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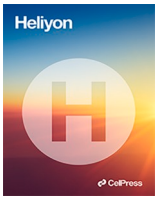

Research article

Analysis of the effectiveness and user experience of employing virtual reality to enhance the efficacy of occupational safety and health learning for electrical workers and graduate students

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ABSTRACT

Introduction: The integration of engineering approaches in education and training is pivotal for reducing workplace incidents. Effective safety education increases workers' awareness of potential risks and fosters a robust Occupational Safety and Health (OSH) culture. Virtual reality (VR) offers immersive experiences that enhance the efficacy of safety training.
Method: This study evaluated VR's effectiveness through two experiments that demonstrated improved learning capacities. The first study employed quantitative methods and quasi-experiments with electrical sector technical support professionals. The second study used a qualitative approach with scenario case studies involving graduate students.
Results: The quantitative study revealed significant improvements in OSH understanding among electrical workers, highlighting VR-based training's superiority over traditional methods. The qualitative study found positive outcomes in VR usability and user experience among graduate students, affirming VR's effectiveness in OSH education.
Conclusion: VR has proven to be an effective and efficient training tool for both graduate students and experienced workers. It significantly advances skills, knowledge, and proficiency in electrical engineering by providing realistic, immersive, and tailored learning experiences. As VR technology continues to evolve, its role in shaping the future of electrical technical education and training appears increasingly promising.

1. Introduction

Occupational safety and health (OSH) is a field of paramount importance dedicated to safeguarding the well-being and welfare of workers in the workplace [1]. This field encompasses a comprehensive set of principles, practices, and regulations designed to prevent accidents, injuries, and illnesses arising from occupational activities [1]. Working in an environment that minimizes the risk of accidents, injuries, and illnesses is the right of every worker (see Figs. 3–5).

The academic literature underscores the critical importance of training and education in enhancing occupational safety and health (OSH) performance. For instance Ref. [2], conducted an analysis of 100 accidents and discovered that deficiencies in workers'

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knowledge and skills pertaining to task execution were contributory factors in 42 % of the incidents examined within the construction sector. Consequently, the provision of training aimed at augmenting the workers' knowledge and skills related to task execution could have potentially led to a reduction in the incidence of accidents.

An engineering approach to reducing the risk of worker accidents involves education and training activities. Furthermore, numerous fields can benefit from training [1]. Safety education is critical for familiarizing workers and raising awareness of potential workplace risks, thereby providing a safe environment, and enhancing safety behavior [1]. Indonesia still implements traditional OSH training and education techniques. However, traditional techniques have several limitations, including a lack of interest and low engagement. By contrast, employee training is highly beneficial in preventing workplace accidents as well as optimizing and increasing company efficiency. Effective training may provide a suitable environment while also focusing on safety issues, hazards, and risks throughout the training [1].

The industrial sector revolution is being driven by new technologies such as immersive technologies, and the Internet of Things [3]. The integration of digital technologies, automation, data exchange, and artificial intelligence in various aspects of industry symbolizes the industrial revolution [4]. A key aspect of the industrial revolution involves the utilization of technological advances, which offer numerous benefits and opportunities, particularly in OSH management. As industries continue to evolve with technological advancements, the methods used for training and education must also adapt to keep pace. Traditional training methods, while foundational, often lack the engagement and realism needed to fully prepare workers for the complexities of modern workplaces. This is where virtual reality (VR) emerges as a transformative tool. By providing immersive, interactive, and highly realistic simulations, VR has the potential to revolutionize training and education across various sectors.

1.1. Virtual reality in training and education

Computer-generated simulations of real-world activities are known as virtual worlds. Most things that can be envisioned, designed, and arranged in a setting offer users an immersive perception of the environment in which the creator is attempting to communicate [5, 6].

Specifically, virtual reality (VR) is a notable technology of the industrial revolution. VR enables the creation of identical work environments and realistic experiences for training purposes. Learners can engage in a three-dimensional space that closely mimics real-world conditions, thereby enhancing their learning experience through immersion and engagement [7]. This immersion provides a sense of presence and engagement, thereby enhancing the learning experience. Enhancement of engagement, effective understanding of the OSH by learners, and highly impactful and memorable experiences are realized through this sense of presence.

Li et al. [8] identified that immersive technologies (ImTs) have been investigated and provisionally implemented across multiple domains of occupational safety and health (OSH) management, including training and education, hazard identification, and the risk perception of construction workers, among others. Pavithra et al. [9] observed that virtual reality (VR), augmented reality (AR), and mixed reality (MR) represent the prevailing trends within the sphere of ImTs.

Further distinguishing between augmented reality and augmented virtuality, researchers note that augmented reality enhances the real world with virtual elements, whereas augmented virtuality is a simulation of reality incorporating real-world aspects. These environments often prioritize visual stimuli but can also convey other sensory inputs such as sound, motion, and haptics [10]. The Presence Theory, as described by Tan et al. [11], refers to the subjective feeling of "being there" within a virtual environment. The level of presence experienced by users in VR can significantly influence learning outcomes and engagement. Understanding how to design VR environments that maximize presence is crucial for enhancing the effectiveness of training in occupational health and safety. Additionally, Le et al. [12] discuss the embodied cognition theory, which posits that cognition is influenced by the body's interactions with the environment. In the context of VR for occupational health and safety training, embodied cognition theory suggests that realistic physical interactions within virtual environments can enhance learning and skill acquisition. By incorporating these theories, VR-based training programs can be designed to provide more immersive and effective learning experiences.

Hazardous situations are often involved in occupational safety training. A risk-free environment for learners to make mistakes and learn from them without any real-world consequences is achieved through VR. Thus, VR is a particularly important field where mistakes can lead to serious consequences. Furthermore, customized training scenarios that mimic the specific challenges and environments of a particular workplace can be achieved through VR. The tailoring increases the relevance and applicability of the training to the actual job responsibilities of learners. Workers can experience and manage safety issues while preventing accidents by developing VR scenarios [13].

Safety performance in a wide range of sectors is strengthened by safety education and training, helping workers identify potential hazards on the job site and effective mitigation techniques. VR can facilitate remoting training, providing individuals access to safety training from different locations. Remote training is particularly valuable in situations where onsite training may be challenging or expensive. Comprehensive information regarding site dangers and hazards, as well as safe behaviors and procedures, can be obtained by workers through these training programs [14].

Compared to conventional methods, VR often leads to higher retention rates and the skills acquired are easily transferable to real-world situations. Effective VR training can significantly reduce the number of fatal and serious workplace incidents, revolutionizing the acquisition and retention of crucial safety skills [15]. Turning to the educational context, students in higher education have shown diverse reactions to virtual worlds. While some students with limited technical resources and experience respond negatively [6], others have positive views influenced by the immersive nature of VR [6,16].

Despite the advancements in occupational health and safety (OSH) training, a significant gap persists in the effectiveness of traditional methods, particularly in their ability to engage learners and provide realistic practice environments. Conventional training

approaches often rely on didactic instruction and static materials, which fail to simulate the dynamic and hazardous conditions workers may encounter in real-life scenarios. This gap is compounded by the limitations of current training methods to foster critical skills. Consequently, there is an urgent need for innovative training solutions that leverage immersive technologies to bridge this gap.

By integrating VR into OSH training, we can address the limitations of traditional methods and develop more effective training programs that improve safety and knowledge and user experience in various industry. The current study focuses on the effectiveness of VR in improving OSH knowledge and the user experience for both graduate students and electrical workers. This approach aims to gather information and provide feedback on VR technology development, helping postgraduate students acquire practical knowledge before starting their careers, and offering electrical workers opportunities to raise awareness and improve OSH abilities.

2. Scope and objectives of this paper

The effectiveness of VR training is analyzed in this study to improve OSH knowledge and user experience. The efficacy of VR among electrician workers at PLN ULP 3 Bantul, Special Region of Yogyakarta, and graduate students focusing on OSH at Universitas Gadjah Mada, Indonesia, is determined and optimized in this study.

3. Materials and method

VR technology is employed in this study in two phases to obtain an overview of the efficacy of OSH training for electrical workers and graduate students. The effectiveness of improving knowledge on OSH through VR for electrical workers is evaluated in the first phase while the effectiveness user experience and usability of VR for postgraduate students are examined in the second phase using the construction scenario. The Oculus Meta Quest 2 and the Joystick are the VR technologies used in this study.

Reliability analyses were conducted using Cronbach's alpha, Average Variance Extracted (AVE), and concordant-discordant measures. Cronbach's alpha was calculated for each subscale to assess internal consistency. AVE was computed to evaluate the level of variance captured by each construct. Concordant and discordant pairs were analyzed using Kendall's Tau to assess the reliability of ordinal data.

The study's sample comprises both graduate students in occupational safety and health (OSH) and electrical workers. The graduate students who are on the verge of entering OSH careers juxtapose technical employees who routinely encounter OSH-related hazards. This heterogeneous sample spans a range of ages educational attainments and professional experiences thus offering a comprehensive perspective on the efficacy of VR training. Graduate students encompassing those with varying educational backgrounds and differing levels of work experience provide valuable insights into the training's impact prior to workforce entry. Conversely technical employees from recent hires to seasoned professionals serve as a practical test bed for VR training's applicability in high-risk scenarios.

By incorporating these distinct groups the study aspires to elucidate how VR training in OSH can be tailored and accepted across diverse demographics thereby enhancing its pertinence and effectiveness. Furthermore this methodological approach assesses VR training's potential to augment workplace safety for individuals currently in or about to enter high-risk occupational environments.

3.1. First phase

This study comprised all 50 electrical workers from PT.PLN ULP Bantul, Yogyakarta. The PLN Bantul area is one of the largest regions in the City of Yogyakarta, resulting in a broad scope of work in this area. Consequently, the number of employees in this region is also quite large, making it a significant consideration in the selection of the research area. The sample was selected using two criteria: inclusion and exclusion. The inclusion criteria were as follows: electrical workers at PT.PLN ULP Bantul, Yogyakarta, and workers willing to participate as respondents and sign an informed consent form. The first phase involved conducting tests on electrical workers using a quantitative technique and a quasi-experimental research methodology. This study employed the pretest and posttest phases to assess the knowledge level of OSH. Following the pre-test, respondents were randomly separated into two groups of 25. The pretest involved a 30 min questionnaire-based technique. Regarding the pretest activities, the intervention took 120 and 15 min for conventional methods and VR media intervention, respectively. After the intervention, the posttest will involve a questionnaire. This activity will take approximately 30 min.

Given that the respondents were homogeneous in terms of their employment duties, the first group received conventional intervention (lecture followed by VR training), and the second group received the VR training followed by the lecture.

The instrument employed in this study was an adapted composite of several authoritative standards: the Competency Standard for Electrical Engineering Personnel in Electrical Power Distribution (Ministry of Energy and Mineral Resources Decree No. 1187. K/30/MEM/2007), the Indonesian Electricity Standard (SPLN 83:1991), the Standard Distribution Construction in Central Java and Yogyakarta (2008), and the Ministry of Manpower and Transmigration Regulation No. 8 (2010). Prior to implementation, the questionnaire was rigorously validated. This instrument consisted of closed-ended questions presented in a multiple-choice format. The interpretation of the questionnaire scores concerning knowledge of Personal Protective Equipment (PPE) usage indicated that higher scores were reflective of a more advanced understanding and knowledge of PPE usage among workers.

3.2. Second phase

The second phase, which was conducted on graduate student respondents, was realized through a qualitative design and a case study methodology. This phase aimed to observe the VR learning experience of students through the previously developed scenarios.

The sample in this study comprised 15 graduate students, 12 new graduates, and 3 with work experience focusing on occupational health and safety. A purposive sampling technique with several inclusion criteria was employed in this study. These criteria included the following: students who were registered during the time this research was conducted; students without experience using VR; individuals with health issues, such as anxiety disorders, vertigo, hypertension, epilepsy, and hypotension; as well as those suffering from claustrophobia and acrophobia. This sample size allows for a focus on quality over quantity, leading to a deeper understanding of the participants' experiences. Additionally, the manageable number of participants ensures that the data collected is easier to analyze, resulting in high-quality outcomes.

Guidance and instructions regarding VR operations were provided to students before the research commenced. The research was conducted in a classroom, with each student experiencing VR devices for 15 min. Students proceed to the interview after the VR testing process, adapting the User Experience Questionnaire [17] and the Usability Scale system [18]. Interviews were conducted for 60 min for each student. Each phase passed the ethical clearance process with the detail numbers KE/FK/1327/EC/2023 and KE/F-K/1524/EC/2023. Fig. 1details the process on each phase (see Fig. 2).

3.3. Experimental setup

The virtual reality (VR) based safety training environment was developed using the Oculus Meta Quest 2 and Joystick, in close collaboration with experts in spesific sectors to design scenarios that accurately simulate real-world conditions faced by electrical workers. These scenarios were programmed to create immersive, interactive, and realistic training modules that enhance the learning experience through immersion and engagement. Participants were trained in two types of environments within the VR setup: the practice environment and the familiarization environment.

The practice environment was designed to simulate typical working conditions encountered by electrical workers, including scenarios such as operating electrical panels, identifying potential hazards, and using personal protective equipment (PPE). The objective was to provide participants with a realistic setting to practice their skills and apply their knowledge safely. Specific scenarios in the practice environment included operating electrical panels, identifying and mitigating electrical hazards, proper use and maintenance of PPE, and responding to emergency situations.

The familiarization environment, on the other hand, was intended to help participants become comfortable with the VR technology

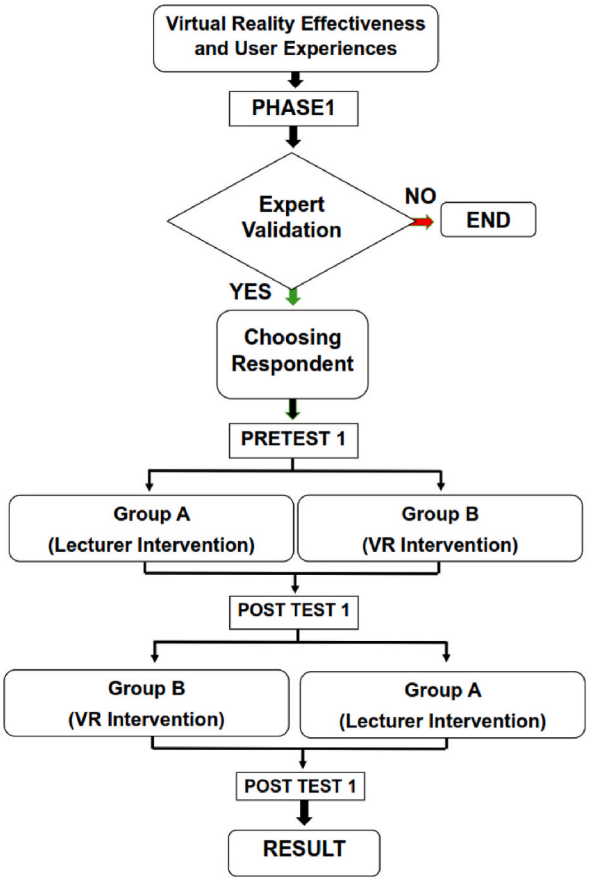

Fig. 1. Phase 1 flowchart.

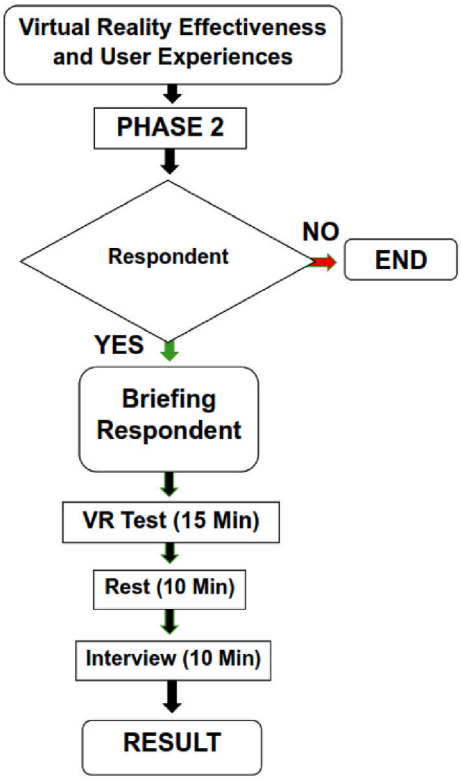

Fig. 2. Phase 2 flowchart.

and the training scenarios before engaging in more complex tasks. This environment was less challenging and focused on basic interactions within the VR system, such as navigating the virtual space, using VR controls, and understanding the interface. Specific scenarios in the familiarization environment included basic navigation and control within the VR system, an introduction to the VR interface and interaction techniques, and simple tasks to build confidence in using VR technology.

The familiarization environment served as an introductory phase where participants could acclimate to the VR setup without the pressure of performing complex tasks, ensuring that all participants, regardless of their prior experience with VR, could comfortably and effectively engage with the training modules. In contrast, the practice environment focused on the application of safety protocols and the development of technical skills in a controlled but realistic setting. This approach allowed participants to make mistakes and learn from them without real-world consequences, thereby enhancing their learning experience and improving their readiness for actual workplace scenarios.

4. Results and discussion

4.1. First phase results

This research mainly conducts discussions with experts in the electrical sector. A scenario design was successfully developed and authorized by the company to understand personal protective equipment at the technical worker level. This scenario design was then utilized as a testing platform for the VR method. Meanwhile, 60–120 min of classroom training on OSH knowledge was involved in the conventional method.

Workers in this research ranged in age from 21 to 44 years old, among which 19 were 45–55 years old, with an average age of 38 years. In terms of work experience, 6 % of workers have worked for less than a year, 10 % for 1–2 years, 16 % for 3–5 years, and 68 % for over 5 years. The steps for integrating training through VR are presented in the following figure. The initial stages for implementing personal protection equipment are included in the first to sixth stages and are the same for both phases. Steps 7 to 10 reveal the differences between phases.

Fifty respondents participated in this study. Analysis results demonstrate that average knowledge of each group increased after implementation of the first intervention (pretest to posttest). The findings of the first intervention reveal that the VR method provided greater quality and significance of knowledge outcomes than conventional methods. Table 1 shows the significance of the results from the questionnaire on OSH knowledge.

The reliability analyses indicated strong internal consistency and convergent validity of the questionnaire. Cronbach's alpha values were all above 0.75, demonstrating acceptable internal consistency. AVE values for the constructs exceeded 0.50, indicating that more

Fig. 3. First to sixth step of the PPE scenario.

than half of the variance of the items was explained by the constructs. Kendall's Tau values indicated a strong positive relationship between the paired items, further supporting the reliability of the data.

An upward trend is observed across all categories based on the average value. From a mean value of 13.00 (SD = 2.63) to 16.80 (SD = 2.44), the first pretest and posttest results in group A demonstrated a significant increase ($t(24) = -6.72$, p-value <0.001). From a mean value of 11.96 (SD = 2.47) to 19.16 (SD = 2.82), group B exhibited a significant increase ($t(24) = -9.51$, p-value <0.001). Information regarding the outcomes of variation between pre- and postintervention in the two methods is presented in Table 2.

Group B (VR intervention; M difference between pre- and postintervention 1 = 7.20, SD = 3.78) revealed a significantly higher mean score ($t[24] = -3.60$, p-value <0.001) than group A (Lecture intervention; M difference between pre- and postintervention 1 = 3.80, SD = 2.82) based on the unpaired *t*-test comparing pre- and postintervention 1 results. This finding shows that VR intervention performed better than lecture intervention.

OSH training is crucial for students and employees. According to de Wit et al. [19], several training techniques help optimize the performance of workers, particularly in OSH, in recognizing potential hazards that can affect work. Meanwhile, Molen et al. [20] stated that OSH training may reduce the number of workplace accidents by increasing understanding of safe work procedures. Bernal

Fig. 4. Scenario for phase 1.

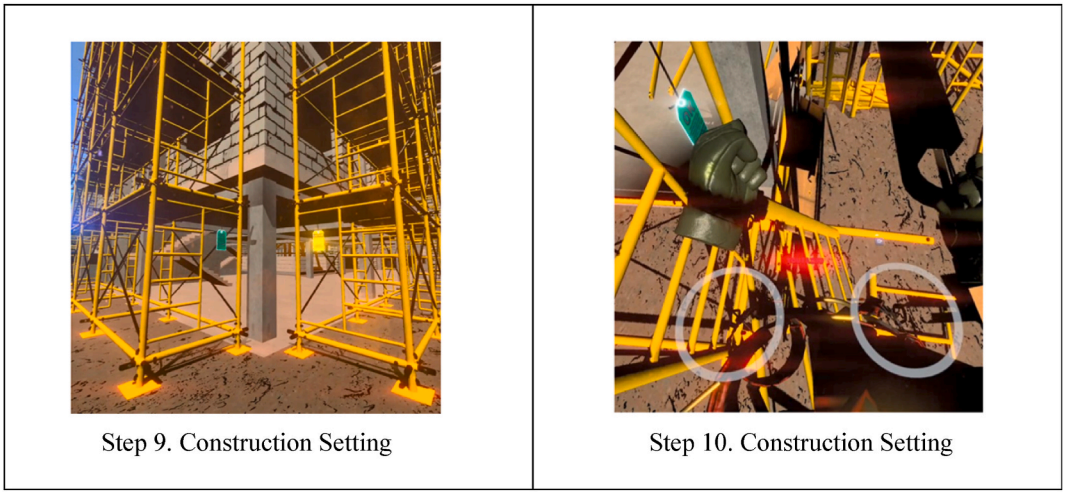

Fig. 5. Scenario for phase 2.

Table 1
Average score from questionnaire.

	Group A *Mean* (SD)	Group B *Mean* (SD)
Pretest	13.00 (2.63)	11.96 (2.47)
Post Test 1	16.80 (2.44)	19.16 (2.82)
Post Test 2	19.96 (2.70)	19.20 (3.09)

Table 2
Intervention comparison.

Group	Mean	SD
Group A	3.80	2.82
Group B	7.20	3.78

et al. [21] found that training with VR has advantages in electrical work, particularly for workers who handle electrical issues, which prioritizes worker safety due to the significant potential for risk.

The importance of VR applications was determined in this research by applying scenarios that were developed with electricity experts. The VR scenarios were created to allow workers to experience real-world settings through simulation media, assuming that VR would raise awareness of OSH that people employ while they go to work. Shi et al. (2019) [22] Indicated that VR can imitate real-world

physical situations and deliver experiences that promote workplace safety awareness. Such an increase in knowledge is due to improvements in the ability of workers to identify possible dangers, enabling them to understand the direct impact of their actions without experiencing real losses, as represented in the scenarios used in this research.

The reliability analyses support the robustness of the questionnaire used in this study. With Cronbach's alpha values all exceeding 0.75, the internal consistency of the survey items is confirmed, which underscores the reliability of the responses collected. The AVE values, all above 0.50, indicate strong convergent validity, meaning the constructs measured are well-represented by their items. Additionally, the high Kendall's Tau values demonstrate a strong positive relationship between paired items, further validating the consistency of the data. These reliability measures reinforce the credibility of the study's findings, providing confidence in the reported effectiveness of VR-based OSH training.

The effectiveness of VR applications can be attributed to several factors. Age and work experience can influence the comfort and familiarity of workers with the technology [23]. However, this research found that work experience and age have no significant effect on VR use. Concerning the relationship between respondent characteristics and variations in knowledge regarding PPE safety among electrical workers, the analysis revealed an absence of significant correlation between age and length of employment with pre-test knowledge scores as well as the differential between pre-test and post-test scores. These findings indicate that the respondents' levels of knowledge are not significantly impacted by either their age or duration of employment. Workers may easily learn to use VR, and such understanding of the scenarios presented can be rapidly acquired during training. This research is believed to provide incremental learning opportunities, starting with simple experiences and gradually introducing highly complex interactions. This gradual progression allows people of all ages to build confidence and competence over time. Adami et al. [24] demonstrated the success of VR training in delivering knowledge regarding occupational health and safety procedures.

The developed scenario for this research is designed with intuitive user interfaces that are easy to navigate, regardless of age or experience. Furthermore, the scenario aimed to provide appropriate challenges and support, ensuring an effective learning experience. The research shows that the design of basic navigation and interaction in the scenario can be easily grasped, enabling the user to focus on the content, as observed in the results. Most workers also feel satisfied and demonstrate positive progress.

4.2. Second phase

4.2.1. User experience

In phase 2, only 15 of the 43 informants who completed the survey met the inclusion criteria for this study. The majority are postgraduate students, with ages ranging from 22 to 43. The user experience, usability, and effectiveness of VR were tested in this phase using the PPE and construction scenario.

The user experience results indicate that most students quickly adapted to this new technology; however, some respondents stated that they needed additional time to get used to it. This finding demonstrates that VR is frequently considered a user-friendly learning method. Based on a study by Marks, White, and Singh [25], the results stated that VR technology can improve education by providing students with an immersive and engaging learning environment.

The appeal of developing learning media through VR is an important variable in this research. This study found a considerable amount of drive in the OSH learning process while using advanced technology. This finding demonstrates that the interesting and creative features of VR simulation are considered to be an immersive and dynamic learning experience. Loseva-Rimsha [26] revealed that VR and AR may provide highly fascinating and easy-to-understand information, as well as make learning visually attractive. VR-based arts-based techniques were employed in junior high schools in another study by Guan et al. [27] to increase creativity and student engagement compared to conventional methods.

In this phase, the relevance of the scenario to the OSH knowledge of students is considered suitable. The accuracy of OSH learning content delivered through VR technology provides an opportunity to improve the interaction between theoretical and practical learning. Adžgauskai, Abhari, and Pesavento [28] stated that content accuracy is important for ensuring that VR learning meets student needs and that VR technology can meet the needs of teachers and students.

4.3. Usability

Interviews demonstrate that VR can help students with limited work experience, particularly in construction, understand OSH. Participants with work experience stated that VR will be useful in providing an overview to workers who do not follow OSH regulations. This finding demonstrates the potential of VR to improve learning effectiveness, particularly in the OSH.

The use of VR in OSH is strongly rated by students and can enhance training in companies. Students believe that this technology has real-world implications and can help companies train their employees interactively and effectively. Students believe that VR enables them to mimic and visualize problems related to OSH. This technology helps in understanding the practical application of OSH principles and introduces relevant topics related to OSH in construction. Shringi et al. [29] investigated efficiency and safety training using VR for electrical technicians. They found that VR headsets improved the efficiency of virtual safety training by providing an improved perception of depth, realism, and depth while increasing the accuracy of hazard identification for critical hazards such as power lines.

4.4. Effectiveness of VR as OSH training

VR has the potential to transform OSH learning by addressing the limitations of conventional methods. In the second phase,

students can realistically experience dangerous conditions through VR simulations without actual physical risks and can accept the risks and preparations in the work environment. Respondents stated that VR technology helps them understand the risks of working at elevations, trains them on using personal protective equipment (PPE) in construction environments, and generally improves their knowledge of OSH. Additionally, VR enables engagement with scenarios that are remarkably complicated and difficult to recreate in conventional classrooms. Hidetoshi and Kosei [30] revealed that VR has been applied to investigate construction sites, observe potential hazards, and improve overall construction safety and OSH knowledge effectively.

4.5. Experiences of using VR as a learning and training method

One of the purposes of this research lies in the seamless integration of VR training into educational programs, preferably aligning with the curriculum and learning objectives, to improve the educational experiences of students. A crucial aspect that directly influences the effectiveness of VR in education involves the user experience of VR training among students and workers. The content within the VR training module has been designed to facilitate engagement and achieve educational objectives. Immersive scenarios and interactive elements can enhance the learning experience, making it highly enjoyable and effective.

Clear definitions of learning objectives were provided for workers and students based on experience and study. Identifying the purpose of VR training helps set expectations in terms of learning. Thus, clear and user-friendly scenarios have been developed. Workers and students can effortlessly explore the VR environment, thereby facilitating a smooth and efficient learning experience.

Significant improvements in the learning experience for both subjects in this research are realized through immersive environments, realistic simulations, and interactive features. VR creates learning experiences for workers and students, as well as simulations that are realistic and similar to real-world circumstances, by designing scenarios that are tailored to electrical and construction work and verified by experts in the industry. This aspect is particularly important for workers and students who may be receiving job-specific training and preparation before starting employment. Guo, Yu, and Skitmore [31] suggest that VR technology can enhance safety training, improve learning objectives, and facilitate hazard identification and control during the preparation phase.

Compared with conventional methods (lecture activities), VR is more attractive to workers and students because it combines interactive features that facilitate the active participation of users in training. Employers can participate in hands-on simulations relating to their responsibilities at work, whereas students can engage in interactive learning activities. This finding was observed in the massive increase in knowledge for electrical workers as compared to conventional methods during the study. Students also claim that using VR can help them learn about real-world scenarios.

The designed VR scenario in this study is compatible with the job setting of workers. Training efficacy is improved due to practical applications and scenarios based on specific activities. Furthermore, workers and students have various learning methods. Workers and students have different learning styles; therefore, VR training is designed to accommodate these disparities. This breakthrough will allow students to have additional collaborative learning experiences. VR can be used to build shared virtual environments, improving collaboration as well as involvement among students and employees. Furthermore, this technology will emphasize career readiness for students by incorporating VR scenarios that simulate real-world work environments, thereby helping them prepare for future professional roles.

The PPE usage scenarios were presented in a general manner and were not highly specific to certain sectors. In these scenarios, various PPE options deemed suitable for the activities were provided. We are currently developing more tailored PPE scenarios that will align with specific activities and sectors, particularly those with significant occupational risks that could lead to work-related illnesses and accidents. The development of these VR training scenarios is crucial and should involve stakeholders actively engaged in OSH activities. Overall, VR training experiences that are effective, engaging, and tailored to the specific needs of workers and students can be realized by developers and educators. A positive UX contributes to increased knowledge retention, skill development, and overall satisfaction with the training program.

5. Conclusion

The integration of VR technology in electrical and construction scenario training has demonstrated notable effectiveness and efficiency, particularly when applied to postgraduate students and experienced workers. The immersive nature of VR, coupled with its interactive capabilities, has yielded positive outcomes in skill development, knowledge retention, and overall training experiences.

VR has been proven to be a powerful tool for enhancing learning outcomes among postgraduate students and electrical workers. The realistic simulations enable a hands-on approach to complex electrical scenarios, aiding in the application of theoretical knowledge to practical situations. VR provides a platform for practical skill development for postgraduate students and workers. Simulations of electrical systems and troubleshooting scenarios allow users to hone their technical skills in a controlled and safe environment, facilitating enhanced preparation for real-world challenges.

The immersive nature of VR engages learners at a deep level. Postgraduate students and workers have demonstrated increased engagement during VR training sessions, leading to improved knowledge retention and a thorough understanding of electrical and construction concepts. VR technology allows for the creation of tailored learning environments that accommodate the specific needs of postgraduate students and workers. Training can be customized to address individual learning styles and preferences due to the adaptability of VR.

From an efficiency standpoint, VR offers cost-effective training solutions. VR provides postgraduate students access to realistic laboratory experiences without extensive physical resources. Meanwhile, VR for workers minimizes the downtime associated with traditional training methods by providing accessible and on-demand virtual scenarios. VR also serves as a valuable tool for the

continuous professional development of electrical workers. This technology allows them to stay abreast of technological advancements, update their skills, and adapt to evolving industry standards through immersive and updated training modules.

The seamless integration of VR into educational programs for postgraduate students and workplace training for technical workers has been evident. This technology bridges the gap between theoretical knowledge and practical application, creating a synergistic approach to learning and skill development.

Overall, VR training has been proven effective and efficient for postgraduate students and experienced workers. VR is considered a transformative tool for advancing skills, knowledge, and overall proficiency in the field of OSH due to its capability to provide realistic, immersive, and tailored learning experiences. With the continuous advancement of VR technology, its role in shaping the future of OSH education and training is increasingly promising.

The inclusion of reliability analyses such as Cronbach's alpha, AVE, and concordant-discordant measures provides robust support for the reliability and validity of the questionnaire survey design. These findings reinforce the study's methodological rigor and the reliability of the results obtained. Despite the promising results, this study is limited by the small sample sizes in both phases. Further research involving larger and more diverse populations is needed to validate these findings and expand on the potential benefits of VR-based OSH training.

CRediT authorship contribution statement

Ari Prayogo Pribadi: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yusuf Mukasyafah Rizqi Rahman:** Investigation. **Chris Dwina Anggiana Br Silalahi:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ari Prayogo Pribadi reports financial support was provided by Universitas Gadjah Mada, Indonesia. There is no conflict of interest between the researcher and any other company. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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