engaging hands-on experience could be more efficient [19] but time-intensive, expensive, and potentially hazardous [20]. To help low-literacy construction workers who may have linguistic and understanding problems at work [14, 21], Lin et al. [19] developed a game-engine based VR serious game which can offer visual representations that remind unsafe conducts; Le et al. [5] proposed an online VR training framework for multiple students to perform role-playing construction safety training with communications within groups and social interactions; Behzadan and Kamat [22] presented an innovative pedagogical tool that adopting remote videotaping, AR, and ultra-wideband (UWB) to better link virtual objects to the real world. One of the advocating evidences is the expedited process of developing complex procedural skills required to operate construction heavy equipment on modern, large scale complex infrastructure projects [7]. Overall, the motivation of safety training can also be intervened by ICT paradigms. For this purpose, one of the proffered research directions is that ICT applications should interface with real-life task scenarios that are often dynamic, complicated and varied.

2.2 Possible Explanations of Effective VR Training

The advantages of using VR in education and training are related to its ability to enable students to interact with each other within virtual three-dimensional (3D) environments. Intuitive sense about the learning subjects can also be developed by interacting with the objects, related messages and signals in the virtual environment. Different from the conventional education and training approaches, such as the utilizations of static pictures or two dimensional (2D) drawings, VR's visual representation allows more degrees of freedom (DoFs) to be integrated. Compared to conventional training methods, ICT innovations for training was reported to be more conducive to development of short-term memory, emotional arousal, attention maintenance, confidence enhancement [23, 24], information retention, and various essential cognitive mechanisms that underpin workers' kinesthetic and psychomotor abilities [25]. Therefore, it was suggested that the future of construction safety education should incorporate VR/AR technologies into the pedagogy.

Psychologically, a possible explanation of the advantages of VR/AR technologies in safety training might be related to the emotional memory enhancement effect. It was used for the phenomenon that events or materials loaded with emotional information are more likely to be retained in individual memory and have a higher recall accuracy compared with neutral events or materials [26]. This effect can be found no matter whether emotional words, emotional pictures or emotional films are used, or whether they are used in recognition tests, free recall or clue recall [27, 28]. Previous studies have found that the enhancement effect of emotional memory is mainly affected by the arousal level of emotional stimulation, and highly aroused emotional stimulation can get priority attention and thus be processed preferentially [29]. Therefore, no matter emotional pictures or emotional words, highly aroused emotional stimulation has better memory effect. Individuals' fear stimulation is a rapid automatic processing, so as to quickly deal with threats.

In construction safety research, the effects of emotional arousal have been recognised [30, 31]. The assessment of emotions of accidents was included in workers' judgement of construction accidents' likelihood and severity [32], and negative emotions from previous experience could lead to the decision of avoid risky behaviour [33]. Furthermore, while positive emotions in learning could lead to higher levels curiosity, interest, and desire to improve performance, research also showed that negative emotions could arise extrinsic motivation to avoid failure [34], lead to better engagement in learning [35]. Lang [36] proposed limited capacity model of motivated mediated message processing (LC4MP) to explain the relationship between emotion and learning motivation.

Fear is an emotion closely related to evolution. It can stimulate workers' defense mechanism and help human survival and adapt to the environment. The formation and expression of fear is activated by the brain regions including the amygdala, anterior cingulate gyrus and the frontal cortex [37, 38]. The use of event-related potential methods can help the study find the neural basis of emotional infection. It is a research method with high time precision, which can help researchers discover a cognitive processing process and reflect the time course of emotional infection. It can record multiple brain components induced by emotions. The occurrence time, amplitude intensity and brain area of these components will be important indicators reflecting the processing of cognitive emotions. Different components represent different psychological cognitive processes, including P200 and P300. P200 is an early positive component, the peak is located after the stimulus is presented to the left and right, and the scalp is in the forehead or the occipital region [39-41]. P200 peak can be used to reflect the emotional valence (or, pleasure) and arousal of the information (or strength). P300 is related to attention, identification, decision, memory, etc. [42, 43].

However, existing measurement of fear are by means of electroencephalography (EEG), electro-cardio (ECG) and galvanic skin response (GSR), and it was difficult for the portable devices of the measurement of these indicators to be adequately accurate (medical level) and instantaneous enough to capture the spontaneous reaction of fear. On the other hand, electromyography (EMG) signals are perfect to measure real time responses if the responses include muscle motions. Portable devices on the open market to accurately measure EMG are also easily accessible. Therefore, this research used EMG which could be measured accurately with a wristband and be recorded instantaneously.

3 Pilot Study

3.1 Experiment Design

3.1.1 Participants

In the pilot study, university students were recruited as participants, including 9 graduate students in Construction Management major, out of which there were five female students and four male students.

3.1.2 Measuring Devices

An episode of VR safety training material for construction workers on Fall-from-Height was mounted with HTC Vive and displayed to each participant.

Electromyography signals were measured with DTing Gesture Control Wristband, which is in the world's first easy-start gesture-controlled robot series. The wristband is able to detect users' gesture behaviour, including forearm movement, hand gesture and finger force. In this research, put around the wrist, it is able to capture the signals with pollicis. The surface electromyography (sEMG) signal, gyoroscope signal, accelerometer signal and more related signals are fused to recognize gestures in high precision.

Heart rates were measured with Polar H10 heart rate sensor because it monitors heart rate more accurate and adaptable and connect heart rates to cellphones by Bluetooth simultaneously. Pictures of the wristband and heart rate sensor were shown in Figure 1.

Figure 1. DTing Gesture Control Wristband (left) and Polar H10 heart rate sensor (right)

3.1.3 Measurement approach

The purpose of the pilot study was to determine if the EMG devices could reveal the instantaneous muscle tensions caused by fear during VR trainings on the prevention of fall-from-heights and to adjust the experiment design for a larger scale of experiments on diverse students to determine the effect of personal factors on training effects.

The participants wore the HTC VIVE headset and watch a small episode of safety training material on fall from height. Meanwhile, they also wore DTing wristband on their left or right wrist (according to their free will) and Polar H10 heart rate sensor around their chest. The wristband recorded the changes in electromyography on their pollicis instantaneously and the signals were uploaded to an application to process them with an Android device. Then it could be exported to Matlab and be further processed and mapped graphically. Polar H10 heart rate sensor recorded their heart rate changes and could also be exported to Microsoft Excel for further analysis.

Follow up questions for reviewing and sharing feelings during VR training were asked and discussed with every participant. However, those questions and discussion topics were not pre-determined in the pilot study, but along a broad spectrum of their after-test feelings and possible suggestions.

3.2 Results and discussions

The pilot study revealed that the EMG devices had successfully captured muscle tensions in the pollicis, as shown in Fig. 2. A group of peaks could be observed at almost the same time at the moment of falling in the VR training.

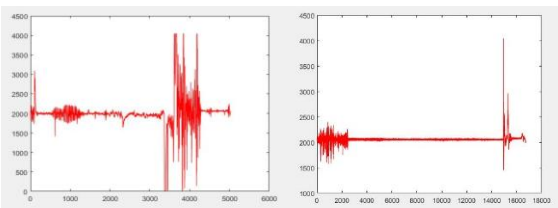

Figure 2. Examples of sudden muscle tensions in pollicis captured by DTing Wristband

However, some participants could be used to the VR trainings after repetitive experiments. Fig. 3 (left) showed that after three trials, the same participants as Fig. 2 (left) showed little tension during the training.

Females and males reacted very different. All female students showed muscle tension to a certain degree at their first trials and reported that VR trainings had raised their fear in the after-test discussions. However, two out of four male students showed little muscle tension and reported “not very scary” in the after-test discussions. Fig. 3 (right) showed a male participant barely tensioned throughout the training, except for the adjustment of his handset at the beginning.

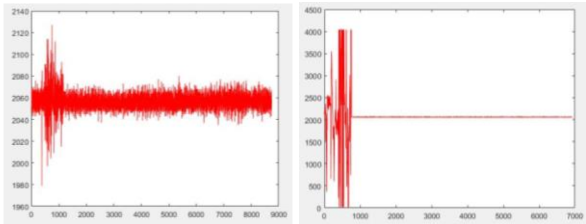

Figure 2. Examples of participants showed little tension during the training after three repetitive trials (left) and from the beginning (right)

The pilot study revealed that several improvements need to be addressed in the experiment design. First of all, the tension of fear could be in different muscles with different participants. Some participants reported tension in the wrist, feeling they “need to grasp something”, and others reported tension in their thighs, feeling that they “could hardly stand straight” and “got cold feet”. Approaches to fix this problem may be providing gesture control bands around the thighs as well as the wrist.

Secondly, the unrelated muscular tensions should be identified and filtered out from tensions caused by fear. Participants could use their pollicis to adjust their HTC VIVE headset and handset, or tensions caused by taking the test, or any other reasons. Fig. 3 shows the signals of a participant feeling tension throughout the training. It would be necessary to filter the actual signals caused by fear of the falling in VR training. Approaches to fix this problem may include developing a filtering algorithm to process the signals, excluding the handset in experiencing the falling to avoid unnecessary muscle tensions and using time stamps to determine the beginning of the signals possibly caused by the falling animation, and so on.

Thirdly, a structured survey should follow up right after the VR training to better review the EMG signals and determine participants’ training effectiveness. As in the pilot study, the follow-up discussion helped the researchers to better understand participants’ reactions to the training materials.

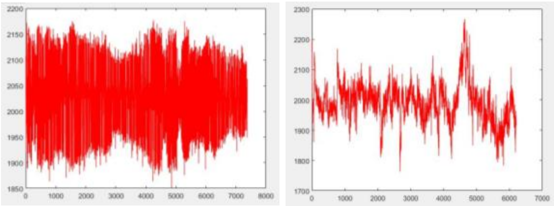

Figure 3. Signals of a participant feeling tension throughout the training.

4 Conclusions

This research tried to validate the effect of VR in construction safety trainings and provide a possible explanation for the advantage of VR training. This research measured the EMG showing muscle tensions of participants watching a piece of VR-based fall-from-height training material with a gesture control wristband. The pilot study confirmed that some participants showed muscle tensions on their pollicis when they experienced falling in the VR training, which indicated that VR-based trainings could raise fear in participants and the fear could improve the effectiveness of training because of the emotional arousal. However, the pilot study also showed that a lot of improvements should be made to the experiment design to provide trustworthy and insightful results.

References

[1] Lavy S., Aggarwal C. and Porwal V. Fatalities of Hispanic Workers: Safety Initiatives Taken by U.S. Construction Companies to Address Linguistic and Cultural Issues. *International Journal of Construction Education and Research*, 6(4): 271-284, 2010.

[2] Menzel N. N. and Gutierrez A. P. Latino worker perceptions of construction risks. *Am. J. Ind. Med.*, 53(2), 179–187, 2010.

[3] Reason J. *Human error*. New York: Cambridge University Press, 1990.

[4] Garrett J. W. and Teizer J. Human Factors Analysis Classification System Relating to Human Error Awareness Taxonomy in Construction Safety. *Journal of Construction Engineering and Management* 135(8): 754-763.

[5] Le Q. T., Pedro A. and Park C. S. A Social Virtual Reality Based Construction Safety Education System for Experiential Learning. *Journal of Intelligent & Robotic Systems*, 79(3-4): 487-506, 2015.

[6] Li H., Chan G. and Skitmore M. Visualizing safety assessment by integrating the use of game technology. *Automation in Construction*, 22: 498-505, 2012.

[7] Hou L., Chi H. L., Utiome E. and Wang X. Y. Cooperative and Immersive Coaching to Facilitate Skill Development in Construction Tasks. *Cooperative Design, Visualization, and Engineering, Cdve* 20169929: 371-377, 2016.

[8] Hou L., Chi H.-L., Tarng W., Chai J., Panuwatwanich K. and Wang X. A framework of innovative learning for skill development in complex operational tasks. *Automation in Construction*, 83: 29-40, 2017.

[9] Shin M., Lee H.-S., Park M., Moon M. and Han S. A system dynamics approach for modeling construction workers' safety attitudes and behaviors. *Accident Analysis & Prevention*, 68: 95-105, 2014.

[10] Choudhry R. M. Behavior-based safety on construction sites: A case study. *Accident Analysis & Prevention*, 70: 14-23, 2014..

[11] Sokas R. K., Jorgensen E., Nickels L., Gao W. and Gittleman J. L. An Intervention Effectiveness Study of Hazard Awareness Training in the Construction Building Trades. *Public Health Reports*, 124 (4_suppl1): 161-168, 2009..

[12] Bena A., Berchialla P., Coffano M. E., Debernardi M. L. and Icardi L. G. Effectiveness of the training program for workers at construction sites of the high-speed railway line between Torino and Novara: Impact on injury rates. *American Journal of Industrial Medicine*, 52(12): 965-972, 2009.

[13] Williams, Q., M. Ochsner, E. Marshall, L. Kimmel and C. Martino. The Impact of a Peer-Led Participatory Health and Safety Training Program for Latino Day Labourers in Construction. *Injury Prevention*, 16: A235-A235, 2010.

[14] Andersen LP, Karlsen IL, Kines P, et al. Social identity in the construction industry: implications for safety perception and behaviour, *Construction Management and Economics*, 33(8): 640-652, 2015.

[15] Evia C. Localizing and Designing Computer-Based Safety Training Solutions for Hispanic Construction Workers. *Journal of Construction Engineering and Management*, 137(6), 452-459, 2011.

[16] Kaskutas V., Buckner-Petty S., Dale A. M., Gaal J. and Evanoff B. A. Foremen's intervention to prevent falls and increase safety communication at residential construction sites. *American Journal of Industrial Medicine*, 59(10): 823-831, 2016.

[17] Jeschke K. C., Kines P., Rasmussen L., Andersen L. P. S., Dyreborg J., Ajslev J., Kabel A., Jensen E. and Andersen L. L. Process evaluation of a Toolbox-training program for construction foremen in Denmark. *Safety Science*, 94: 152-160, 2017.

[18] Bosche F., Abdel-Wahab M. and Carozza L. Towards a Mixed Reality System for Construction Trade Training. *Journal of Computing in Civil Engineering*, 30(2), 2016.

[19] Pedro A., Le Q.T., Park C.S., Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality. *J. Prof. Issues Eng. Educ. Pract*. 142 (2): 04015011, 2015.

[20] Wang X., Dunston P.S., A user-centered taxonomy for specifying mixed reality systems for AEC industry. *J. Inf. Technol. Constr. (ITcon)*, 16 (29): 493–508, 2011.

[21] Lin K.-Y., Lee W., Azari R. and Migliaccio Giovanni C. Training of Low-Literacy and Low-English-Proficiency Hispanic Workers on Construction Fall Fatality. *Journal of Management in Engineering*, 34(2): 05017009, 2018.

[22] Behzadan A.H., Kamat V.R. Enabling discovery-based learning in construction using telepresent augmented reality, *Automation in Construction.* 33: 3–10, 2013.

[23] Sacks R., Perlman A., Barak R., Construction safety training using immersive virtual reality, *Construction Management and Economics,* 31 (9): 1005–1017, 2013.

[24] Juang J., Hung W., Kang S., SimCrane 3D+: A crane simulator with kinesthetic and stereoscopic vision, *Adv. Eng. Inform.* 27 (4): 506–518, 2013.

[25] Bhandari, S. and Hallowell M. R. Emotional Engagement in Safety Training: Impact of Naturalistic Injury Simulations on the Emotional State of Construction Workers. *Journal of Construction Engineering and Management*, 143(12), 2017.

[26] Hamann S. Cognitive and neural mechanisms of emotional memory. *Trends in Cognitive Sciences*, 5(9): 394-400, 2001.

[27] Kensinger EA, Corkin S. Memory enhancement for emotional words: Are emotional words more vividly remembered than neutral words? *Memory and Cognition*, 31: 1169- 1180, 2003.

[28] Talmi D, Schimmack U, Paterson T, et al. The role of attention and relatedness in emotionally enhanced memory. *Emotion*, 7: 89-102, 2007.

[29] Kern RP, Libkuman TM, Otani H, et al. Emotional stimuli, divided attention, and memory. *Emotion*, 5: 408-417, 2005.

[30] Fassbender E., Richards D., Bilgin A., Thompson W. F., and Heiden W. VirSchool: The effect of background music and immersive display systems on memory for facts learned in an educational virtual environment. *Comput. Educ.*, 58(1), 490–500, 2012.

[31] Tixier A. J. P., Hallowell M. R., Albert A., van Boven L., and Kleiner B. M. Psychological antecedents of risk-taking behavior in construction. J. Constr. Eng. Manage., 140(11): 04014052, 2014.

[32] Bechara A., Damasio H., and Damasio A. R. Emotion, decision making and the orbitofrontal cortex. *Cereb. Cortex,* 10(3): 295–307, 2000.

[33] Slovic P., and Peters E. Risk perception and affect. *Curr. Dir. Psychol. Sci.*, 15(6): 322–325, 2006.

[34] Pekrun R., Elliot A. J., and Maier M. A. Achievement goals and achievement emotions: Testing a model of their joint relations with academic performance. *J. Educ. Psychol.*, 101(1): 115–135, 2009.

[35] Chung S., Cheon J., and Lee K. W. Emotion and multimedia learning: An investigation of the effects of valence and arousal on different modalities in an instructional animation. *Instruct. Sci.*, 43(5): 545–559, 2015.

[36] Lang A. Using the limited capacity model of motivated mediated message processing to design effective cancer communication messages. *J. Commun.*, 56(S1): S57–S80, 2006.

[37] Feinstein J. S., Adolphs R, Damasio A., and Tranel D. The human amygdala and the experience of fear. *Current Biology*, 21(1): 34-38.

[38] Admon R., Lubin G., Stern O., Rosenberg K., Sela L., Ben-Ami H. et al. Human vulnerability to stress depends on amygdala's predispositon and hippocampal plasticity. *Proceedings of the National Academy of Sciences*, 106(33): 14120-14125, 2009.

[39] Carretie L., Mercado F., Tapia M., and Hinojosa J. A. Emotion, attention and the "negativity bias" studied through event-related potentials. *International Journal of Psychophysiology*, 41: 75-85, 2001.

[40] Thomas S. J., Johnstone S. J. and Gonsalvez C. J. Event-related potentials during emotional Stroop task. *International Journal of Psychophysiology*, 63131: 22I-231, 2006.

[41] Sergei, A., Alexei, N. G. and Julius, K. Categorization of unilaterally presented emotional words: an ERP analysis. *Acta Neurobiological Experiment*, 60: 17-28, 2000.

[42] Maguire M., Brier M. R and Moore P. S. et al. The influence of perceptual and semantic categorization on inhibitory processing as measured by the N2-P3 response. *Brain and Cognition*, 71: 19G-203, 2009.

[43] Briggs K. E. and Martin F. H. Affective picture processing and motivational relevance arousal and valence effects on ERPs in an oddball task. *International Journal of Psychophysiology*, 72: 299-306, 2009.