EVALUATION OF IMMERSIVE VR EXPERIENCES FOR SAFETY TRAINING OF CONSTRUCTION WORKERS: A SEMI-QUALITATIVE APPROACH PROPOSAL

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ABSTRACT: *The diffusion of Building Information Modeling (BIM) and advanced visualization technologies in the increasingly digitalised construction sector is fostering the development and implementation of disruptive approaches for workforce Health and Safety (H&S) training. Project-specific risks, safety procedures and information can be administered through immersive Virtual Reality (VR) experiences where construction site environments and activities are reproduced without exposing the trainees to real hazards. However, despite numerous research and industry applications demonstrating the potential benefits of these technologies, a standardized framework and methodology for the evaluation of VR safety training effectiveness for construction workers is still lacking hence hindering its large scale-adoption and recognition from policymakers. Within the scope of previous authors contributions on the development and implementation of BIM-based VR experiences for construction workers' safety training, this paper aims to address the evaluation of their effectiveness proposing a novel semi-qualitative approach based on the integration of trainees' subjective and objective data. A post-experience evaluation questionnaire is developed to collect trainees' direct and qualitative feedback about the experience immersivity and perceived safety content transfer. Furthermore, the integration with trainees' spatial tracking data is proposed to complement the qualitative feedback with the quantitative evaluation of their use of the virtual space for safety training purposes. The application of the presented approach in case study is currently undergoing and the related results will be subject of future contributions.*

Keywords: *Virtual Reality (VR), Construction worker, Safety training, Evaluation, Spatial tracking, Heatmap visualization, Survey*

1. INTRODUCTION

Despite recent technological innovations and policy improvements in workforce Health and Safety (HS) are contributing to a low but steady reduction in accident rates, the construction industry is still one of the most dangerous, accounting for one fifth of yearly workplace fatal accidents in the European Union alone (Eurostat, 2022). In this regard, the growing adoption of real-scale immersive visualizations of complex site scenarios and construction activities enabled by Building Information Modelling (BIM) and Virtual Reality (VR) technologies are supporting HS managers in the early identification and mitigation of safety risks (Babalola et al., 2023). Moreover, since their early applications, it has been acknowledged that immersive VR simulations of project-specific site layouts and activities can improve the transfer of safety contents and preventive procedures to the trainees, while empowering their awareness in later real-site hazardous contexts (Rokooei et al., 2023). However, the administration of VR experiences for construction workers safety training is far from substituting traditional methods (e.g., slides) and is still confined to a minor share of early adopters. In fact, while economic and technical barriers have progressively shrunk, the lack of standardized frameworks and methods for the evaluation of the effectiveness of construction site VR training still stands as a major obstacle for its recognition from policy makers

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Vito Getuli, Valentina Fornasari, Alessandro Bruttini, Tommaso Sorbi, Pietro Capone, *Evaluation of Immersive VR Experiences for Safety Training of Construction Workers: A Semi-Qualitative Approach Proposal*, pp. 288-297, DOI 10.36253/979-12-215-0289-3.27

and hence for their large-scale adoption in the industry. In this context, several contributions have shown how the quantification of the trainee’s ability to perform cognitive and practical tasks in the VR environment (e.g., hazard identification, activity simulation) can be used to objectively assess the training effectiveness (Li et al., 2018). Nonetheless, the qualitative evaluation of VR training, collected via post-experience questionnaires administered to the trainees, is often overlooked or tailored on a specific application, so that its reuse in other case studies is impractical.

To address the mentioned open issues in the evaluation of VR safety training experiences for construction workers, this paper proposes a novel approach based on the integration of trainee’s subjective perception and objective VR spatial usage. The former is collected through a questionnaire administered to the trainee after the experience and divided in five inquiry areas. For the latter, the acquisition of the users’ spatial track during the VR experience and its restitution in a BIM environment through an heatmap visualization is proposed to evaluate the trainees’ use and understanding of the virtual environment in relation to safety training purposes. The present work stems from previous authors’ contributions in the development and administration of BIM-based immersive VR site simulations to construction workers for HS training and management purposes and is currently being tested in an infrastructure project case study whose results will be subject of future contributions (Getuli, Capone, Bruttini, & Sorbi, 2020; Getuli et al., 2018, 2021, 2022).

2. BACKGROUND

The use of virtual reality as a safety training technology is gaining attention in the construction industry. While many of the current studies mainly focus on the development of VR-based safety training programmes, it is noticeable that there is still a lack of research focusing on assessing its effectiveness. In this section, an overview of the state of the art with regard to the use of immersive virtual reality used in the realisation of training sessions for workers is given and, finally, the identified open problems and obstacles to implementation that this research aims to address are reported.

2.1. BIM and Virtual Reality for construction workers’ safety training

Increasing use of BIM is favouring the adoption of VR in the Archtiecture, Engineering and Construction (AEC) sector. Typical applications for VR include construction safety planning and training (Azhar, 2017), production planning and design review sessions (Wolfartsberger, 2019).

In recent years, several studies have shown that BIM models can be used to represent construction site layouts and extract data for space and activity optimisation (Tao et al., 2022) and apply automated safety rule checking to simplify hazard recognition and assessment and risk assessment activities (I. Kim et al., 2020). Most of all, the spatial understanding and information visualisation capabilities provided by construction site BIM models have been harnessed to transfer general and project-specific HS knowledge with the implementation of VR technologies for the reproduction of construction site scenarios and activities for worker safety training and site planning (Getuli & Capone, 2018).

Several studies investigated the use of virtual reality to allow construction workers and supervisors to have easy access to the BIM through a simple VR interface and also for the education of students, defining an efficient educational tool by integrating VR application and BIM model information to develop 3D, 4D, and 5D simulations (Esfahani, 2023) and offering suggestions to AEC educators and students in implementing BIM-into-VR in different courses.

The use of virtual reality as a safety training technology is gaining attention in many different fieds: using a fully immersive VR has been shown to offer numerous benefits in terms of the effectiveness of health and safety training including risk assessment, machinery and/or process operation training in various industries (Toyoda et al., 2022).

VR is gaining attention also in the construction industry, but while many of the current studies mainly focus on the development of VR-based safety training programmes, it is noticeable that there is still a lack of research focusing on improving its effectiveness. It has been shown that telepresence experienced through VR and learners' perception of the risk of occupational accidents significantly influence their satisfaction with VR-based safety training, thus influencing its effectiveness (Yoo et al., 2023).

2.2. Construction workers' safety training evaluation

The evaluation of the effectiveness of simulations developed in VR during the training sessions or the validation of the experience carried out is a key step to identify different problems and to be able to solve certain situations by fully improving the training activity for trainees, but while VR-based training has been proven to improve learning effectiveness over conventional methods, there is a lack of study on its learning effectiveness due to the implementation of training modes. It is known that BIM and VR for safety training of construction workers are useful in many contexts (Afzal & Shafiq, 2021), although there is still no standardized method to evaluate the effectiveness of safety content transfer. In fact, most of the proposed methods are specific to individual case studies or applications in different fields, and the effectiveness of the training administered as perceived by the trainee and the spatial understanding of the worksite scenario and activity in VR is often overlooked.

The evaluation of the user experience in virtual environments can be done either with subjective methods, such us questionnaires (H. K. Kim et al., 2018) or with objective methods, like eye-tracking, or brain activity measurements (Hertweck et al., 2019).

Regarding to the evaluation of the VR safety training of construction workers, several survey methods were proposed, including the creation of a questionnaire containing open and closed questions to evaluate various aspects of the VR interface on a scale of 1 (poor) to 5 (excellent) with subsequent collection of further data through observations and conversations with participants during and after the VR tests (Johansson & Roupé, 2019). Questionnaires are a widely used and well-known tool to collect user feedback and changes in mental states during various activities (Robinson, 2018) including VR applications.

Although the use of objective measurement methods is promising, questionnaires are the most frequently used tool in user experience studies for VR. These questionnaires can be used as pre-, real-time, or post-assessment methods. In pre-surveys, the user is not immersed in a virtual environment: this can lead to a less dominant difference between VR and the traditional desktop presentation of questionnaires. After immersion into the virtual environment, however, it is important to investigate the influence of the type of questionnaire presentation on user experience (Safikhani et al., 2021).

Another important topic is the movement or spatial tracking of workers during VR simulation of construction activities, that has been shown to be useful for ergonomic evaluation of workstations or assembly procedures (Getuli, Capone, Bruttini, & Isaac, 2020).

Some studies demonstrate the effectiveness of VR simulations of assembly lines and task scenarios in an ergonomic approach to workplace design, aimed to optimize the production and the human-machine interaction (Caputo et al., 2018). Through the collection and analysis of the position tracking of a worker (Michalos et al., 2018) and human motion and posture tracking systems is possible to obtain reliable and repeatable measures to be used for evaluation of activity and workplace-related working postures.

2.3. Open issues

Although BIM and VR for construction workers' safety training has been proven beneficial in many studies, there is still a lack of a standardized method to evaluate safety contents transfer effectiveness. Most methods are specific to single case studies or applications; they are used to assess the training on objective quantification of the trainee ability to accomplish tasks in the VR environment but overlook trainee's perceived effectiveness of the administered training and spatial understanding of the construction site scenario and activity in the VR, and ignore the subjective worker perception.

Movement or spatial tracking of the trainees/workers during VR simulation of working activities has been proven beneficial for the ergonomic assessment of workstation or assembly procedures but not yet to evaluate the spatial understanding of the trainee in VR safety training experience that could instead be leveraged in the safety content transfer evaluation of HS training VR experience.

3. PROPOSED APPROACH

The aim of this paper is to propose an evaluation method of VR safety training experiences for construction workers that is based on the integration of a qualitative survey of the experience and spatial tracking data of participants. To this end, first a dedicated questionnaire was developed to evaluate both the immersiveness of VR experiences and the effectiveness of the safety content presented. Then a study on the benefits of tracking and visualizing trainees' use of space in the virtual environment is proposed. Finally, the proposed approach was validated within a case study previously developed by the authors and used for BIM-based construction worker safety training in VR.

As mentioned above, the proposed approach is based on the integration of two main categories of data, as illustrated in Figure 1. The overall goal is to collect a set of data from trainees experiencing immersive VR training, aimed at evaluating the effectiveness of the virtual experience. The detailed description of the types of data to be collected and the specific purpose for which they need to be obtained then follows in Sections 3.1 - 3.2.

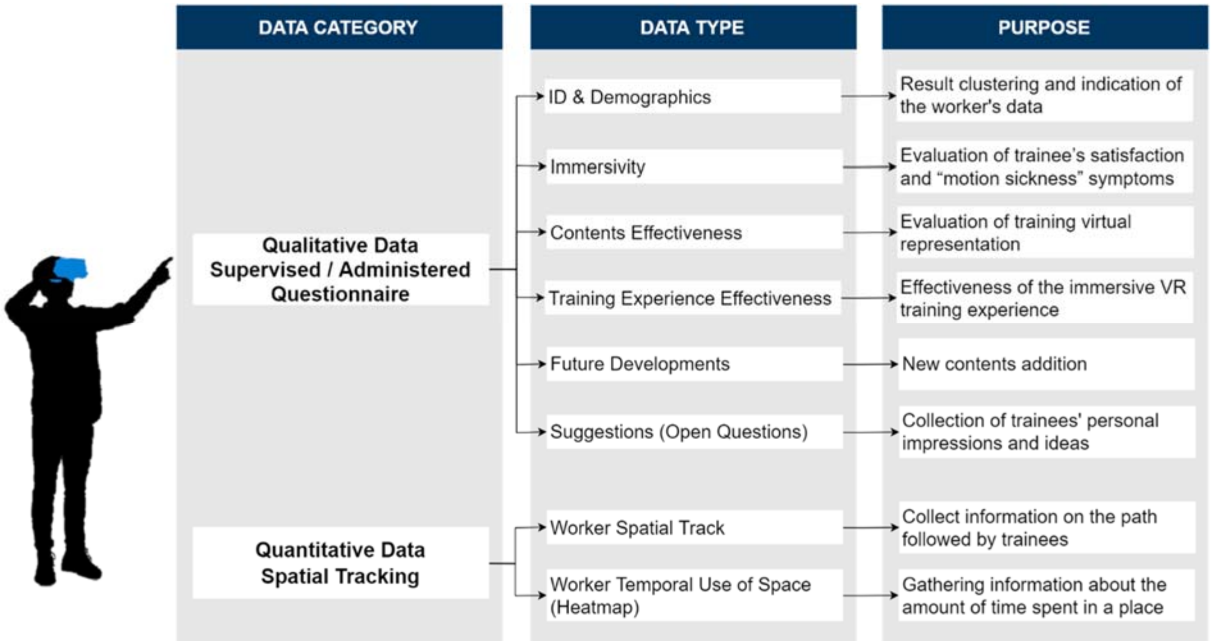

Fig. 1: VR safety training experience effectiveness evaluation approach – Data schema

3.1. Post-experience evaluation questionnaire

The approach adopted for the creation of the evaluation questionnaire led to the distinction of two main sections: the first section includes the trainee's personal data, while the second section corresponds to the actual evaluation part. The latter includes both a series of evaluation questions, for each of which the trainee can give a score on an increasing scale from one to five (where five represents maximum satisfaction), and an open "suggestions" section to collect trainees' personal impressions and ideas. Table 1 shows the sections and subsections with an indication of the purpose for which it was deemed necessary to include them, a brief description, and an explanatory example.

3.2. Trainee's spatial tracking and use of space visualization

From the immersive VR experience, data are collected not only directly, by filling out questionnaires, but also indirectly with the acquisition of the worker's position in the virtual environment. The latter procedure involves capturing the position of the worker in the VR environment during the entire course of the simulation in order to analyse the actual use of the workspace and is recorded with a data acquisition rate of 1 Hz. The 3D point sequence resulting from this process is then converted for the generation of heatmaps within which the position of the worker is represented with a gradient of colour ranging from green to purple.

As with the formulation of the questionnaire, mentioned in the previous paragraphs, an approach was defined to analyse worker movement during the immersive VR experience in order to visualize position tracking. This methodology involves taking into account not only the spatial coordinates, but also the time duration required for the performance of the experience.

Table 1: Questionnaire contents

Data type	Description	Example
ID & demographics	The worker's data, which includes an identification code/number (ID) for classification of the completed questionnaire and an indication of the worker's age, role/occupation and company, with the purpose of clustering the results obtained. [Text]	ID (Number) Age; Company; Role
Immersivity	Questions related to the user's ability to get immersed in the virtual experience, useful for assessing how engaged the trainee actually was in the virtual training scenario. It consists of an assessment of the trainee's satisfaction in terms of both ease of use and comfort (also related to the possible onset of symptoms of "motion sickness"). [Single rating – Likert scale]	How much did you like the experience? [min 1; max 5]
Contents' effectiveness	Questions regarding the virtual representation of the site and security content, aimed at evaluating the effectiveness of the experience against the objectives of the training session. [Single rating – Likert scale]	How accurately does the virtual construction site reproduce the real one? [min 1; max 5]
Training experience's effectiveness	Questions pertaining to the overall effectiveness of the experience, aimed at investigating the actual usefulness of the immersive VR training session and whether it turns out to be as comprehensive and exhaustive as a traditional training session. [Single rating – Likert scale]	Do you think this experience is useful in understanding the hazards present on the construction site? [min 1; max 5]
Future development	Questions concerning the introduction of new automation or virtual content aimed at enhancing the immersive VR training experience through the inclusion of even virtual objects with enhanced interactivity. [Single rating – Likert scale]	Would you like to be able to grasp and use objects from the construction site? [min 1; max 5]
Suggestions	Open question to collect personal impressions and ideas from the trainees. [Text]	Suggestions

Table 2: Heatmap schema contents

Data type	Description	Example
ID & demographics	See Table 1	See Table 1
Training experience duration	The duration of the experience from start to finish, excluding the tutorial that is run at the end to explain the operation to trainees, takes into account how long it takes the user to complete the experience. [time in seconds]	523 sec
Worker spatio-temporal track	The graphical representation is given by a series of points that correspond to the coordinates of where the user was every 1 second and are used to create an image that shows the path followed by the worker distinguished with different colours. [Frequency in Hz]	Image with coloured representation of the worker's followed path. [min. green, max. purple]

4. IMPLEMENTATION

The area in which this paper is located is part of a previous research project in which the authors' goal was to develop a prototype protocol for the design and delivery of safety training to construction workers, based on an innovative and interactive learner-centred approach. This protocol was designed and then tested for validation in a construction project in Italy that served as a case study for the development of VR training session content and implementation (Getuli et al., 2021). During and after the exploration of the site phases implemented, the worker undergoing the experience was invited to provide indications and opinions regarding the work environment in which he/she was working. This was done with the aim of both validating the different site layouts designed and to collect any objections and/or observations from the worker, thus enhancing their experience and giving it due importance within the development process of the virtual reality training experiences covered by this research work.

In order to collect direct feedbacks and suggestions to better drive the decision of the development direction of the implementation of the proposed VR training protocol, an evaluation questionnaire (Fig.4) was administered from a staff member to every trainee involved after they finished their test training session. The authors drawn the questions in relation to the following development areas, weighting the number of the questions for each one according to their research objectives:

- **Immersivity**: (question 1 to 4) Evaluation of the trainee's satisfaction in terms of ease of use and comfort (also related to eventual "motion sickness" symptoms occurrence).
- **Contents' effectiveness**: (question 5 to 10) Evaluation of the site's and the safety contents' virtual representation in respect of the purposes of the training session.
- **Training experience's effectiveness**: (question 11 to 14) Evaluation of the overall effectiveness of the immersive VR training experience.
- **Future development**: (question 15 and 16) Evaluation of the introduction of audio and enhanced object's interactivity as new features to be implemented in future developments.

For each evaluation question the trainee can give a score on an upward scale from one to five, where five represents the highest satisfaction. Furthermore, an open "suggestions" section is added to collect personal impressions and ideas from the trainees. All the results were collected and processed in anonymous form.

User Data	
ID:	
Age:	
Company:	
Role/Job:	

	Questionnaire	min - max
Immersivity	1) Did you enjoy the experience?	1 2 3 4 5
	2) Were you comfortable during the experience?	1 2 3 4 5
	3) Was it easy to use the viewer and controller?	1 2 3 4 5
	4) Did it bother you not being able to see your body in the virtual world?	1 2 3 4 5
Contents' Effectiveness	5) Are the signal arrows helpful in figuring out where to go?	1 2 3 4 5
	6) Does the virtual construction site sufficiently replicate the real one?	1 2 3 4 5
	7) Do the work spaces indicated for the work seem adequate?	1 2 3 4 5
	8) Are the safety and hazard spaces useful in signaling hazardous areas?	1 2 3 4 5
	9) In your experience, are the work procedures reproduced correct?	1 2 3 4 5
	10) Do you think this experience is useful in getting to know the worksite before entering it?	1 2 3 4 5
Training Experience's Effectiveness	11) Do you think this eperience is useful in understanding the hazards present at the worksite?	1 2 3 4 5
	12) Is this type of training useful for an inexperienced worker?	1 2 3 4 5
	13) Is this type of training useful for an experienced worker?	1 2 3 4 5
	14) Would you prefer to see people and machines in motion ?	1 2 3 4 5
Future Development	15) Would you prefer to hear sounds and noises inside the worksite?	1 2 3 4 5
	16) Would you like to be able to grasp and use worksite objects?	1 2 3 4 5

Suggestions

Fig. 2: Scheme of the VR training session evaluation questionnaire administered to the trainees

In addition to the data collected in active form through the questionnaires, an algorithm for recording the position of the worker in the virtual reproduction of the worksite was integrated into the VR training experience applications. In this way, during the training experience, with an acquisition frequency of 1 time per second (1 Hz), the coordinates of the worker's position are recorded in relation to both the work spaces designed for the simulated construction activities, and in general in his movement within the construction site, so that his aptitude for recognising risk areas can be assessed a posteriori at both the site and activity scales.

The interpretation of the movement traces acquired by the VR device during training in the form of sequences of points in the virtual space of the worksite was conducted by developing an additional analysis algorithm capable of reporting this information within the BIM model of the worksite and providing a graphic interpretation by means of heat-map visualisations. These visualisations allow the temporal dimension of the path followed by the worker in VR to be reported in a planimetric elaboration, distinguishing with different colours, in accordance with a pre-set gradient, the areas where the worker spent the longest time (violet, red) from those of short passage (green).

The tracking of the worker's position recorded during the VR activity simulation is done by visualizing the worker's use of space based on a temporal heat map, which consists of a 2D representation of the 3D position points recorded by the worker. The time dimension of the position tracked by the worker is graphically represented through a colour gradient (green to red), so that a red-coloured area represents a previously recorded position (red indicates a position occupied longer during the VR simulation). The heat map is then automatically generated using a custom algorithm specially developed by the authors.

Comparison of the generated heat map with the initial configuration of the workspace, in a BIM modeling environment, allows for early identification of possible planning errors; in fact, the results of the analysis of the obtained data are necessary for the next planning step, i.e., modification of the workspace configuration.

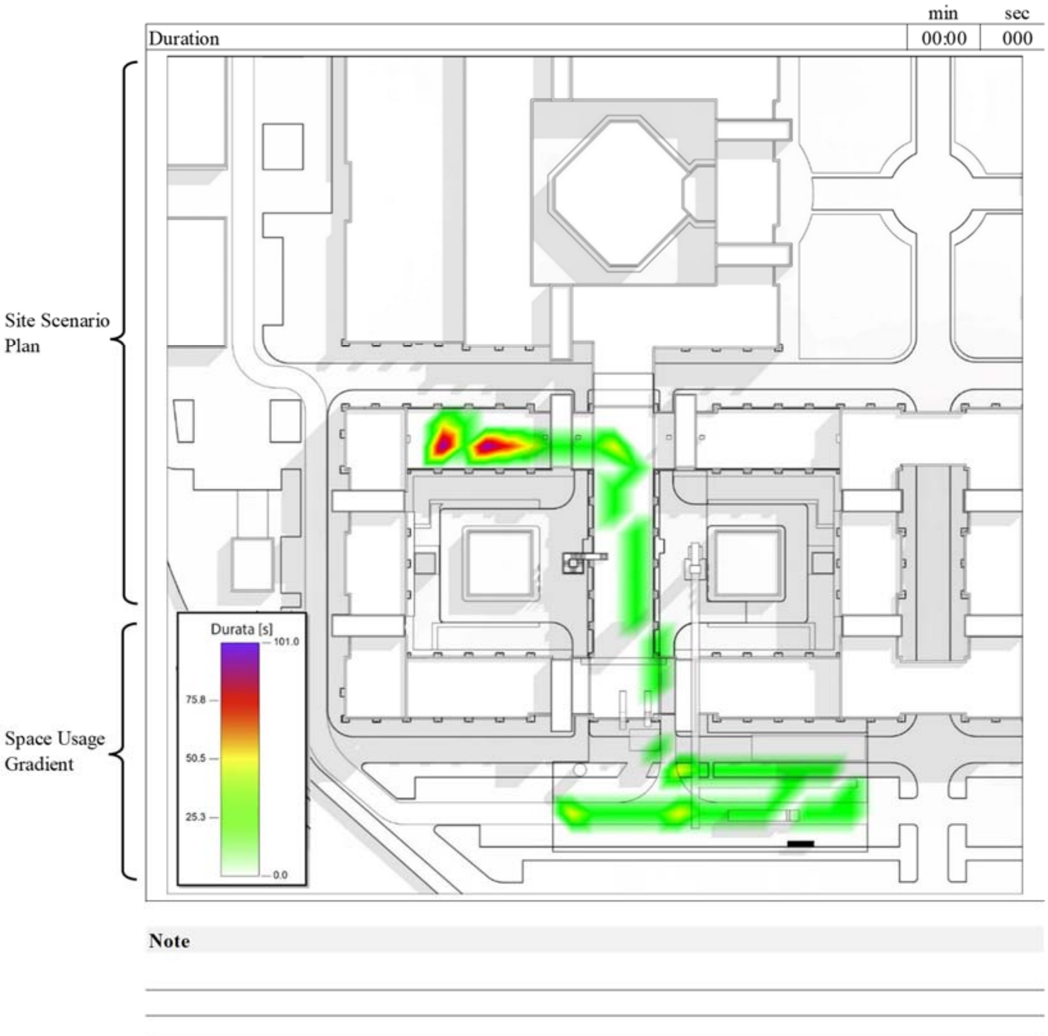

Fig. 3: Heatmap visualization (plan view) of the trainee usage of the virtual training environment

5. CONCLUSIONS

The present work, through implementation of an approach based on the integration of two main categories of data, with the overall objective of collecting a set of data from trainees experiencing immersive VR training to evaluate the effectiveness of the virtual experience, contributes to the development of a standardized method of evaluating the effectiveness of safety content transfer to workers that does not neglect the trainee's perceived effectiveness of the administered training and spatial understanding of the worksite scenario and activity in VR, as is the case with most of the methods proposed in the literature that are specific to individual case studies or applications and evaluate training based on an objective quantification of the trainee's ability to perform tasks in the VR environment.

The developed questionnaire, dedicated to evaluating both the immersiveness of VR experiences and the effectiveness of the safety content presented, and the proposed study on the benefits of tracking and visualization of learners' use of space in the virtual environment, allowed us to conduct an evaluation of safety training experiences in VR for construction workers, based on the integration of both a qualitative survey of the experience and the participants' spatial tracking data. Spatial tracking of trainees and their movement in space during the VR simulation of work activities proved useful for the evaluation of trainees' spatial understanding of the VR safety training experience.

Finally, the proposed approach was validated within a case study previously developed by the authors in which the authors' goal was to draft a prototype protocol for the design and delivery of safety training to construction workers, based on an innovative and interactive learner-centred approach. That protocol was designed and then tested for validation in a construction project in Italy that served as a case study for the development of BIM-based construction worker safety training in VR. During that work, a total of 6 VR training experiences were developed for workers, the contents of which consisted of the 3D models needed to reproduce the construction site scenario of the case study in the first 3 phases of construction: site set-up, installation of the external staircase and erection of the tower crane. At the same time, 4 training days were organized, during which the results of the proposed questionnaires were collected with reference to the different VR experiences carried out.

During and at the end of each VR training session of the 6 different site phases implemented, the worker undergoing the experience was asked to fill out the questionnaire developed to provide input and opinions on the work environment they were in, for the evaluation of the session, in order to enhance the experience and collect useful data for the development of subsequent implementations. The results obtained from the above evaluation and the discussion of the related case study previously mentioned will be the subject of further publication.

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