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Virtual reality application for construction safety training

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A R T I C L E I N F O

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A B S T R A C T

Safety has been one of the main concerns in the construction industry in recent years. Construction fatalities, injuries, and accidents impose unrecoverable losses and enormous costs every year. Despite all advancements in new methods, tools, equipment, and regulations, the rate of accidents, especially in fatal four, has not considerably improved. This fact has motivated safety professionals and researchers to explore further innovative ways to remedy the problem. One of the outcomes of safety studies is training. Continuous yet effective training can present essential safety knowledge to new employees and refresh the comprehension of current employees. However, such training sessions require funds, time commitment, and logistics. In recent years, the implementation of virtual reality (VR) for safety training has decreased the impact of obstacles and facilitated continuous training. This paper briefly addresses the design and development of a VR module for safety training in the roofing sector. The VR application was entirely designed and developed through an industry-based expert flow, using an agile methodology. A quantitative approach was employed to analyze the data and investigate various aspects of the VR module. The results showed that the VR module positively impacts roofing professionals' perceptions of the applicability of VR applications as supplementary training tools. The influential factors identified in this research can be considered in the future design and development of VR-based safety applications.

1. Introduction

The construction industry is among the leaders in the number of work-related injuries and fatalities, which makes safety a critical aspect of this industry. For instance, the Bureau of Labor Statistics (BLS, 2017) reported more than 800 fatalities and more than 227,000 incidents in construction in 2017. The best approach to improve the industry's safety performance is to mitigate incidents in the first place. One way to achieve this target is through better education and training of construction workers. Historically, different approaches have been used to train construction workers on safety, such as video recordings, hand-outs, and hands-on training. Each of these methods has its advantages and disadvantages. The hands-on education with the highest impact has the highest cost and risk associated with it. Mixed reality technology, including virtual reality (VR), has been used in different aspects of construction (Ensafi, Thabet, Devito, & Lewis, 2021). VR technology brings a new medium to train construction workers without putting them at risk. Concurrently, it is a more immersive and realistic alternative compared to training options that use videos and hand-outs.

Specifically, safety training has been one major target area for utilizing this technology as it can realistically simulate high-risk environments (Shendarkar, Vasudevan, Lee, & Son, 2006). Users can get training in an immersive environment, either in an open-world exploratory experience or a directed one, and perform safety checks or complete tasks to get the required pieces of training done (Kamat, et al., 2010). Previous studies have shown the effectiveness of VR technology in construction safety training (Sacks, et al., 2015; Guo, Yu, & Skitmore, 2017). Various potential advantages such as low maintenance cost, accessibility, repeatability, and user customization make the emerging technologies favorable for construction training. These technologies bring some drawbacks too. Relatively high capital cost, lengthy design and development process, subject customization, and hardware/ software limitations are among the disadvantages. However, efforts are in progress to advance VR technologies, eliminate the existing disadvantages, and expand the applications of VR-based tools. Meanwhile, roofing construction workers are specifically a high-risk population due

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to their work conditions (working at height) (2015). Roofing construction workers are exposed to particular safety issues due to the nature of the roofing jobs which distinguishes their work from workers in other construction sectors. Here, handling and safeguarding the ladder plays a critical role. Furthermore, working on the roof requires special attention to the roof environment and the specific tool types used in roofing jobs. However, the roofing sector in the U.S. construction industry is still using traditional safety training sessions.

VR can potentially be a proper medium for training roofing workers as it can realistically simulate high-altitude situations while posing no actual falling risks (Ergun, 2015). Although the potential effectiveness of VR in construction safety training has been indicated, there is no particular study focused on roofing workers. Furthermore, most studies so far are research-oriented and have focused on the effectiveness of this technology (Xu & Zheng, 2021; Azhar, Han, & Dastider, 2020). This paper discusses the development of an industry-oriented VR construction safety training program for roofing workers, followed by an initial evaluation of industry perception toward the use of VR in construction safety training. Unlike traditional research-oriented models, the industry-oriented approach used in this project stemmed from the industry's needs and was developed alongside the industry's point of view. This research project aimed to design and develop a VR safety application for roofing professionals while keeping them engaged throughout the module. The development of the roofing safety application in this research helps other researchers to use the adopted methodology and build upon that. While some previous scholars have explored the use of VR for safety training, the approach presented in this study practically translates the needs of end users to the design and development of the VR application through an academic research project.

The overarching research question in this study was to explore how roofing professionals perceive VR applications for safety training. First, the agile methodology adopted in the development of the VR module is presented, and then the quantitative result of the survey utilized to capture the industry perception is shown. The integrated process used in the development of the VR training module can help industry practitioners to ensure the final product is valuable. A similar approach can be followed in the development of prospective VR-based tools. Furthermore, the survey results show that exposure to VR training positively impacts industry practitioners. Especially, VR can be an effective tool for safety training for younger generations. This research contributes to the body of knowledge by providing a safety training module specifically for the construction roofing sector. This means the roofing professionals will interact and learn safety instructions that are more applicable to their routines rather than general safety training.

2. Literature review

Traditionally, safety managers have monitored the activities of a construction site by referring to their work experiences and relying on visual observations. However, in recent years, various technologies have been developed that help monitor the safety performance of construction sites (Alizadehsalehi, Yitmen, Celik, & Arditi, 2018; Zou & Sunindijo, 2015). Advanced technologies, such as computer simulation (Baniassadi, Alvanchi, & Mostafavi, 2018; Marzouk & Ali, 2013), integrated design approaches (Malekitabar, Ardeshir, Sebt, & Stouffs, 2016), and virtual reality (VR) and augmented reality (AR) technologies (Alvanchi et al., 2021; Li et al., 2018) have enhanced the safety of construction sites (Jin, et al., 2019; Mihic, Vukomanovic, & Završki, 2019; Park & Kim, 2013). VR is a digital information visualization technique that rapidly grew in the shadow of the recent advances in information technology (IT) (Billinghurst, Clark, & Lee, 2015). VR technology creates realistic environments where the user is completely immersed in a computer model. This technology is based on highly dynamic and responsive computers and can respond quickly to user interactions, decisions, and manipulations. VR models can process various inputs such as speech, movement, sound, or position (Blach, Landauer, Rösch, & Simon, 1998; Parvinen, Hamari, & Pöyry, 2018). VR has made a significant contribution to advanced construction management in recent years. It is effectively used as a visualization tool, worker training technology, safety management tool, and quality and defect management tool (Ahmed, 2018). With the advent of VR, the trend of investing in complex VR applications to create environments for visualizing complex workplace conditions and creating risk prevention knowledge and training has increased (Li, Yi, Chi, Wang, & Chan, 2018). VR technologies provide platforms for training, monitoring, and controlling the safety of construction projects, reducing the number of accidents at construction sites (Ahmed, 2018). Li et al. (2018) have examined the application of VR in safety management. They have shown the capability of VR technology in various areas of safety, including hazard identification, workforce training, skills transfer, ergonomics, etc. Getuli et al. (2020) have improved the typical planning process in construction sites by simulating construction activities using virtual reality. Applying this method in a real case study has shown its positive impact on planning and sharing safety information between project partners and its official representation in a safety and health plan. The review article by Li et al. (2018) showed the applications of VR techniques in construction safety methods are divided into three categories, including 1) "safety planning," 2) "safety inspection," and "safety training." Safety training is generally done to increase the capability of hazard recognition.

Some reasons that lead to high-risk situations include limited safety information of employees on-site and lack of safety awareness and training (Wang, Wu, Wang, Chi, & Wang, 2018). In general, human error is considered the leading cause of many injuries in the engineering community (Garrett & Teizer, 2009). It contributes to more than half of occupational accidents which can be directly affected by effective training programs (Zhao & Lucas, 2015). Over the years, it has been recognized that training should play an important role, and various ideas for educational solutions have been developed and implemented (Xu & Zheng, 2021a,b; Pedro, Le, & Park, 2016; Le, Pedro, & Park, 2015; Le Q. T., et al., 2015). Traditionally, construction safety education is provided in the classroom environment by slides or videos (Wang, Wu, Wang, Chi, & Wang, 2018). These methods do not represent the real construction environment (Saleh & Pendley, 2012). Visualization technologies can improve safety training by providing visual information and off-site virtual exercises (Guo, Yu, & Skitmore, 2017). Visualization technologies help construction staff better understand safety instructions and operations by combining safety information, presenting it visually, and enhancing interaction and collaboration (Guo, Yu, & Skitmore, 2017). One of the visualization technologies that has been widely accepted for educational purposes in the construction industry is virtual reality (Wang, Wu, Wang, Chi, & Wang, 2018; Bhoir & Esmaeili, 2015; Kassem, Benomran, & Teizer, 2017). Virtual reality technologies provide safety education, training, warning, information, and learning platforms for construction safety management (Ahmed, 2018). Sacks et al. (2013) showed that using innovative VR methods for safety training was more effective in identifying and assessing building safety hazards than equivalent training using conventional safety training methods. The implementation of VR technology for training allows workers to experience hazardous situations without injury, so safe and efficient training is created (Xu & Zheng, 2021). Bhoir and Esmaeili (2015) reviewed virtual reality environment applications in construction safety and showed that the VR acceptance rate for safety training was minimal, and safety experts preferred hands-on exercises. Many studies have shown that VR and AR are the most effective safety education and management tools in recent years (Ahmed, 2018). Jeelani et al. (2020) proposed a personal safety training protocol that used robust, realistic, and comprehensive virtual environments. They improved risk detection and management performance using stereo-panoramic environments for performance evaluation and feedback and a virtual construction site for instructional training.

3. Methodology

The main objective of this project was to evaluate the applicability of VR technology for safety training purposes along with users' perceptions. The methodology of the study was adjusted to the sponsor's requirement, which prioritized roofing professionals as the primary users of the module. The methodology of the project was designed based on the progressive elaboration concept as the development team continuously used the industry inputs as the main source of scenario development and validation, as shown in Fig. 1. After project initiation and preliminary review, the structure of the project was defined. During the project development phase, the data model was created, and initial data were analyzed. In the next step, the VR application setting was explored, and the optimum sets for hardware, software, and application were defined. To optimize the development process and the mass use, Oculus Quest 2 was selected as the VR headset for the application. Also, among game engines, Unity was deemed appropriate for the type of the current project. In the next step and through interactions with industry experts, action plans were developed. Action plans incorporated safety regulations and instructions in various scenarios. Ten different sections consisting of ladder-related tasks were separately designed and developed. The main themes of the sections include 1) assessing the job site for the best ladder location, 2) selecting the ladder to use based on building height and weight rating, 3) inspecting the ladder for grease, mud, structural damage, and missing parts, 4) setting up the ladder, 5) ladder securing, 6) maintaining secure contact with the ladder, 7) ladder use for material transportation, 8) dismounting the ladder at the roof, 9) un-securing and descending the ladder and lowering the ladder to the ground, 10) safe roof work inspection, and 11) loading ladder on the truck for safe transport. In each section, the assumption about the user was a newly hired roofing worker who needs to evaluate the safety concerns and risks in different steps of ladder-related tasks. Fig. 2 presents screenshots of different features of the VR applications that the trainee experiences during the training using the VR headset.

After developing each section, it was tested by industry experts to ensure the applicability and correctness of embedded components and required actions. The experts were referred to the research project by the sponsoring organization, which is the primary professional organization for roofing contractors in the U.S. In the project initiation phase, one of the terms that the researchers and the sponsor reached an agreement on was the full involvement of the sponsor representatives in the design and development processes. This led to the formation of the Task Force which was involved from the beginning of the research project to the end. They acted as the quality control unit in the design and development processes. This process was in addition to the internal review process to ensure the validity of the VR application. When the beta version of the application was prepared, it was available for general users' feedback. The industry taskforce members invited their employees to use the application and express their feedback. A link to the survey was provided to users to follow and respond to the questions. Questions provided in the survey covered the main content related to traditional safety training and the applicability of VR technology as supplementary tools. A quantitative method was chosen to obtain data and the quantity of user experience. After the demographic section, a five-level Likert scale was used to measure the agreement levels or magnitude of impacts. Responses were collected in a 10-day period. After collecting the data, they were cleaned and modeled in statistical software packages. In total, 46 valid samples were used in the analysis. To explore the consistency and reliability of the survey, Cronbach's alpha measurement was used. A Cronbach's alpha of 0.80 and 0.89 weres obtained from the analysis of the data in impacting factors and VR feature sections, which categorizes the internal consistency of the instrument as very good.

4. Results

The data gathered through the online platform were combined, cleaned, and coded. After data evaluation, 46 responses were deemed suitable for analysis. The data model was used in statistical software for descriptive analysis. Table 1 shows the demographic information of the participants. As shown in Table 1, the majority of subjects were male, over 51 years old, and with more than 25 years of work experience. Also, respondents were mostly high-level executives from companies with 51 to 200 employees.

In the next section of the questionnaire, safety-related questions were asked. Participants were requested to specify the number of training hours that new employees receive. As shown in Table 1, 45 % of participants reported that new employees are trained for more than 16 h.

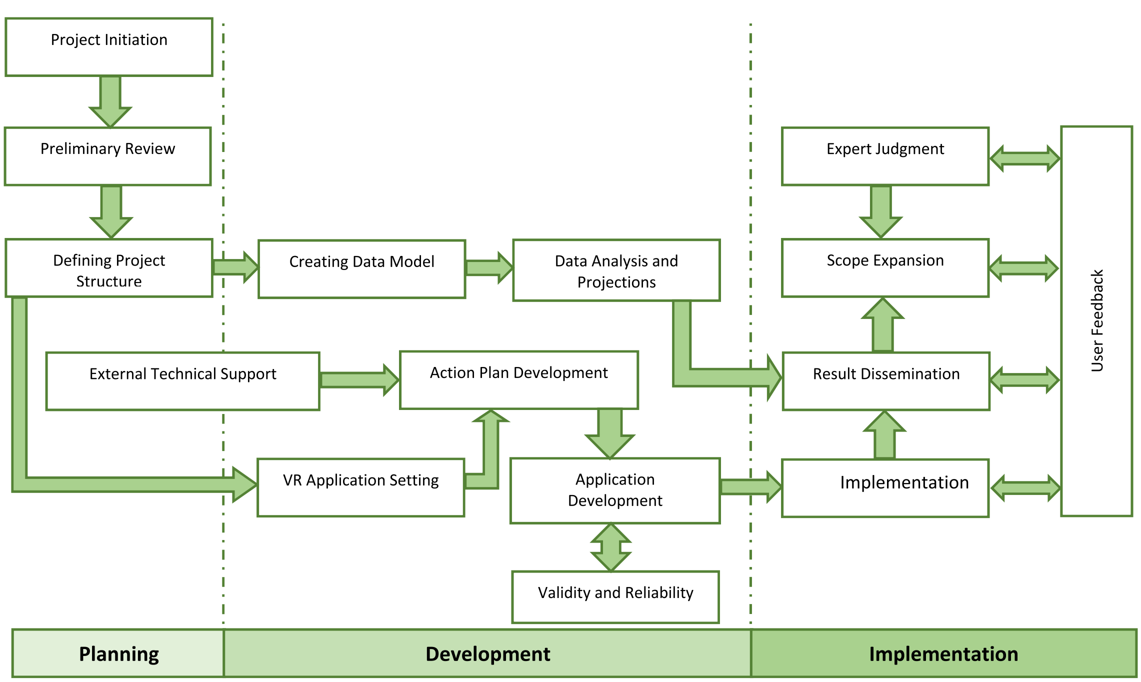

Fig. 1. Research methodology scheme.

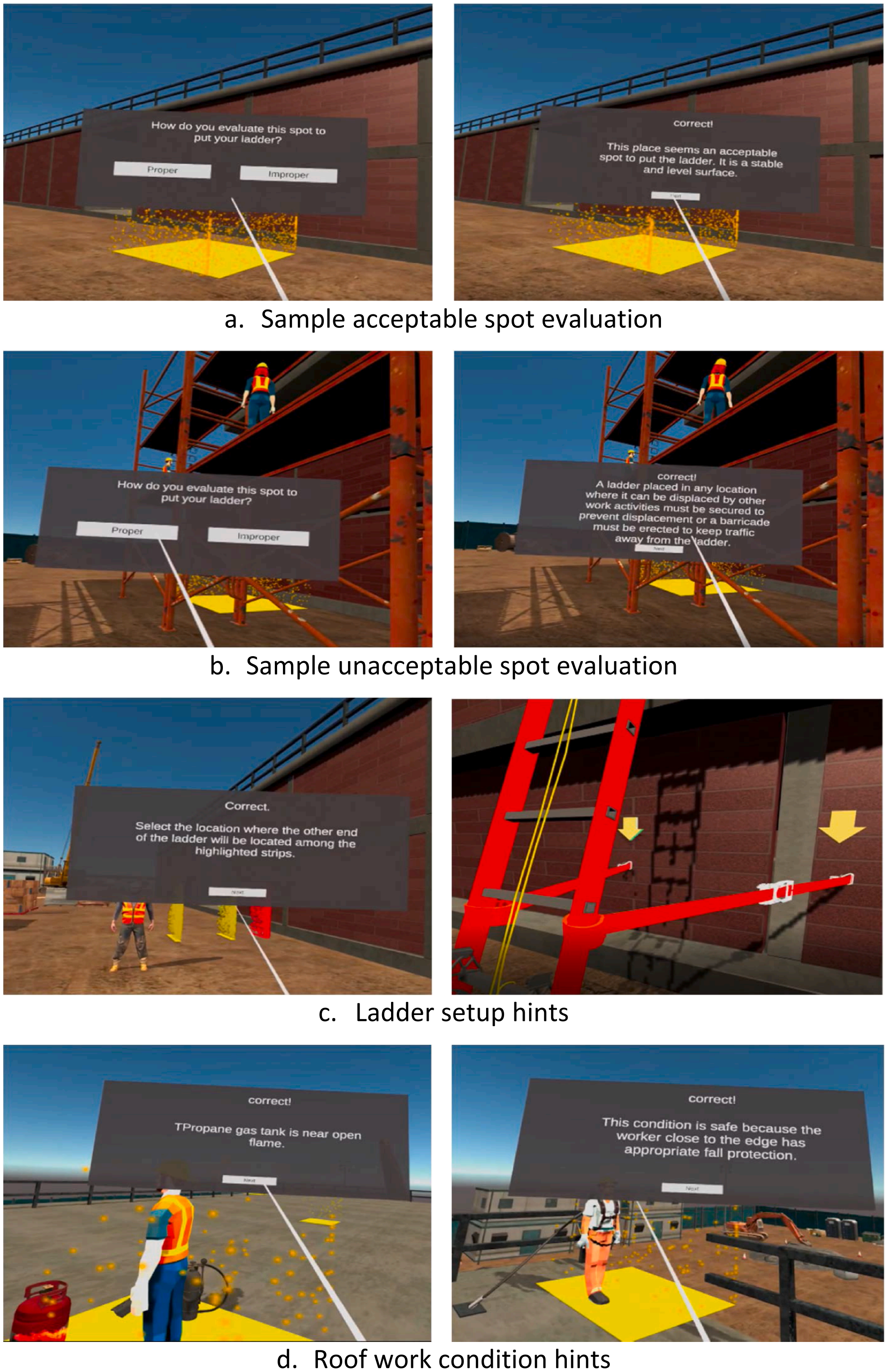

Fig. 2. VR application interface snapshots.

Also, 91 % of participants reported that their current employees need to attend safety training sessions to refresh their knowledge. Additionally, participants were asked how frequently their employees need to attend ongoing safety training. The percentage of time intervals is shown in Table 1.

In the next question, participants were asked to specify the main reason for accidents in the roofing industry. While careless workers' attitudes had a high percentage, 42 % of participants believed lack of knowledge or ineffective training was a source of accidents (Fig. 3).

Participants also rated to what extent they believe different factors impact accidents in the roofing industry, using a five-level Likert scale (Very Low:1; Very High:5). The percentage of each level is shown in Fig. 4.

The next section of the survey consisted of questions related to VR and its application for safety training. First, participants were asked to rate their familiarity with VR in general, using a five-level Likert scale.

Table 1
Participants' Demographics.

Gender	Male	Female			
%	93	7			
Age (years)	21–30	31–40	41–50	51–60	61+
%	4	9	28	39	20
Experience (years)	**$1 \le x < 3$**	**$3 \le x < 7$**	**$7 \le x < 15$**	**$15 \le x < 25$**	**25+**
%	2	13	7	24	54
Position	**President/ CEO**	**Project Manager**	**Sales Rep./ Manager**	**Office Engineer**	
%	85	9	4	2	
Size of Company (# of employee)	**<20**	**20–50**	**51–200**	**201–500**	**500+**
%	0	2	74	11	13
Majority of Hires' Experience	**$1 \le x < 3$**	**$3 \le x < 7$**	**$7 \le x < 15$**	**$15 \le x < 25$**	**25+**
%	51	39	4	2	4
Training Hours	<4	5–8	9–15	16+	
%	20	22	13	45	
Training Intervals	Within 3 mo.	Within 6 mo.	Within 1 year	At will	
	56	18	21	5	

The percentage of each level is shown in Fig. 5.

In the next question, participants expressed their agreement level with the statement "virtual reality is highly applicable to workforce training in the roofing sector." While 39 % of participants agreed with the statement, 53 % were neutral, and only 8 % of them did not agree with the applicability of VR in safety training (Fig. 6).

Similarly, participants were asked if they believed virtual reality could help the new generation of the workforce to gain required safety instructions while enjoying the virtual reality environment. The majority of participants (55 % agreement, 37 % neutral, and 8 % disagreement) showed positive perceptions toward the effectiveness of VR for new generation training. The percentage of each level is shown in Fig. 7.

Participants also expressed their intent to seek opportunities to use virtual reality applications for safety training in their companies. While 45 % of participants showed their agreement to use VR for training purposes, 44 % were neutral, and only 11 % of participants disagreed with the approach. Fig. 8 shows the percentage of each agreement level.

In addition, participants showed a positive reaction toward the VR application after partaking in the safety module. They were asked if their confidence about the use and applicability of virtual reality increased after they tried it for the first time, using a five-level Likert scale. Fig. 9 shows the percentage of each agreement level. Also, various VR features were provided to participants to rate using a five-level Likert scale. The weighted average of factors is shown in Table 2. While all features were evaluated of interest (above mid-point), three features of "ease of use," "comprehensive and detailed instructions," and "appealing audio/visual components" were among the top three desired features.

Finally, participants were asked to specify the biggest obstacle to the mass adoption of virtual reality technology in the roofing industry, and five common barriers were provided to be selected. The percentage of each obstacle is shown in Fig. 10. As shown, consumer and business reluctance to embrace VR was selected as the main impediment (30 %).

5. Discussion

VR has provided a new medium for immersive education. It is

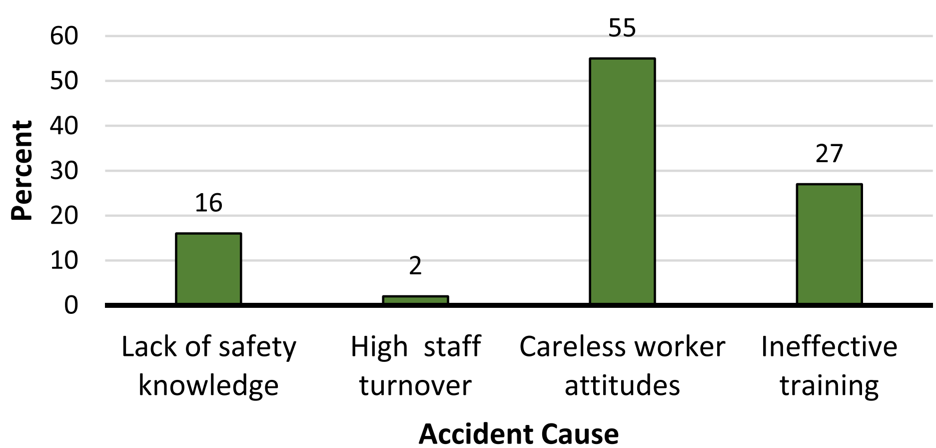

Fig. 3. Perceived main cause of accidents.

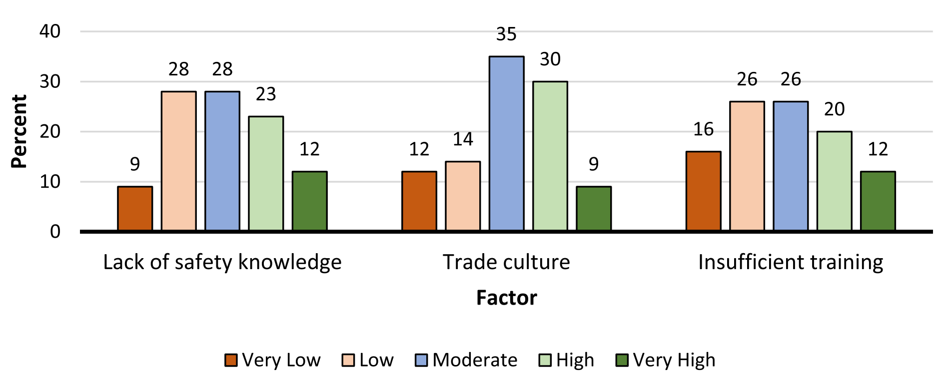

Fig. 4. Impact of factors on accidents.

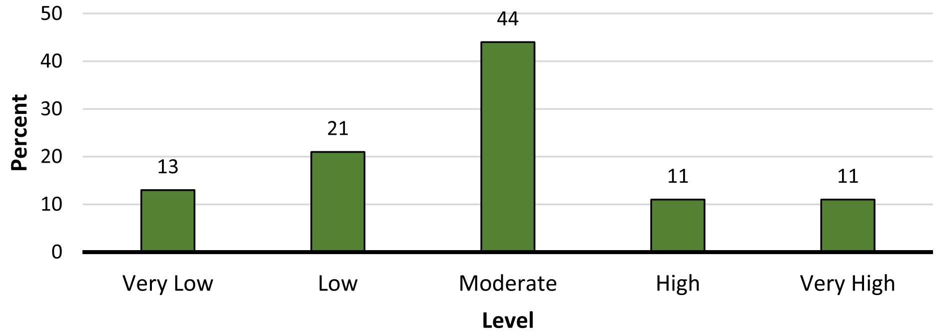

Fig. 5. Level of familiarity with VR.

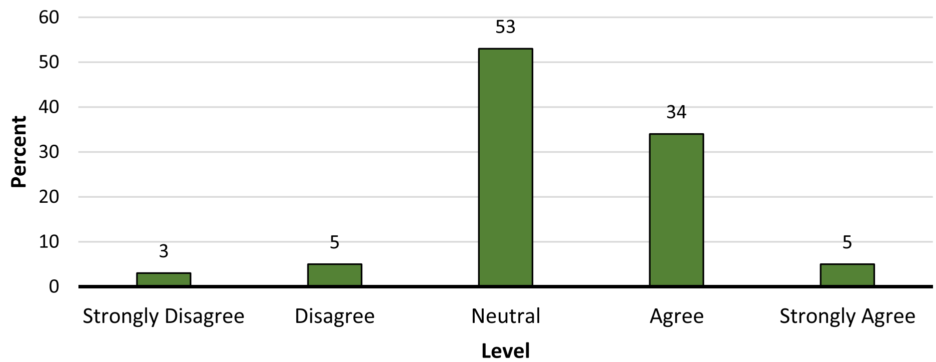

Fig. 6. Level of agreement with VR Applicability.

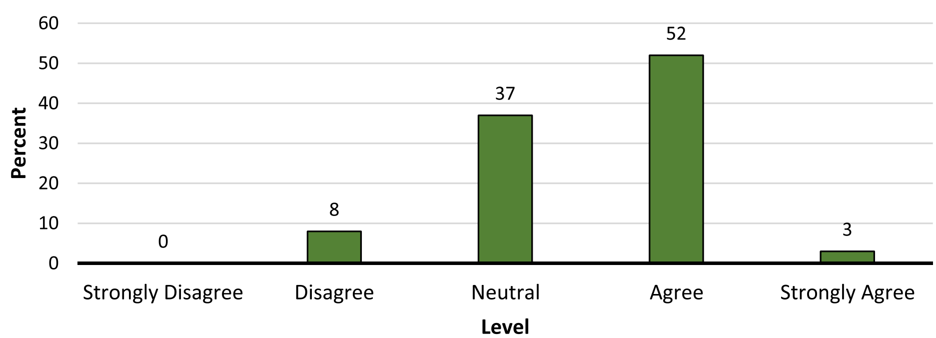

Fig. 7. Level of agreement with VR effectiveness for the new generation training.

particularly beneficial in recreating potentially dangerous situations such as construction environments. It can provide a safe space for training construction workers without the fear of failure or any real consequence. Furthermore, after the initial development cost, it is relatively cheap to educate workers in VR in comparison to creating a real-life training scenario. This cost-effectiveness becomes more apparent when we consider the number of people who can use a VR application or where one person can replay a scenario multiple times without any additional cost or preparation.

The results presented in Table 1 show that 85 % of the respondents were the president/CEO of medium to large size companies with 41–60 years old and more than 15 years of work experience. These data show that the follow-up results and discussion are at a managerial level of medium-large size companies. This signifies the importance of the results presented that show the decision makers' perspective on the use of VR in the construction industry. As a result, this paper can help researchers and developers better understand the requirements and thoughts of their ultimate stakeholders and adapt their workflow based on them. Another factor worth mentioning is the experience of new hires in these companies. The majority of new hires have between 1 and 3 years of experience which can be beneficial in deciding on the level of information and complexity of scenarios when developing VR applications.

In the safety-related section questions, the results showed that the majority of the companies require new employees to train for more than 16 h, while the intervals are mostly within three months. This shows the importance of safety training in the surveyed companies. On the other hand, some companies require less than four hours of training and no mandatory intervals. This shows that there are still companies that do not put safety as their top priority. The training hours and intervals in Figs. 1 and 2 can be used as a guideline for researchers and developers when they are designing their modules and making decisions on the length and intervals of training. The fact that 42 % of the participants think that lack of knowledge or ineffective training is the main source of accidents means that there is a need for better safety training which VR can potentially fill this gap. Furthermore, VR can also help identify and correct careless worker attitudes. The results presented in Fig. 4 also signify the need for better training and a change in the trade culture.

The next section of the results is related to VR and its application for safety training. Almost half of the participants had moderate familiarity

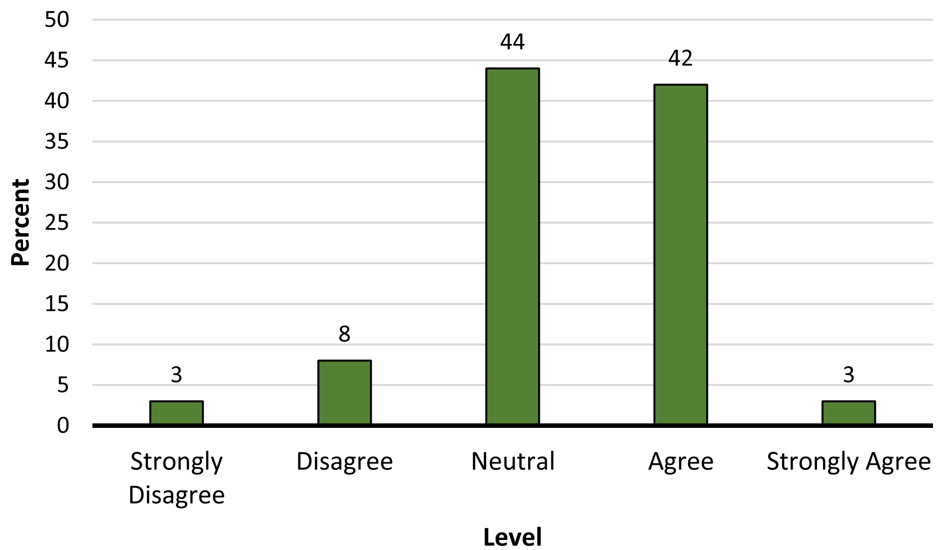

Fig. 8. Level of agreement with VR application for training.

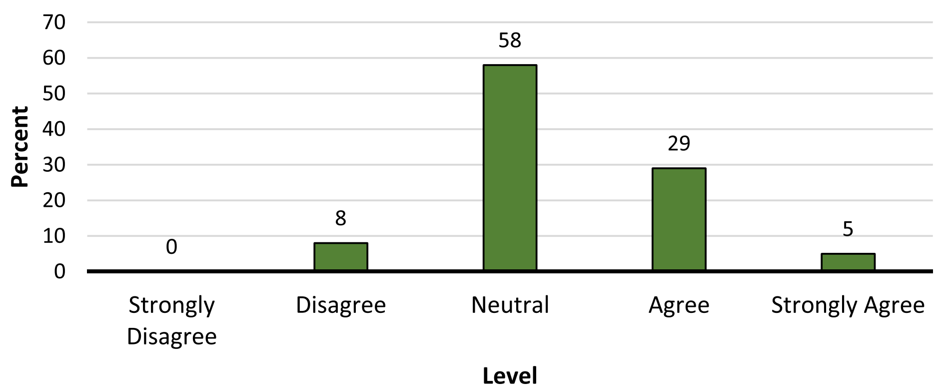

Fig. 9. Level of agreement with VR engagement.

Table 2
Weighted average of VR application features.

Feature	Training module length	Appealing audio/ visual features	Providing comprehensive and detailed instructions	Type of building/ equipment used for modeling	Providing textual information	Point/scoring indicators	Easiness of use/navigate
Weighted Average	3.24	3.66	3.68	3.42	3.05	3.18	3.89

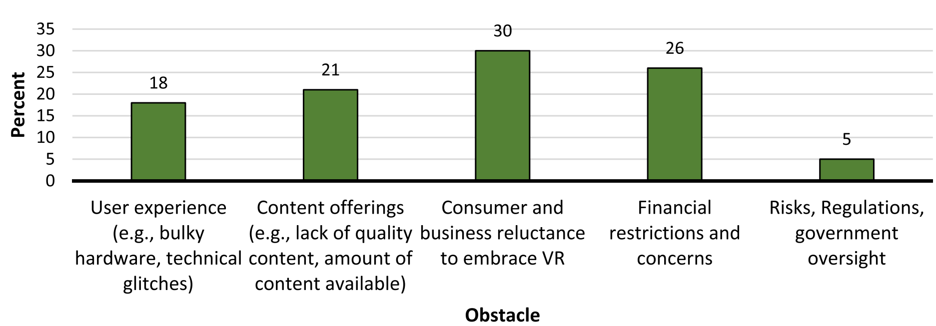

Fig. 10. Percentage of obstacle in VR mass adoption.

with VR, while the majority of the rest had low to very low familiarity. This fact is consistent with the data existing among other more traditional trades in the construction industry, such as concrete, structure, and cladding (unlike interior design). As a result, increasing awareness regarding VR applications in safety training should be a priority. (Wang, Wu, Wang, Chi, & Wang, 2018; Zhao & Lucas, 2015; Xu & Zheng, 2021;

Pedro, Le, & Park, 2016). Furthermore, the results in Fig. 6 showed that there was a relatively positive conception of the applicability of VR to workforce training in the roofing sector, but still, there is room for increasing awareness. This can happen through a comprehensive presentation of VR potentials and capabilities that fit their actual needs instead of a fancy tool that may have some positive impacts. Interestingly, the majority of the participants agreed or didn't have a negative opinion on VR effectiveness for the new generation training. Putting these all together shows that industry leaders are inclined to utilize VR technology in their companies. Specifically, 45 % of the participants indicated that they have the intention to use VR applications, while 44 % had a neutral opinion. As a result, new VR developments already have a market and can be simultaneously used to increase awareness and change the large neutral population toward a positive opinion on the implementation of this technology in their company.

Exposure to the developed VR application in this study made a positive impact on 34 % of the participants. It can be deduced that with more applications developed and more exposure happens, a better and more positive attitude toward VR safety training in the construction industry can be expected. This finding also indirectly underscores the lack of sufficient VR applications for roofing safety training purposes (Xu & Zheng, 2021; Azhar, Han, & Dastider, 2020). The results in Table 2 provide a baseline for designing new VR training modules in the roofing sector. Specifically, those polled felt the ease of use, comprehensive and detailed instructions, and appealing audio/visual components should be weighted stronger when making compromising decisions in the development process. The last question regarding the obstacles to mass adoption of virtual reality technology in the roofing industry showed that the leaders of this industry consider "consumer and business reluctance to embrace VR" as the main obstacle. Considering the demographic information of the participants, this result showed an internal struggle among the leaders of the industry where they have a positive attitude toward the industry but at the same time see a reluctance in the business to adopt the technology. Furthermore, the "financial restrictions and concerns" and "content offerings" were the next obstacles. These hindrances can be expected to lessen as the price of VR hardware is reduced, and more content becomes available.

6. Conclusion

This paper provided a short description of the design, development, and implication processes of a VR application for construction safety training. Following the national statistics on fatal four, falling was selected as the main theme for the application. The main objective of this study was to explore to what extent roofing professionals considered a VR application as a supplementary tool to improve their safety knowledge. While all employees typically receive safety instructions at the beginning and throughout their employment, it is helpful to review the content iteratively. However, the nature of safety instructions may be dull to some and therefore does not attract the attention of employees, especially the younger ones. This project aimed to provide safety instruction while keeping users engaged throughout the module. To provide practical safety content, a professional expert advisory board was set up to provide feedback during different stages of the design and later in the development process. This ensured the design and development teams that the correct information was provided and simulated in the VR application. After the module completion, a survey was designed and distributed to the roofing professionals to explore their opinions about the use of VR for safety training in the context of their area. The results indicated positive attitudes of professionals toward the application of VR for safety training. While the findings of this study highlighted the role of VR applications, the generalization of the results is not warranted. A larger sample size with different levels of familiarity with VR would enhance the reliability of the research. Also, classifications of subjects based on age, level of safety expertise, company size, positions, and traditional safety training routines would reveal additional conclusions in future studies.

CRediT authorship contribution statement

Saeed Rokooei: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Alireza Shojaei:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Amin Alvanchi:** Software, Project administration, Methodology, Conceptualization. **Reza Azad:** Software, Conceptualization. **Nasim Didehvar:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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