Virtual Construction Safety Training System: How Does it Relate to and Affect Users' Emotions?

Fan Yang[1] and Jiansong Zhang, Ph.D.[1*]

[1]School of Construction Management Technology, Purdue University, United States of America
* Corresponding Author

yang2352@purdue.edu, zhan3062@purdue.edu

Abstract -

The construction industry is witnessing an increasing adoption of virtual reality (VR) technology for training and education purposes. Given this trend, it becomes essential to critically investigate the impact it has on learners, especially when compared to traditional paper-based learning method. In this paper, the authors developed a close-to-reality virtual system using the Unity3D game engine. Participants engage in learning safety protocols, operating a virtual crane, and assembling a steel structure within this environment. Corresponding paper-based instructional materials were also developed for comparison. The study involved 16 participants who were randomly assigned to either the VR training or the traditional paper-based training, their brainwaves data were recorded through electroencephalography (EEG) headset during the training progress to assess their emotions. Results show that an individual is most likely to experience exciting emotions when they are training in the VR system compared with the traditional training method. The correlation with actual safety performance, however, remains unclear and requires further investigation.

Keywords -

Virtual reality; Construction training; EEG; Emotion analysis

1 Introduction

Construction is a complex, high-risk industry due to the diverse set of skilled workers' involvement [1]. Consequently, the identification of hazards is of paramount importance within the construction industry. Extensive analysis of construction accidents reveals that unsafe site conditions, lack of proper training, unsafe worker behaviour, and unsafe method and task sequencing are the main causes of accidents [2]. Despite the construction industry's consistent emphasis on on-the-job training, security risk assessments using two-dimensional drawings make it difficult to identify many potential hazards [3].

The use of Virtual Reality (VR) technology in the context of construction training has attracted considerable interest in recent research publications. Several studies have demonstrated how VR applications may help with critical issues that the construction industry faces, especially those related to skill development, safety training, and operational efficiency.

To address these challenges, the authors proposed a VR-based construction training system. This system aims to furnish users with comprehensive training before engaging in on-site activities. This highly realistic three-dimensional (3D) environment was developed using Unity 3D game engine, allowing the system to simulate detailed safety protocol training, crane operation and steel structure assembly procedures, thereby delivering virtual on-the-job training. Although there have been many studies using VR for construction training, a significant research gap exists in comparing the emotional impacts on users between virtual reality method in construction training and traditional paper-based training method. Emotions are key indicators of an individual's thoughts, underlying psychological conditions, and resultant behaviors [4]. Thus, discerning users' emotional states is vital for evaluating the efficacy of varying training approaches. Electroencephalography (EEG) signals can reflect people's emotional state in real-time objectively [5]. To ascertain the participant's emotional state during the training, this study employed EEG to quantitatively assess brain activity, providing a standardized gauge of user experience. In our controlled experiment, 16 participants were assigned to two groups for comparing VR and traditional learning methods, analyzing arousal and valence dimensions from EEG data.

2 Background

Despite attention to construction site injuries, accident rates in this high-risk industry double the industrial average [6], often due to limited safety knowledge and awareness among workers and engineers. Traditional education methods fail to provide adequate safety training for on-site performance [7].

2.1 Game simulation in construction education

The scope of traditional learning methods, such as paper-based materials, DVD videos and discussions has been questioned as ineffective for the construction industry [8]. According to [9], active project-based approaches in construction education are more effective in fulfilling educational goals than traditional lecture-based methods. Especially when Generation Y students, known as the ”Internet Generation,” have transitioned into the workforce. They are more interested in game-based learning with an entertainment twist than traditional learning methods [10]. The use of game simulations for educational training dates back to 1991 with Microsoft Flight Simulator [11]. Despite not utilizing VR technology and instead relying on a combination of mouse, keyboard, and joysticks, the experiments have demonstrated a notable positive impact on learners and the method was subsequently widely used in the aircraft industry. With the technology advancement, game technology and game engines are now being increasingly utilized in the construction domain. For example, [12] proposed the integration of BIM and gaming, demonstrating a virtual, interactive framework's potential in design education; [13] described an innovative safety assessment approach using game technology, which involves immersing workers in 4D virtual risk scenarios specific to their projects, coupled with a range of potential action strategies, thereby enhancing their knowledge and skill levels in real-world situations; [14] introduced a BIM-based simulation method combining game technology and robotics to enhance automation in modular wood construction. And later, the same authors implemented this method in the game engine-based environment, where a workflow encompassing extraction of BIM information, development of the wood frame assembly process, and validation through game engine simulations was conducted, laying the groundwork for future productivity assessment with physical robotic integration [15].

2.2 Virtual reality in construction

An immersive, interactive digital environment opens new opportunities for enhancing educational experiences [16]. For example, [17] presented a virtual training program, in which workers actively engage in realistic scenarios, making decisions based on their knowledge or intuition. This interactive approach significantly enhances workers' safety awareness and skills; [18] conducted comparative training experiments, revealing that virtual reality-based construction safety training significantly enhances learning retention and attention span; [7] reviewed the need for effective safety education in construction, where traditional methods fall short in providing practical experience. It proposes an innovative online social VR system with role-playing and interactive learning modules, proven effective in enhancing construction safety education; [19] presented an immersive safety training environment for construction workers, addressing poor hazard recognition in dynamic work environments. It emphasizes personalized, realistic training using 360° panoramic images and videos, offering a more immersive training environment with a high degree of presence. As VR gains prominence in construction, researchers have advocated for its inclusion as a standard component within the construction curriculum system [20], and also beginning to pay more attention to evaluating the effectiveness of VR in their studies. For example, [21] conducted a comparison between VR training and in-person training for the control task of a demolition robot. Experts evaluated the participants' behaviour along three dimensions: knowledge acquisition, operational skills, and safety behaviour, by measuring against specific targeted operational skills and safety behaviours in each learning module; [22] introduced a VR training module tailored for the precast/prestressed concrete industry, concentrating on PPE, strand tensioning, and suspended loads training. The module's efficacy compared with traditional video-based training methods was evaluated using questionnaires. The advent and evolution of VR headsets have marked a shift in research from screen-based VR to immersive headset experiences in recent years. While this change enhances immersion, it also brings issues like VR sickness in many users [23]. Consequently, it is evident that there is a growing emphasis among researchers on users' psychological and physiological responses in construction training.

2.3 Psychophysiological studies in construction

Construction safety is directly related to the physical and emotional states of construction workers which have been studied using different methods. For example, [24] used heart rates as a reference to measure user response to hazardous construction scenarios; [25] used physiological measurements of energy expenditure, including oxygen consumption and heart rate data, to assess construction workers' physiological thresholds. Recently, Heart rate, heart rate variability and skin temperature were used as the physiological impact of the construction VR experience study [26]. “EEG is a noninvasive measurement of the brain's electrical activity, which is generated by firing neurons in the brain” [27]. EEG data is commonly used to examine two fundamental properties of affective experience: valence and arousal. Arousal is associated with the user's level of excitement/calmness and valence is associated with the user's level of positivity/negativity [28]. There has been a century-long discussion on their relationship. According to Kron et al., [29] valence and arousal can be separated in emotional experiences. Based on the famous active learning theory [30], creating excitement in the classroom can motivate students to be active learners. Recent years have seen a surge in the use of EEG signals in construction studies, primarily because wireless wearable EEG devices have expanded its functionality non-intrusively, moreover, EEG offers rich information about an individual's mental status [27]. [31] compared three different light design alternatives by using VR simulation and the EEG of the participants was recorded to assess their emotions. [32] collected EEG data from users when they were using VR for construction safety training, through statistical modelling and machine learning-driven EEG analysis, 6 workers with high-risk health conditions were identified successfully. [33] provided a method for continuous monitoring of mental fatigue in construction workers, utilizing EEG data and advanced quantitative methods to prevent fall hazards.

3 Approach

This study was accomplished through the following four steps: in the first step, an immersive VR construction laboratory environment was developed in the Unity 3D game engine, version 2022.3.8f1. Unity is a versatile and widely used game engine, providing a comprehensive set of software solutions that facilitate the creation, execution, and monetization of interactive 3D content. Secondly, training elements were selected and integrated to enhance the ability of VR to interact with users, using the Oculus Quest as the wearable device and the OVR SDK in the Unity platform as the VR interaction toolkit, working in concert to form a prototype of the training system. Thirdly, paper-based training materials were derived for this study from lecture documents of the CM150 course at Purdue University. Finally, Comparative experiments were conducted and EEG data were collected through user experiments to determine the user's emotional state. This study employed the famous James Lange's theory to categorize emotions into two basic dimensions of emotional arousal and emotional valence, respectively [34]. Emotional arousal is the extent to which an individual's emotions are activated in reaction to a stimulus, ranging from passive to active. Conversely, emotional valence denotes the degree of pleasantness or unpleasantness of an experience, spanning from negative to positive.

4 Virtual Reality Training System

This training system is developed using the Unity 3D and Visual Studio, using primarily programming language C#. To experience the developed virtual world, the participant will need to wear the Oculus headset. Participants can navigate in the module using touch controllers. By using the left controller, the participant can move forward and backward, while the right controller helps to rotate 90 degrees. Each controller is represented as a virtual hand. These two virtual hands can be used to perform tasks in the virtual world. The audio and visual instructions are provided whenever necessary to show the VR module of the developed hardware facility.

Before creating the VR environment for this study, guided by VR development theory [35], the authors addressed three critical questions:

1. *Q:* "Who is the user?" *A*: The user is defined as an individual with novice-level or limited experience in the construction domain.

2. *Q*: "What do the users need?" *A*: The users require a comprehensive grasp of crucial safety protocols, crane operations, and steel structure assembly before real-life construction site involvement.

3. *Q*: "Can VR meet these needs?" *A*: Some of the needs that surpass the capabilities of traditional paper-based learning methods can be addressed through the advantages offered by VR.

While fieldwork in steel assembly encompasses extensive detailed knowledge and hands-on techniques, replicating every aspect in a VR environment is impractical. Guided by VR design theories [35], we have selectively chosen aspects of this knowledge that are most amenable to VR representation, such as visual elements, 3D spatial interaction, physical manipulation, and procedural learning. Based on this, we developed the virtual reality system including three major parts: safety protocol training, crane operation, and steel structure assembly. The below sections present these three parts.

4.1 Safety protocol training

The authors sourced Personal Protective Equipment (PPE) models in .fbx format from open-source websites and imported them into Unity assets, including high visibility undershirts, safety goggles, protective hats, and hard-toe boots. The training guide's audio, corresponding to each PPE, was created using a text-to-speech artificial intelligence platform. Users will complete this part of training by grabbing the correct PPE and properly outfitting the worker model, while also listening to corresponding instructional audio throughout the process, as shown in Figure 1.

4.2 Crane operation

In the second phase of the training system, the authors imported a fixed-post jib crane model into Unity. The virtual crane replicated its real-world three-degree-of-freedom movement by enabling rotation, lateral movement, and vertical motion across three distinct parts of the crane model. Concurrently, a virtual operator panel mirroring a real-world counterpart was developed, featuring six buttons (i.e. Lift up, Lift down, Move Left, Move

Figure 1. Safety protocol training part in VR

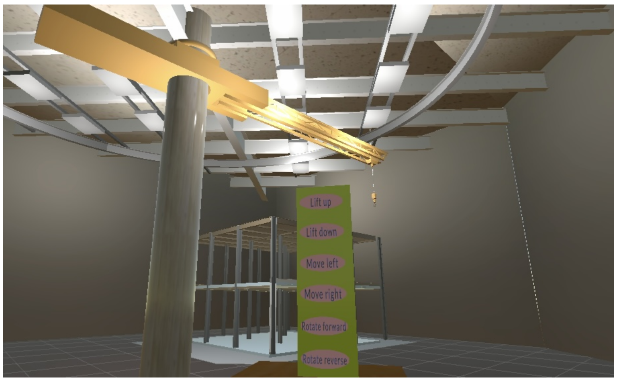

Figure 2. Crane operation part in VR

Right, Rotate Forward, Rotate Reverse) that allow users to control the crane's movement in six directions within the virtual environment, as shown in Figure 2.

4.3 Steel structure assembly

In the third part of the training, the users undertake the assembly of a classic steel structure, which is composed of columns, beams, floors and roof. The users will familiarize themselves with the steps involved in steel assembly starting by getting familiar with the steel components. Two steel columns and a steel beam are placed on a table, and the user needs to grab them in VR. When the user grabs a column or beam, a highlighting function will be triggered at the target position in the steel structure assembly space to guide the user there, and when the user places the component, there will be an alignment function to accurately align the component to the target position and angle to reduce the user's workload. Considering the numerous components in the steel structure, manually installing each one would be overly burdensome. To streamline this process, users are enabled to click buttons for batch installation, simplifying and accelerating the assembly, as shown in Figure 3.

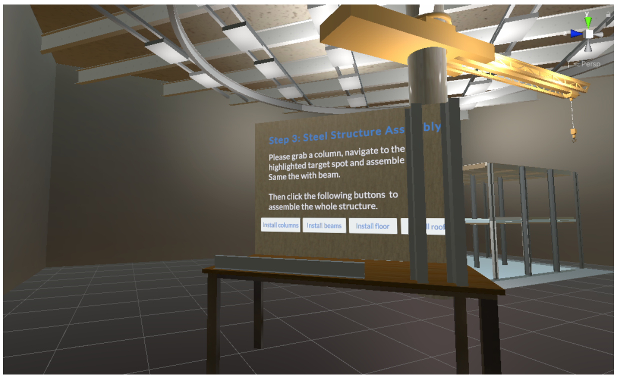

Figure 3. Steel structure assembly part in VR

4.4 Interaction with users

VR interface metaphors are the conceptual tools that translate the experiences of the real world into the digital environment to help users understand and interact with VR systems more intuitively. During the development of this study, key metaphors were implemented to facilitate user interaction within the VR environment:

1. Direct Manipulation: Enables users to reach out and grab objects directly by the virtual hands in the virtual environment.
2. Ray Casting: Allows for the selection of objects by casting a ray from the user's head or hand towards the target.
3. Movement: Empowers users to navigate and move freely throughout the VR environment.

Affordances design in VR refers to the practice of designing objects and environments that intuitively communicate their purpose and usage to the user. A good cognitive model requires that the behaviour of the mapped object meets expectations. Adhering to this design principle, the VR environment in this study features interactive elements such as clickable virtual buttons, objects that can be picked up, descriptive virtual billboards, and a control panel for operating the virtual crane.

5 Experiment

This study has recruited 16 participants including eight females and eight males. They reported no history of neurological diseases, mental/physical disabilities, cognitive impairment, or heart diseases, and were randomly divided into two groups: one for VR training and the other for traditional paper-based training. Following an initial demonstration and overview of the experimental procedures, participants in both groups engaged in self-directed learning. Details on each step will be described in the following sub-sections.

5.1 Device description

This study involves the use of two devices. Oculus Quest is a VR HMD with a headset and two hand controllers, allowing the users to view and operate the VR system. Emotiv EPOC+ EEG headset is a brain-computer interface for EEG raw data collection, it has 14 electrodes (AF3, F7, F3, FC5, T7, P7, O1, 02, P8, T8, FC6, F4, F8, AF4) and two reference channels. In this study, it captures EEG data at a sampling rate of 128 Hz.

5.2 Experimental setup and procedures

Before commencing each experiment, participants were thoroughly briefed on the experimental procedure and the specific training objectives, this included detailed instructions on the functionalities of the equipment and its proper usage. For the VR-based training group, strict sanitary measures were implemented: the equipment was disinfected with alcohol wipes before each session. After that, participants received a comprehensive demonstration of the hand controller's fundamental operations, encompassing navigation, viewpoint alteration, virtual ray casting, and object manipulation within the VR environment. Then participants wear the VR device and the EEG device at the same time, immerse themselves in the VR environment detailed in the preceding section, following the provided clues and procedures within the VR to complete the training.

For the traditional training group, instructional documents were collected from the lecture slides and reading materials of CM150 course at Purdue University, a fundamental course for undergraduate construction management technology students. Relevant content covers: 1) Safety Training. Instructions on properly wearing helmets, boots, reflective vest, goggles, etc. before entering the construction site. 2) Crane Operation. The concept of crane degrees of freedom, corresponding control panel, and hazardous areas on construction sites with cranes. 3) Steel Structure Erection. Types of structural steel components, common parameters, sequence of construction, etc. These were printed out and used as materials for traditional learning. Figure 4 shows the scene of the experiment.

The EEG device's felt pads were fully hydrated with saline before starting each experiment, and after mounting them on the user's head, the contact quality and EEG signal quality of each channel were confirmed to be green using the Emotive Pro software. EEG data recording started after the commissioning of the EEG equipment was completed, and stopped after the participants signaled completion of VR training or paper-based training. Problems encountered during the data recording phase include:

1. The incongruity between wearing VR and EEG device at the same time led to mild discomfort for users.

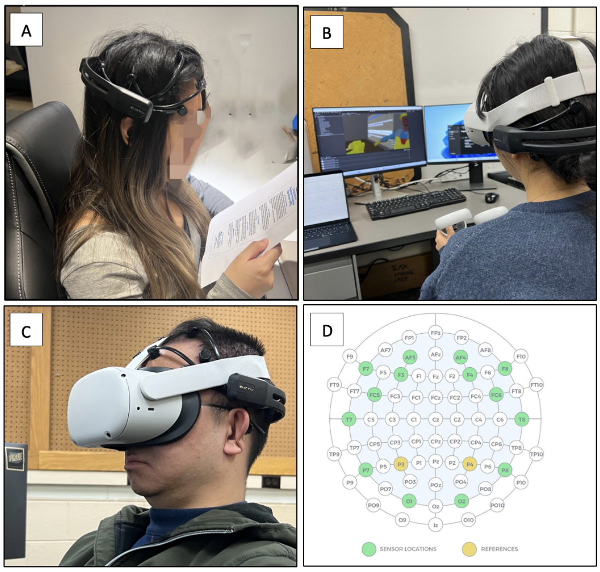

Figure 4. (a) Participant in paper-based training; (b) Participant in VR-based training; (c) Details of how a participant wears two devices; (d) Channels and references of EEG device.

2. Dense hair affects the quality of the electrode-scalp connection.
3. The EEG device that has been tuned for connectivity and signal quality was interfered with while wearing the VR device.
4. The bodily and head movements of users had impact on EEG signal quality, occasionally leading to transient signal disruptions.

5.3 Data acquisition and EEG data preprocessing

EEG raw data were acquired at 125 Hz sampling rate from users by using Emotiv Epoc+ device and Emotiv Pro software. EEG signals can be categorized by frequency into Delta wave, Theta wave, Alpha wave, Beta wave, and Gamma wave. Among them, alpha waves are in the range of 8-14 Hz, linked to activities involving mental coordination, calmness, alertness, and learning. An increase in alpha wave activity can indicate a state of relaxation or meditation. Beta waves are in the range of 14–30 HZ, present during states of alertness, problem-solving, decision-making, and focused mental activity. Beta waves are indicative of a highly engaged mind and are often encountered during tasks that require active thinking, focus, and concentration. The famous James Lange's theory divides emotions into two basic dimensions that are emotional arousal and emotional valence [34]. This study uses data from alpha and beta waves for arousal and valence analysis was based on the calculation method proposed by [36], the arousal level of the mind can be determined by computing the ratio between the powers of beta and alpha waves (i.e., Beta/Alpha). The formula below was used to calculate the valence level using alpha and beta waves in channels F3 and F4:

$$Valence = Alpha_{F4}/Beta_{F4} - Alpha_{F3}/Beta_{F3}$$

Before further analysis, preprocessing the captured EEG signals is crucial. A high signal-to-noise ratio can significantly impact the data. In this study, the EEG data were preprocessed in EEGLAB (MATLAB toolbox) as the following steps:

1. The data were high-pass filtered at 1 Hz and low-pass filtered at 50 Hz.
2. Independent Component Analysis (ICA) was used to decompose the signals into 14 independent components. Then, these components were separated from heart, line noise, eye, and muscle components.
3. The data underwent a manual review to meticulously eliminate any residual artifacts, including eye blinks and other potential disturbances.

6 Results and Analysis

Figure 5 summarizes the emotional state analysis results for the 16 participants, the valence and arousal level for the two groups was shown as spots in the figure. We adopt Whissel's arousal-valence emotion space [37] as our taxonomy. Arousal (how exciting/calming) and valence (how positive/negative) are the two basic emotion dimensions found to be most important and universal. Based on the results, it was found that: (1) EEG data shows VR-based learning elicits higher arousal levels, showing that users felt significantly more excited about VR-based learning; (2) At the valence level, both paper-based and VR-based learning modalities exhibit comparable means and distributions, indicating that users did not show a significant difference in the degree of positivity or negativity towards VR-based learning compared to traditional paper-based learning methods; (3) The distribution of arousal levels in paper-based learning demonstrates greater centralization, whereas virtual VR learning exhibits a more dispersed pattern, implying that there are significant individual differences in participants' experience of how exciting/calming VR is compared to paper-based learning. Based on active learning theory [30], the excitement brought by a high arousal level can lead to a more active learning experience for users.

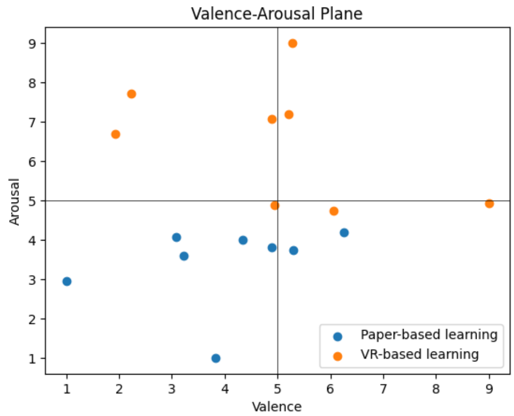

Figure 5. Arousal-valence emotion plane

7 Conclusion and Limitations

This research introduces a VR-based training system, designed in alignment with VR design theory, to virtualize the knowledge and skills involved in steel construction into three components: safety learning, crane operation, and steel assembly. A case study with 16 participants, divided into VR and traditional paper-based learning groups, was conducted to assess the impact of this VR system on users' emotional states. Analysis of EEG data revealed that VR-based learning induced a high arousal level, indicating a more exciting emotional state, yet both VR and traditional learning methods elicited similar valence (positive/negative) responses. This finding suggests that VR can effectively make users more excited, serving as a valuable adjunct to traditional paper-based methods. This finding suggests that VR can effectively stimulate user excitement by amplifying arousal levels, which leads to more active learning. However, the users who are in a negative valence space (such as aversive motivation or unpleasant emotions) should exercise caution with VR use. It has the potential to shift their emotional state from low-arousal negative valence (such as sadness) to high-arousal negative valence (such as anger) according to Whissell space [37].

Future work will explore how this data will be related to user experience and learning efficiency. The following limitations are acknowledged: 1) Despite efforts to align the content of VR and paper-based learning, the distinct nature of these mediums may lead to variations in learning stressors and experiences, thereby affecting EEG outcomes. 2) The participants' general unfamiliarity with VR technology could have influenced their emotional responses as they adapted to the VR skills, a factor absent in paper-based learning. Therefore, emotional changes related to device usage should be isolated in future studies. 3) With the growing use of machine learning algorithms for EEG data analysis, further research comparing these methods' results is merited to gain deeper insights. 4) This study presents the initial phase of establishing a virtual construction lab, and therefore the focus limits to basic functionality and elements from learning materials. Future efforts will incorporate AI-assisted VR learning and scenario-based demonstrations, enriching the educational realism of the construction training experience.

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