User Experience and Workload in Robot-Assisted Virtual Reality Welding Training

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ABSTRACT

Remote virtual training for tasks that involve intensive human motor participation is gaining popularity in the emerging education 4.0 era. However, the user experience and the underlying cognitive characteristics while facing the state-of-the-art training platform are less understood. This paper implements a robot-assisted virtual reality training system for welding training. The virtual reality system creates an immersive environment, and the robotic device provides the necessary physical interaction. A total of 28 participants who had no prior welding experience were recruited to learn welding skills. The participants were trained under the conventional training condition, visual guidance condition, and haptic guidance condition. Participants' eye-tracking data and subjective feedback were evaluated to investigate the user experience and the cognitive characteristics differences while being trained under different conditions. The results indicated potential cognitive benefits of haptic guidance in the motor-intensive welding training task. This study inspires the design of remote workforce training protocols in the future.

KEYWORDS

Virtual reality; haptic feedback; cognitive load; robot; training

INTRODUCTION

The shortage of skilled laborers, such as welders, outlines the importance of workforce training. To address this challenge and create a more distributed training experience, remote training with Virtual Reality (VR) is gaining attention in the emerging education 4.0 era. However, tasks that involve intensive human motor participation, such as welding, present unique challenges due to the difficulties of guiding the correct motion remotely. Therefore, previous researchers have focused on creating visual (Ipsita et al. 2022) and haptic guidance (Ye et al. 2023) in VR to develop feasible and effective remote welding training. Both of these guidance mechanisms have been found beneficial for enhancing the motor skill learning of welding. However, while previous studies mainly focused on the capability and effectiveness of the welding training system, relatively little is known regarding the user's subjective experience and workload while getting trained with the novel techniques.

User experience is an essential aspect when considering a training method. Training methods perceived as engaging, motivating, and easy to use are more likely to boost trainees' willingness to participate and the effectiveness of the training methods (Kwon 2019; Ye et al. 2022). By evaluating the user experience of a training method, researchers can gain insights and identify areas that need improvement. Similarly, a user's workload during training is essential to estimate potential physical, emotional, and cognitive strain. Overall, evaluating the user experience and workload during VR-based welding training is crucial for improving the overall effectiveness of the training method. However, such an evaluation is still missing in many current studies (Ipsita et al. 2022).

This study investigates the impact of different training methods on the trainees' experience during VR welding training. We implemented a VR-robot coupled welding training system that was capable of providing various training methods such as video demonstration, VR visual guidance, and haptic force guidance. Twenty-eight participants were recruited to examine the user experience and workload. We evaluated the subjective experience and workload by collecting and analyzing the interview responses and questionnaire answers, such as NASA TLX (Hart 2006). Objective measurements such as eye-tracking data were also analyzed to understand the cognitive processes during the training. The rest of the paper addresses the related research, the methods we implemented, and the results.

LITERATURE REVIEW

VR welding training

Virtual Reality (VR) welding training is a rapidly growing field that offers numerous benefits over traditional training methods. For example, one of the most significant advantages of VR welding training is the capability to visualize and customize the training process and pipeline (Hadinejad et al. 2021; Ipsita et al. 2022). Traditional welding training relies on static images or video to learn the process, while VR welding training enables immersive multi-angle observation (Xie et al. 2015). In addition, the immersive virtual experience provides guidance in a way that can hardly be achieved in real-life, such as visualizing the difference between the user's welding trajectory and the desired trajectory while the user is practicing. Furthermore, VR welding training is also considered inexpensive, accessible, and risk-free (Papakostas et al. 2022).

However, it is challenging to duplicate the physical experience of welding in a VR training environment. To mitigate this issue, previous research proposed and examined multiple ways of haptic feedback to recreate the physical experience of welding. Wang et al. (2006) made one of the earliest efforts that used a hand-scale haptic device, Phantom (3DSystems 2022), for welding simulation, in which the user could hold the haptic device and feel resistance while touching the virtual welding surface. Achour and Daoudi (2020) extended the haptic feedback to muti-directional by designing specialized hardware to simulate forces during welding. Furthermore, Ye et al. (2023) proposed a haptic guidance method for welding training. Haptic feedback is the force or vibrotactile response generated by external devices while interacting with the virtual environment. In contrast to passively receiving feedback, the haptic guidance proposed by Ye et al. (2023) actively guides the user to approach the correct motion, simulating a virtual tutor teaching welding in an over-the-shoulder manner. These efforts present substantial advancements in creating kinematic welding experiences through external devices.

Static media guidance, VR visual guidance, and haptic guidance represent a roadmap that integrates welding training with increasingly immersive and embodied experience. However, it is still unclear whether different guidance/learning methods could induce various difficulties and whether users may perceive substantially different workloads and experiences. Therefore, it still deserves further investigation into the user experience and workload in VR welding training.

User experience and feedback methods

The relationship between VR feedback methods and user experience/workload is an essential consideration when developing and deploying VR welding training systems. User experience is defined as the overall experience a user has while interacting with a system or product (Allam and Dahlan 2013), and workload refers to the cognitive, physical, and emotional demands needed (Marshall 2002). It is believed that user experience and workload significantly impact the willingness to cooperate, concentrate, and get engaged, further influencing the overall effectiveness of implementing a system in the long term (Ye et al. 2023).

Previous research traced the potential link between VR training feedback methods and the user experience/workload, but no consensus has been reached. On the one hand, visual and haptic feedback Rusli et al. (2019) presented a mobile arc welding learning platform that guides users through text, images, videos, 3D models, and animations. They found that users reported positive comments on ease of use, usefulness, motivation, and engagement. Pitts et al. (2012) suggested that haptic feedback can partially compensate for visual feedback. Meanwhile, users reported more willingness to participate and less perceived difficulty when using haptic feedback. On the other hand, Philbrick and Colton (2014) and Ye et al. (2022) also found increased workload while training with haptic feedback. As such, the relationship between user experience, workload, and feedback methods during training should be discussed under individual contexts. By understanding the relationship between VR feedback methods and user experience/workload, developers can design effective VR welding training systems that optimize performance and user experience.

METHODOLOGY

Implemented System

To analyze the potential differences in the user responses during VR welding training, the first step is to create different learning and feedback conditions. We implemented a robot-VR coupled system for welding training as described in our previous study (Ye et al. 2023). As shown in Figure 1, the welding training system comprises two major components: a VR environment to simulate the welding process and the virtual physics during interaction and a robot arm for users to grasp and provide haptic feedback as well as force guidance. The simulation capability of the game engine supports the VR environment. The robot arm is controlled using Robot Operating System (ROS), which is closely connected to the VR environment via ROS# (Siemens 2019) to adapt to the virtual events in real-time. Meanwhile, a digital twin robot arm model is constructed in VR to provide a coordinated visual-motor experience. Our previous study describes more details (Ye et al. 2023; Zhou et al. 2023).

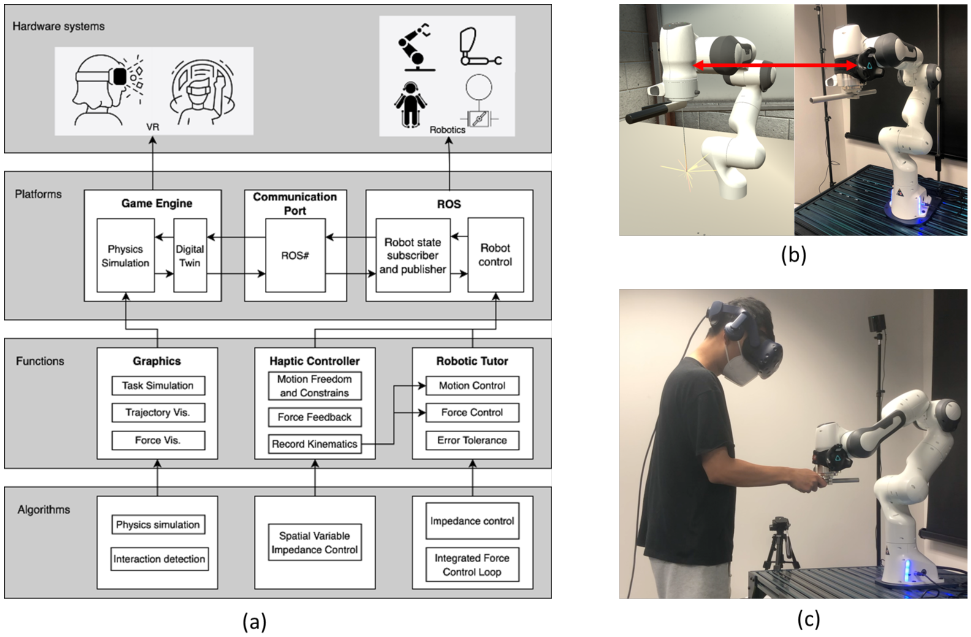

Figure 1. (a) Architecture of the implemented system; (b) Synchronization between the robot arm and the VR system; (c) Example of using the training system

Guidance Conditions

As shown in Figure 2, the welding training system enables three modes of training and guidance: static media guidance, VR visual guidance, and haptic guidance. In static media guidance conditions, participants will be presented with conventional media, such as videos and figures to learn how to weld. The VR visual guidance condition visualizes the sample welding motion in real-time. Finally, the haptic guidance condition utilizes a specialized robot control algorithm in which the robot arm actively guides the user to approach the sample motion, simulating a virtual tutor grabbing the user's hand over the shoulder. These three guidance methods rely on distinct learning mechanisms and thus provide important insights for understanding the user experience and workload.

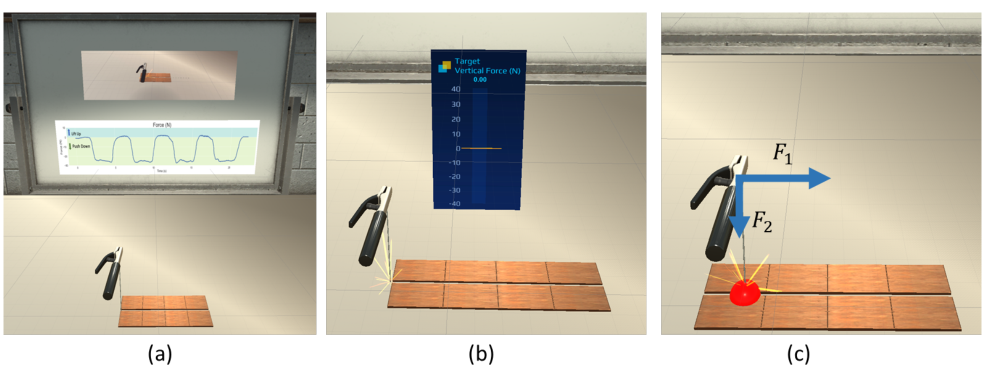

Fig. 2: Guidance modes in the VR welding training. (a). Static media guidance; (b). VR visual guidance; (c). Haptic force guidance. Note that the arrows are for demonstration purposes and are not shown to users.

Experiment Procedure

All participants were screened and consented first. Then we introduced the background and the experiment procedure. Specifically, we played demonstration videos to familiarize participants with the experiment. To reduce the impact of variations between participants, we adopted a within-subject design in which participants needed to learn the welding in all three conditions in a randomized order. As such, we randomized the three guidance conditions' order and randomly assigned participants after setting up the equipment. Within each condition, participants first get trained under the corresponding guidance format and then practice the motion without any guidance. The training-practicing combination was repeated three times. At the end of each condition, a questionnaire survey was performed to collect subjective evaluations of the workload. After completing all three conditions, interview sessions were conducted to collect participants' user experience.

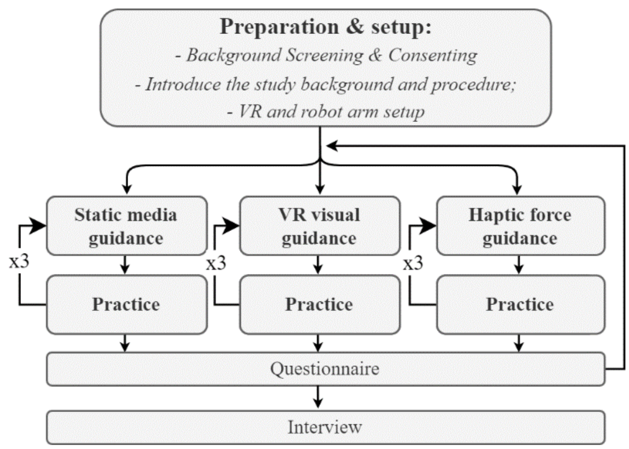

Fig. 3: Experiment procedure

Evaluation metrics

We evaluated the user experience and workload through three metrics: eye-tracking features, questionnaire responses, and interview responses. The VR equipment used in this study has a built-in eye tracker (TobiiPro 2022) which records the pupillary size variations. Pupillary size is generally considered an effective indicator of cognitive load (Payne et al. 1968). Therefore, we referred to previous publications to estimate the cognitive load from the raw pupillary size data (Gavas et al. 2017; Shi et al. 2020; Ye et al. 2022). Apart from the objective measurement, we collected participants' subjective experiences using NASA Task Load Index (TLX) questionnaires (Hart 2006) and through interviews. The NASA TLX questionnaire is a widely used subjective assessment tool for measuring the mental workload of a task. It has been applied in many fields, such as healthcare, manufacturing, and computer programming.

RESULT

Cognitive Load Estimated by The Pupillary Response

The built-in pupilometer on the VR headset measures the pupillary response. We processed the pupillary size data following previous practices (Zhou et al. 2023). The general processing pipeline starts with outlier removal, interpolation, and smoothing, then calibrates with baseline and brightness effects. The processed pupillary size indicates the pupillary responses induced by cognitive activities. Figure 4 shows the result. The data were not normally distributed according to the Anderson-Darling test (Scholz and Stephens 1987). As such, we implemented the Wilcoxon signed-rank test for the pairwise analysis. Results showed significant differences between static media guidance and the other two guidance conditions ($p = 0.002$ with VR visual guidance and $p < 0.001$ for haptic guidance). However, no significant difference was found between the visual and haptic guidance regarding pupillary response ($p = 0.227$).

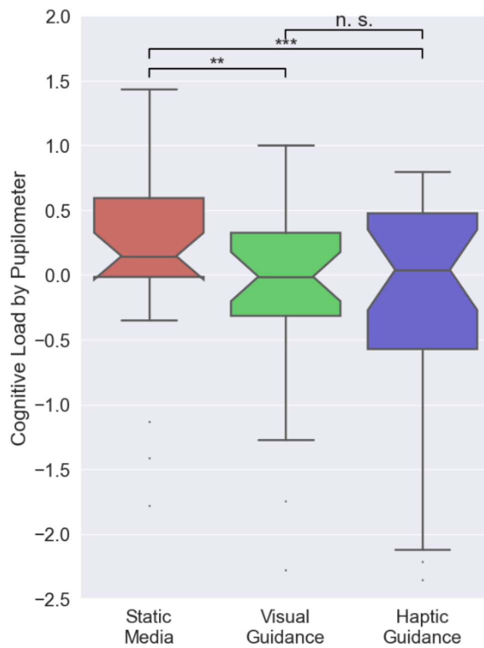

Figure 4: Cognitive load measured by pupilometer

Subjective Workload

We analyzed the subjective workload from three indices of the NASA TLX questionnaire: mental load, physical load, and emotional load. Following the same analysis pipeline as the cognitive load analysis, we found that participants generally reported higher mental load when learning in visual ($p = 0.016$) and haptic ($p = 0.013$) guidance compared with using static media. However, no difference was detected between the visual and haptic guidance ($p = 0.726$). Furthermore, no difference was detected among all guidance methods regarding physical and emotional load.

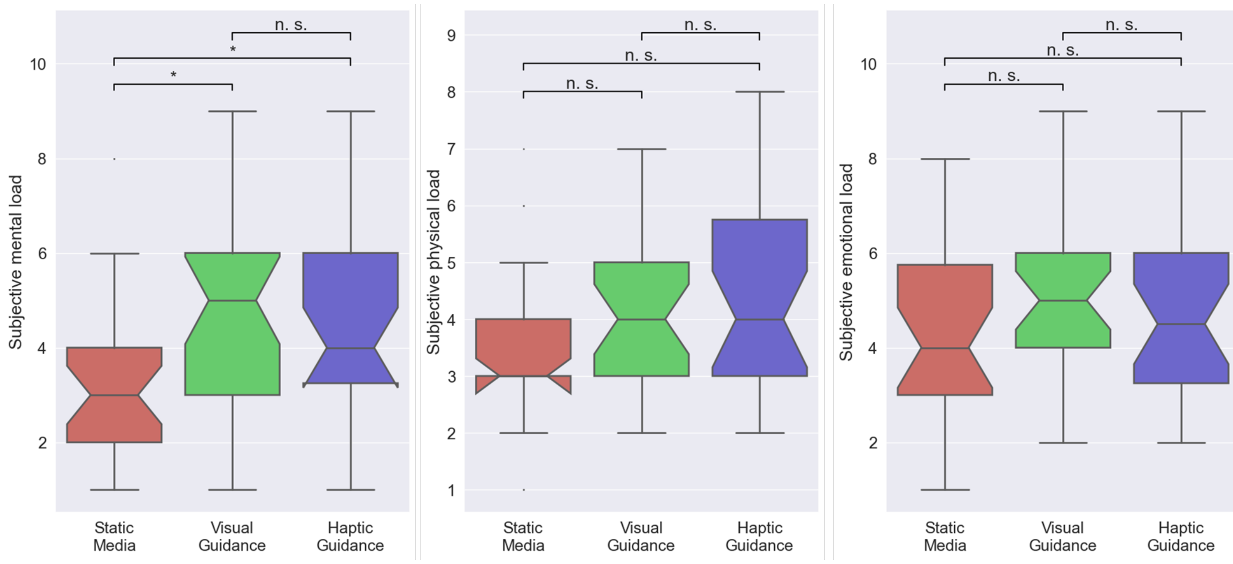

Figure 5: Subjective workload

Interview Responses

After finishing the experience, an interview was conducted to collect user feedback. We recorded the keywords and opinions that the participants mentioned in the discussion. The amount of information provided largely differed among participants, so no quantitative analysis was performed. In general, participants reported that it took an effort to understand the visual and haptic guidance methods while using static media was familiar to them. However, although two participants reported that they did not perceive any difference while learning with these three guidance methods, the others who provided relevant feedback (twelve participants) believed that visual and haptic guidance made welding learning easier. Among the twelve participants, five preferred haptic guidance, and three had no preference.

DISCUSSION

The human-subject experiment shows that the impact of the guidance method on user experience and workload is complex in VR welding training. On the one hand, the cognitive load measured by physiological features showed reduced information processing activity while training with visual or haptic guidance. On the other hand, participants' subjective evaluation indicated higher mental effort associated with visual and haptic guidance than convention media. These conflicting findings echo previous studies (Philbrick and Colton 2014; Pitts et al. 2012). The post-experiment interview sessions reveal a possible explanation: the visual and haptic guidance methods are more challenging to understand initially but could be more informative and easier to use during the training. In other words, novel training methods such as VR visual guidance and haptic force guidance possibly induce an immense familiarization burden compared to conventional media but improves subsequent experience after the familiarization. This interpretation coincides with the experiment findings in a way that the user's subjective experience in this experiment evaluated the overall mental load, including the familiarization stage and training stage. In contrast, the cognitive load measured by pupillary responses was recorded only during the training stage.

There are some limitations associated with this study. First, this study does not provide enough evidence to support the above interpretation. It is a future agenda to perform studies assessing the familiarization and training stages separately. Furthermore, most recent research found that the user experience might be associated with the novelty of training methods (Rutten et al. 2020). A user might perceive a better experience when facing a novel system. But such an effect might gradually disappear after repeated practice. This potential effect is essential in welding training and training at large because repeated practice is still an unprecedented requirement for training. As such, it is necessary to remove the impact caused by the system novelty when evaluating user experience in future studies.

CONCLUSIONS

This study performs a pupillometry analysis and questionnaire analysis to examine the user experience and workload under different guidance methods in VR welding training. We found that learning through conventional static media, such as images and videos, was easier than learning through visual or haptic guidance regarding the user's subjective mental effort. Meanwhile, the pupillary response feature showed that the user's mental processing activity was higher when learning with conventional static media. These results indicate that VR welding training might involve several different learning stages which affect user experience at different levels. Meanwhile, this study also shows that integrating advanced technology for training might not always be beneficial. Therefore, the decision-making process for implementing a new technology should consider many factors, including user experience and workload.

For future work that considers the user experience and workload, it is recommended that the familiarization stage should be separated from the training stage in the temporal domain. This separation ensures that the familiarization difficulty does not interfere with the actual user experience and reduces the impact of system novelty on the user experience.

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