INTEGRATING SPATIAL TRACKING AND SURVEYS FOR THE EVALUATION OF CONSTRUCTION WORKERS' SAFETY TRAINING WITH VIRTUAL REALITY

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SUMMARY*: This paper addresses the absence of standard frameworks and methods for evaluating the effectiveness of Virtual Reality (VR) safety training for construction workers, which hinders its recognition by policymakers and hence its widespread adoption from the industry. To achieve this goal, the study introduces an original two-fold evaluation method centered on the trainees. First, a dedicated questionnaire is developed to assess the immersivity of VR experiences and the efficacy of safety contents' presentation as perceived by the trainees. Second, dedicated algorithms are developed and implemented to record the trainees' positions in the virtual environment and visualize them in form of spatial tracks and heatmaps in a BIM environment. This combined methodology is applied for the evaluation of a VR safety training campaign carried out for case study project involving three training sessions and 12 workers. The case study application demonstrates the feasibility of integrating trainees' subjective feedback with their objective use of the virtual space and the effectiveness of the proposed evaluation approach for the assessment of VR safety training experiences. The insights obtained from both the considered data sources are provided with a focus on the emerged directions for the improvement of the implemented VR safety trainign protocol. Eventually, the study limitations are discussed and the potential integration of additional physical tracking devices is proposed to enhance the granularity of the trainees' objective data considered in the VR training evaluation.*

KEYWORDS*: Virtual Reality (VR), Construction workers, Safety training, Evaluation, Spatial tracking, Heatmap visualization, Survey.*

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1. INTRODUCTION

Despite the constant enhancements and innovations applied to workforce health and safety (HS), construction still stands as one of the most dangerous industries due to the complex nature of construction sites and activities and the sheer number of concurrent hazards to which workers are continuously exposed (Rodrigues et al., 2022). There were 5,486 fatal work injuries recorded in the United States in 2022, a 5.7-percent increase from 5,190 in 2021 (US Bureau of Labor Statistics, 2022), and 3,347 fatal accidents at work in the EU during 2021, a decrease of 11 deaths compared with the year before; among them, more than a fifth (22.5 %) of all fatal accidents at work in the EU took place within the construction sector (Eurostat, 2021). These figures capture the gravity of this social and economic burden and have motivated increasing research efforts to improve HS in construction through the application of digital technologies and innovations.

In this regard, promising results are brought by the growing adoption of Building Information Modeling (BIM) and immersive Virtual Reality (VR) in the construction design and planning phase. In fact, the availability of information-rich BIM models of construction sites enabled real-scale virtual navigation of as-planned scenarios, effectively supporting HS managers in the early identification and mitigation of risks (Kim et al., 2020; Zhu et al., 2022). Moreover, the adoption of VR simulations of site layouts and activities has long been recognized beneficial for construction workers' training (Sacks et al., 2013) and extensive contribution has recognized its ability to improve the transfer of project-specific safety contents and preventive procedures, while increasing trainees' awareness of hazards in later real-site work conditions (Getuli, et al., 2020; Jiang et al., 2022).

However, despite more than a decade of successful research applications and industry cases, the adoption of BIM-enabled VR experiences for construction workers' safety training is still confined to a minor share of early adopters (Afzal and Shafiq, 2021; Babalola et al., 2023). While economic and skill barriers are progressively reducing, the lack of standardized frameworks and methods for the evaluation of the effectiveness of construction site VR training still stands as a major obstacle to its recognition from policymakers and hence for their large-scale adoption in the industry.

Several contributions have quantified the trainees' ability to perform cognitive and practical tasks in the VR environment to objectively assess the training effectiveness, such as for risk identification (Yoo et al., 2023), activity simulation (Adami et al., 2023; Jelonek et al., 2022). Likewise, further studies focused on the acquisition of the trainee's posture during VR-simulated working activities to assess the ergonomic performance of equipment and assembly procedures in construction applications (Anifowose et al., 2022) as well as in other industries. In fact, especially in manufacturing scenarios, the repetitive nature of the work tasks makes the ergonomic assessment of the workplace design a core requirement for which VR activity simulations and worker's position tracking tools have been implemented (Grajewski et al., 2013; Makarova et al., 2015). Nonetheless, the integration of objective parameters and subjective trainees' feedback for the evaluation of VR safety training effectiveness is still scarcely investigated.

This paper extends a previously presented concept of a novel approach for the evaluation of the effectiveness of VR safety training experiences for construction workers based on the integration of trainees' subjective perception and objective VR spatial use tracking (Getuli et al., 2023; Hajirasouli et al., 2023). The former is collected through a questionnaire with Likert-scaled close-ended survey items administered to the trainees after the experience. The latter consists in the spatial tracking of trainees' position in the VR environment and its visualization in form of a heatmap in a BIM environment to understand the trainees' use and perception of the virtual construction site scenario. The demonstration of the proposed approach was carried out with a case study developed contextually with a campaign of prototypical VR training experience for construction workers within a long-standing framework for the planning, management and administration of HS contents with BIM and VR, published by the authors in previous contributions (Getuli et al., 2020a, 2020b, 2018, 2021; Getuli and Capone, 2018).

The article is structured as follows. Section 2 presents a selection of works related to the adoption of BIM and VR technologies for construction workers' safety training and their effectiveness evaluation and concludes with the standing open issues that motivated this work. Sections 3-4 describe the research framework and methodology adopted for the development of the two-fold approach for the qualitative subjective data collection (questionnaires) and quantitative trainees' spatial tracking in the virtual environment which are described in detail in Section 5. Then, the case study demonstration of the approach is presented in Section 6. The results of the data collected for three training sessions, involving 12 workers are discussed to highlight the potential benefits in terms of training effectiveness assessment according to the proposed approach. The conclusions and limitation of this work are finally presented in Section 7.

2. RELATED WORKS

The use of mixed and immersive visualization technologies for safety training is receiving increasing attention in the construction industry. In the last decade, virtual and augmented reality has been successfully applied in various disciplines and for different purposes throughout the whole project lifecycle, such as design review and communication (Johansson and Roupé, 2024), stakeholder engagement (Davila Delgado et al., 2020), education and training (Ding and Li, 2022; Proboste Martinez et al., 2024), facility maintenance and operation (Agostinelli and Nastasi, 2023). In this context, the adoption of immersive VR for workforce safety training, with scenarios based on construction site layout and activity simulation, is one of the most interesting use cases for both research and industrial applications because of the potential benefits provided in terms of safety content transfer, increased trainees' involvement, and the minimization of risks and costs associated with the exposure to real hazards in on-site construction training (Babalola et al., 2023).

In this section, it is first provided an overview of the state-of-the-art applications of immersive VR for workforce safety training with a particular focus on those employed in the construction sector. Then, methods and techniques adopted in related works for the evaluation of the trainees' satisfaction and the assessment of the training sessions' effectiveness are presented. Eventually, the standing open issues hindering a broader adoption of immersive VR for construction workers' safety training are presented along with the factors limiting the assessment of VR training sessions' effectiveness, and hence their recognition and acceptance for practice.

2.1. Immersive Virtual Reality for construction workers' safety training: drivers and barriers

In the last decade, the exponential growth of services and applications of VR offered by the gaming and entertainment industry lowered the costs and favoured the spread of this technology for professional purposes. In the Architecture, Engineering, Construcion and Operation (AECO) sector, the hardware and software necessary to explore projects' models and data through immersive virtual experiences are not confined to experimental setups anymore and are becoming accessible to practitioners. However, affordable VR headsets and platforms alone would not be sufficient to justify this trend. In fact, the increased adoption of BIM and the related availability of 3D models enriched with semantic information stands as a fundamental enabling factor. Regardless of the specific discipline or use case, BIM-to-VR workflows relys on the accurate geometrical representations and information contained in BIM models to build the immersive virtual environments that are subsequently experienced by the stakeholders.

One of the most relevant areas of application of VR in construction is HS management and workforce training. The integration of BIM and VR offers enhanced visualization and simulation capabilities of real site conditions that proved to be effective for developing, communicating, and implementing site safety plans compared to 2D drawings (Azhar, 2017). VR-supported design review sessions allow users to identify HS issues earlier and to address them more effectively (Babalola et al., 2023). Worforce training for assembly sequences (Anifowose et al., 2022), work procedures (Obukhov et al., 2023), and construction activities, and advanced planning (Muhammad et al., 2020) can improve productivity on construction sites.

It is acknowledged that BIM models can be used for multi-dimensional representations of construction site layouts from which relevant data can be extracted to optimize spaces and activities (Tao et al., 2022), while automated safety rule checking can simplify hazard recognition and evaluation, as well as risk assessment (Kim et al., 2020; Zhang et al., 2013, 2015). In turn, the enhanced spatial understanding and contextual information provided by BIM site models can be leveraged to transfer project-specific knowledge with the implementation of VR site scenarios dedicated to workers' safety training and site planning sessions (Getuli et al., 2020a, 2020b, 2018). Likewise, immersive virtual environments are not useful only for practitioners, but also for educational purposes with very promising results compared to traditional methods (Castronovo et al., 2023). BIM-enabled VR applications offers AEC educators innovative and engaging tools that put students at the centre of their learning experience (Alizadehsalehi et al., 2021; Esfahani and Mari, 2023).

For the reasons discussed above, the integration of BIM and immersive VR provides an ideal tool for safety training in the AECO sector. However, as highlighted by (Li et al., 2018), existing gaps related to technical features, application domains, safety scenarios, and evaluation methods are hindering its broader adoption. In particular, with most studies focusing mainly on the development of VR-based safety training applications, there is still a lack of consensus on the methods to be applied for the assessment of their effectiveness.

2.2. Evaluation of VR safety training for construction workers

VR-based safety training is acknowledged to be more engaging for trainees over traditional methods (e.g., slides) and hence more effective in safety content transfer (Afzal and Shafiq, 2021; Getuli et al., 2021; Proboste Martinez et al., 2024; Sidani et al., 2022). However, the recognition of a standard method for the evaluation of the effectiveness of VR immersive construction site simulations is still missing. Most of the proposed methods (Obukhov et al., 2023; Shringi et al., 2022) are specific to individual case studies and applications, and often overlook the trainees' perceptions and their spatial understanding of the VR worksite scenario and activity. For the assessment of trainees' experiences in immersive virtual environments two main methods can be adopted: qualitative approaches which take into account trainees' subjective feedback reported via interviews or questionnaires (Obukhov et al., 2023; Shringi et al., 2022); quantitative approaches, instead, which measure and interpret objective data resulting from the observation of the trainees during the experience, e.g., eye-tracking (Das et al., 2020); brain activity measurements (Hertweck et al., 2019).

Concerning the former, several survey methods, including Likert-scale questionnaires and interviews with the trainees comprising both close- and open-ended survey items, have been proposed to evaluate various aspects of the VR experience, from the usability of the user interface (Johansson and Roupé, 2019) to the perceived effectiveness of different training modes (Lee et al., 2023). Questionnaires are widely used to collect user feedback and investigate their perceived VR experiences (Grundling et al., 2022; Robinson, 2018). They can be used as pre/post-assessment methods or even real-time. However, regardless the moment when they are administered, it is important to consider the influence of the type of questionnaire on the user experience (Safikhani et al., 2021).

On the other hand, several applications in the manufacturing and construction industries proved the importance of the observation and measurement of objective trainees' features during VR experiences for the enhancement of ergonomic, safety and productivity of work activities. A previous work from the authors demonstrated how the spatial tracking of trainees during the exploration of VR construction site scenarios and activities can inform the modification of safety plans and procedures (Getuli et al., 2020b). With a focus on the ergonomic aspects of the work procedures for the manufacturing sector, other studies demonstrated the effectiveness of VR simulations of assembly lines to optimize the human-machine interaction (Caputo et al., 2018; Stefania et al., 2017). Workplace-related working postures and activities can be evaluated through reliable and repeatable measures of workers' position tracking during VR simulated scenarios (Caputo et al., 2019; Caputo et al., 2018; Michalos et al., 2018). Likewise, monitoring and acquisition of trainees' objective data during the experienced VR training sessions could be exploited to gain insights on their use of the virtual space and understanding of the training scenario.

2.3. Open issues

Integrating BIM and VR for the development and administration of immersive experiences that enable the navigation of accurate reproductions of construction site scenarios and the interaction with the simulated activities is acknowledged as one of the most promising perspectives for the enhancement of construction workers' safety training. However, the lack of standardized methods for the evaluation of their effectiveness in terms of safety contents' transfer and user self-efficacy perception still stands as a barrier for their recognition from policy makers and therefore for their broader adoption for practice.

Several of the documented evaluation methods are limited to specific case studies and applications and assess the effectiveness of VR training on the mere quantification of the trainees' ability to perform tasks in the VR environment, while neglecting their subjective perception of learning efficacy and spatial understanding of both the site scenario and the worksite activity. Moreover, the tracking of trainees' use of space during VR simulation of work activities was shown to be useful for different purposes, from the ergonomic evaluation of workstations and work sequences to the optimization of site spatial planning and safety procedures, but the insights that this objective data could provide is still mostly neglected for the evaluation of VR safety training effectiveness.

To address these issues and to foster the broader adoption of BIM-based VR for workforce safety training in the construction sector, this paper proposes a novel approach for the assessment of these experiences based on the integration of objective (trainees' spatial tracking) and subjective (questionnaires) data. In the following paragraphs, the developed approach is collocated within the original authors' framework for the development, management, and administration of VR safety training in construction and the results of its prototypical implementation are discussed.

3. RESEARCH FRAMEWORK

This paper presents part of the results of an ongoing research effort of the authors aimed to increase safety performance on construction sites through the adoption and integration of BIM and VR technologies for workers' safety training. In this section, it is first presented the collocation of this study within the broader research framework previously conceptualized in (Getuli et al., 2018), and then developed in (Getuli et al., 2020c). Afterwards, it follows the discussion of the methodology adopted for the development and case study validation of the novel approach for the evaluation of VR safety training effectiveness based on the integration of trainees' objective (i.e., spatial tracking) and subjective (i.e., questionnaire) data introduced in (Getuli et al., 2023).

In Figure 1 the adopted reference framework is reported. Its ultimate goal consists in delivering project-specific VR training sessions that are based on the accurate virtual reproduction of the physical assets to be constructed along with the planned activities, construction site's configuration, and associated specific risks and safety procedures. Therefore, the first step regards the acquisition of the federated BIM model of the project with all the relevant information contained in the coordinated disciplinary models (e.g., architectural, structural, MEP, etc.). On this basis, the different configurations of the site layouts and the sequence of the activities are planned and delivered in the 4D BIM that shall drive the development of the VR training scenarios. For this purpose, the model shall include the representation of the planned activity workspaces and all the relevant site objects (e.g., machinery, equipment, etc.) provided of their 3D geometries and safety data (Getuli et al., 2021; Getuli and Capone, 2018). In the third step, based on the information and construction schedule contained in the 4D BIM, the HS manager plans the VR training sessions. Each virtual scenario corresponds to a construction site layout and set of activities considered relevant for safety purposes and include the information necessary for the development of different training typologies, i.e., layout-oriented, component first assembly, and emergency management (Getuli et al., 2020a). For each scenario, the correspondent BIM contents are then transferred to a game engine environment (e.g., Unity) for the development of the VR training sessions. In this phase, the features which allows the trainees to navigate and interact with the VR environment are implemented and part of the static BIM contents are replaced with dedicated objects enriched with multimedia contents (e.g., audio, animation, etc.) (Getuli et al., 2021). Eventually, the VR training deployed for Android mobile VR devices and is administered to construction crews in supervised collaborative sessions in which, in turns, the individual experience of each trainee is projected and shared to the other attending members of the crew, fostering discussion and awareness of safety procedures.

This work aims to complete the framework described above by providing a method for the collection of trainees' subjective feedback and objective data for the assessment of VR training effectiveness. The former consists in the administration of a questionnaire to the trainees for the evaluation of four areas of the experience, namely immersivity, contents' effectiveness, training experience's effectiveness, and future developments. The responses, provided according to a Likert scale are analyzed for the evaluation of the experience, the assessment of the trainees' self-efficacy and for the discovery of hidden issues in the training contents or execution.

For the objective data, the tracking of the trainees' position in the VR environment is performed during the training experience and subsequently returned in the BIM environment in form of a heatmap showing the prevalence of trainees' presence in the construction site scenario. This allows a granular spatial understanding of the trainees' use and perception of the planned site configuration. The evaluation of both objective and subjective trainees' data enables the assessment of the VR training effectiveness and informs the HS manager on the need for either the modification/addition of training scenarios or the improvement of training contents and interaction. Moreover, although outside the scope of the present paper, the evaluation of the trainees' use of the virtual space can be used to elicit their operational knowledge and adjust possible hidden issues in construction site plans (Getuli et al., 2020b).

4. METHODOLOGY

In in Figure 2 the methodology adopted to develop and implement the proposed approach for the evaluation of VR safety training experiences is reported. The evaluation purpose is twofold: assess the effectiveness of the VR experience from a trainee perspective (e.g., immersivity) and identify weaknesses and strengths to cyclically improve the development of VR training experiences.

The initial stage regarded the development of the tools for the data collection, including a post-experience evaluation questionnaire, for trainee's subjective feedback, and a suite of algorithms for the real-time recording of the trainee's position in the VR space to be subsequently visualized in a BIM environment.

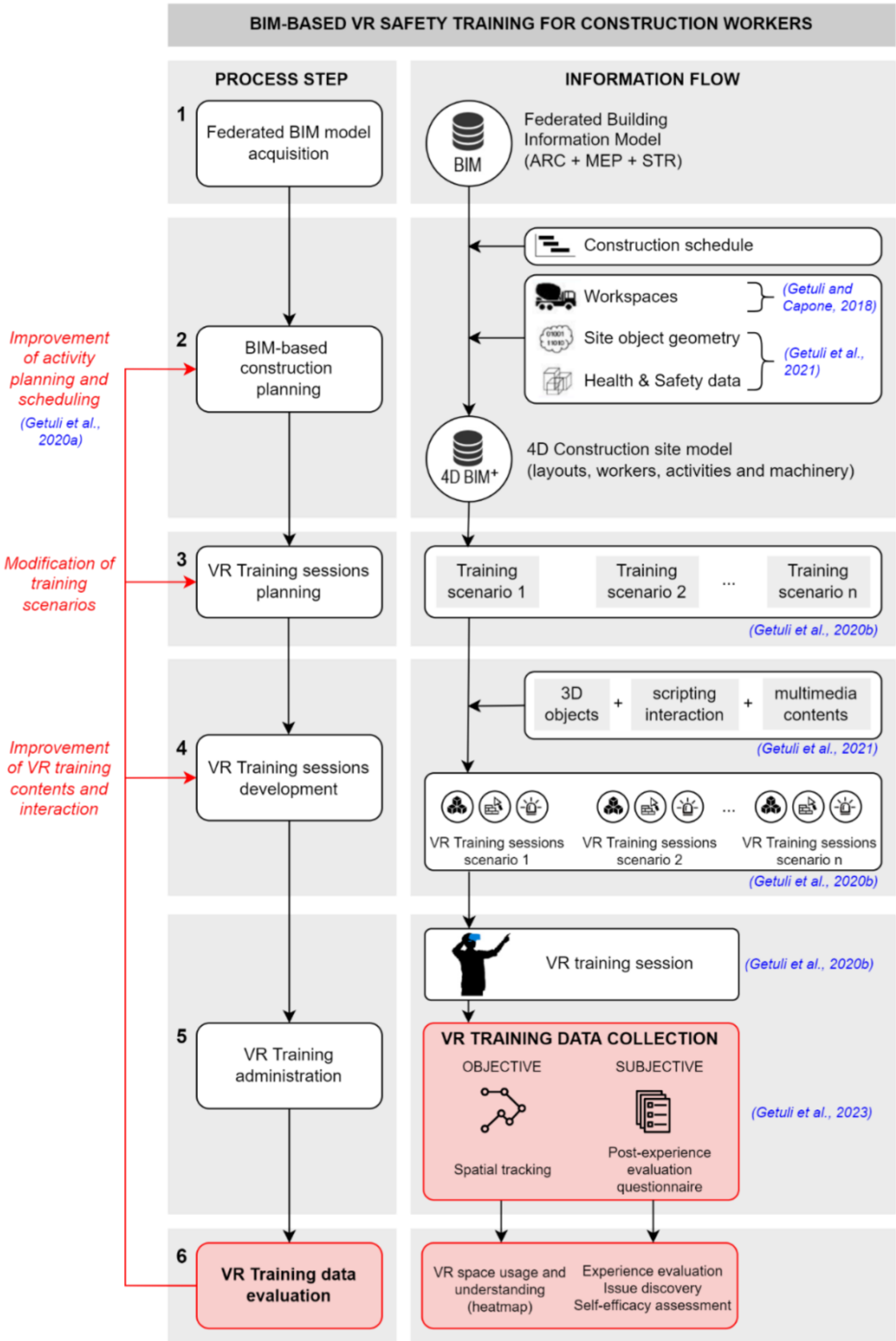


Figure 1: BIM-based VR safety training implementation framework with training data collection and evaluation.

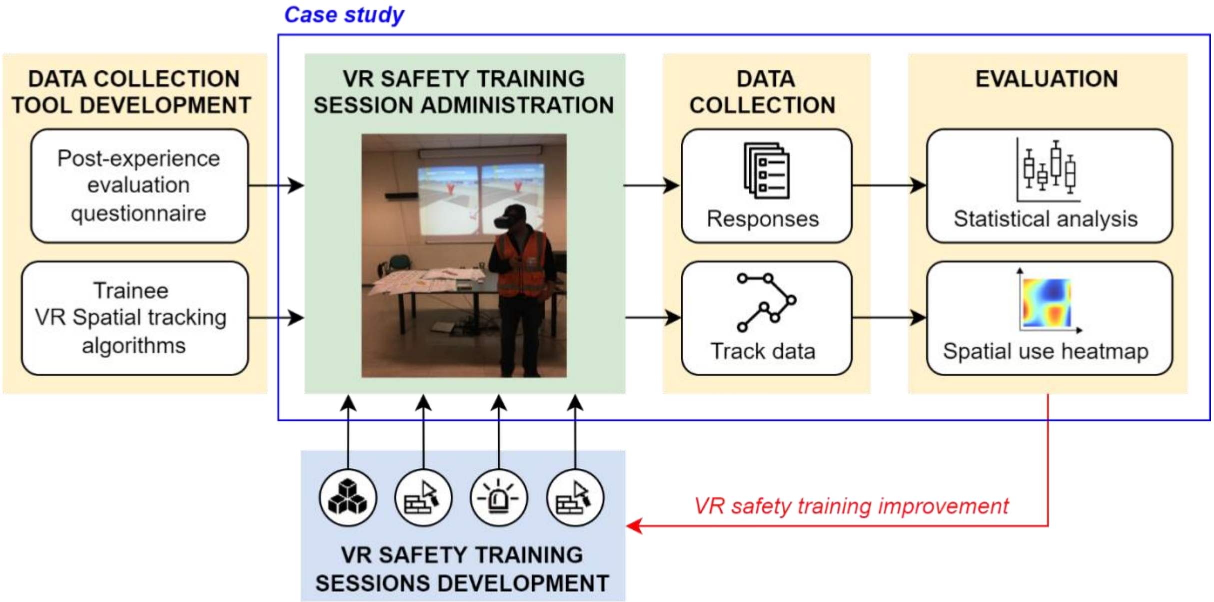


Figure 2: Research methodology.

The development of the questionnaire (see Section 5) was carried out according to the following three steps:

- *Identification of the areas of inquiry* – A review of the literature on existing VR construction safety training applications and assessment questionnaires was carried out, leading to the identification of four areas of inquiry serving our evaluation purpose: immersivity, contents' effectiveness, training experience's effectiveness, and future developments.
- *Implementation of survey items* – Considering the identified areas of inquiry, a total of 16 items was defined. For the responses the Likert scale method was chosen due to three main benefits, namely: *quantifiable responses*, allowing for the quantification of qualitative data and enabling the statistical analysis of the responses across different variables or groups; *adaptability*, in terms of the number of response options and the wording of the statements; and *ease of interpretation*, with higher scores usually associated with stronger agreement, satisfaction, or endorsement of a particular statement, hence improving the reliability of the data collected.
- *Validation of implemented survey items*: Before proceeding with the administration of the questionnaires, the defined survey items were validated by inviting feedback from fellow experts who had not participated in their development. All the implemented items were considered unambiguous and leaving no room for interpretation. During this internal validation round, it was deemed necessary to implement an additional open-ended field to the questionnaire in order to collect also unstructured trainees' opinions and observations.

For the recording of the trainees' position in the VR space and its subsequent restitution for evaluation in a BIM environment (see Section 6), the approach developed and discussed in (Getuli et al., 2020b) was adopted. In this paper, an overview on the functions of the custom algorithms developed and implemented in both the VR application and the chosen BIM authoring environment is provided, acknowledging that the technical details are addressed in the aforementioned contribution.

In the dedicated VR applications, a specific routine is embedded to collect the trainee's 3D coordinates at 1 Hz frequency and to store them locally on the mobile device as an ordered list of 3D points at the end of the training experience.

During the evaluation phase, the file containing this spatial track is imported and visualized in the 4D BIM as both a polyline and a heatmap overlayed in plan views of the construction site layout correspondent to the training scenario. In the developed approach Autodesk Revit is used as BIM authoring and visualization environment and Autodesk Dynamo for the implementation of the algorithms that import, process, and return the collected trainee's track into the BIM model.

The implementation of the developed questionnaire and VR spatial tracking tool was demonstrated as described in Section 6 on a set of three VR training sessions related to a case study project which involved a total of 12 workers from two companies.

The distribution of the responses to the questionnaire items were considered both singularly and grouped for area of inquiry, and their values have been reported in a boxplot chart for evaluation and discussion. Instead, the recorded spatial track and related heatmaps overlayed on the construction site plans in the BIM environment were manually reviewed and analysed to understand how the trainee had used the virtual space. The higher time spent in unexpected areas would suggest either an unforeseen salient location for the trainee or a place where he encountered issues with the required task or with the control system that need to be addressed in the further developments. On the contrary, less or no time spent in areas of the scenario deemed important for training purposes would point out the need for improving the visual clues which allow the training autonomous execution. The discussion of the results obtained in the case study demonstration is reported below and considered both to validate the evaluation approach and to inform the future steps the authors' ongoing research.

5. VR SAFETY TRAINING EVALUATION APPROACH: DATA AND TOOLS

This section discusses the information and the data acquisition tools for the evaluation of VR safety training sessions centred on the trainees' experiences introduced in (Getuli et al., 2023; Hajirasouli et al., 2023) that were implemented and demonstrated with a case study application in this work. The proposed approach leverages two distinct categories of data collected from the trainees (see Table 1): subjective feedback and objective positions in the VR scenario.

The former is collected through the administration of a dedicated post-experience evaluation questionnaire, supervised by a training assistant, to each trainee after the execution of the VR training experience. The survey includes a preliminary set of identification data and demographics, functional to the organization and analysis of the responses, a set of 16 qualitative items with Likert scale to allow the quantitative analysis of the responses, and eventually an open-ended field for the collection of trainees spontaneous opinions about weaknesses and strengths or suggestions for further developments. The latter consist in the recording of trainee's positions in the VR environment throughout the experienced training session and its subsequent processing and visualization within the BIM model of the planned construction site layout in terms of both a spatial track, i.e., polyline orderly connecting the position points, and a planar heatmap visualization which highlights the locations where the trainee spent more time.

In the following paragraphs 5.1 and 5.2 the details of the implemented post-evaluation questionnaire and the spatial track and heatmap visualization tools are presented.

Table 1: VR safety training evaluation: trainee's data categories and tools.

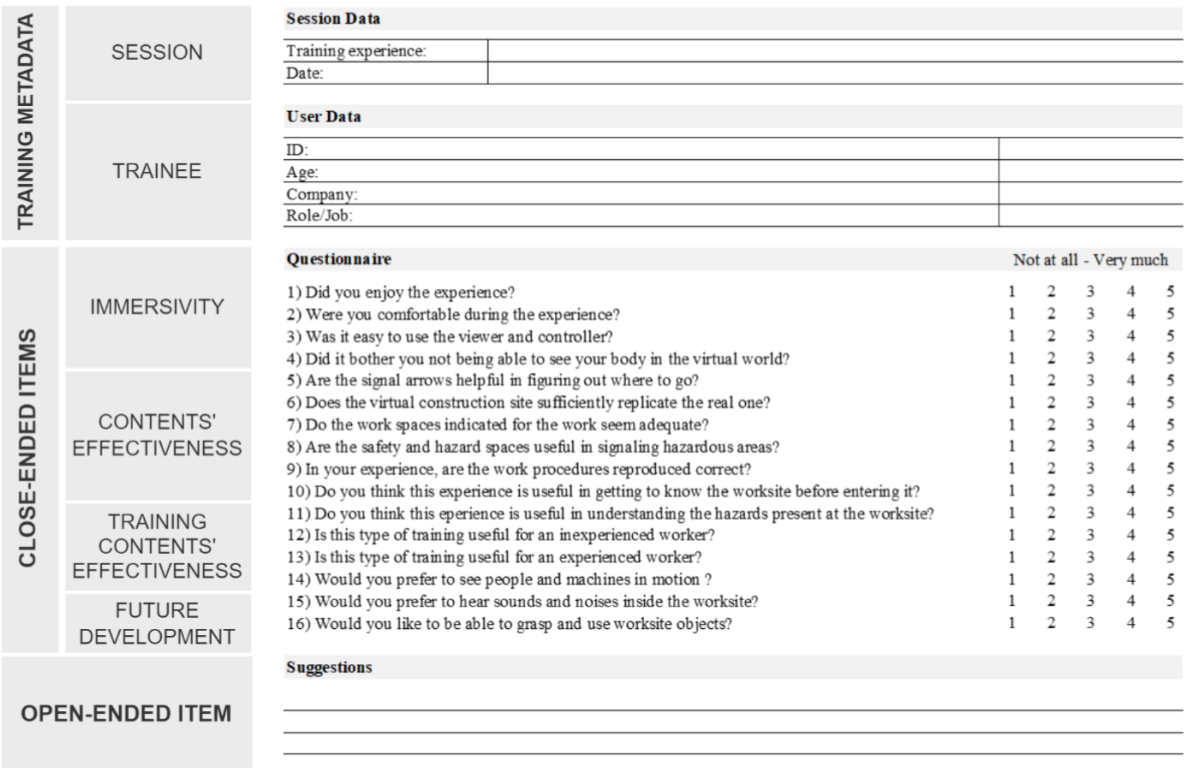
Data category	Tool	Data types / Inquiry area	Evaluation purpose
Subjective trainee's feedback	Post-experience evaluation questionnaire (Qualitative items, Likert scale)	ID & Demographics	Response clustering and analysis
		Immersivity	Sense of presence; VR scenario accuracy; motion sickness symptoms
		Contents effectiveness	Accuracy and efficacy of VR scenario elements
		Training experience effectiveness	Learning of site configuration, specific risks and safety procedures
		Future developments	Addition of new training contents, features, interaction capabilities
		Suggestions (open-ended questions)	Perceived strengths and weaknesses, further areas of improvements
Objective trainee's position	VR spatial track recording and processing algorithms	Trainee's spatial track	Exploration of the training scenario, presence in dangerous/forbidden site areas
		Trainee's temporal use of space (heatmap)	Presence (attention) distribution, site spatial planning assessment, identification of salient areas of the scenario or interaction issues

5.1. Post-experience evaluation questionnaire

The post-experience evaluation questionnaire, depicted in Figure 3, was implemented in this study in accordance with the presented methodology. Following each training session, participants were asked to complete a paper-based single-page survey form. A training assistant was readily available to support participants in comprehending the survey items, if needed. The form is structured into three sections and the survey items are tailored on the VR experiences developed and implemented in the training campaign described in the case study demonstration (see Section 6):

- *Training metadata*: Data necessary for the identification of the training session and the trainee. This includes the experience name (e.g., "CLT wall installation – Block B") and date of execution, trainee's ID (optional), age, company, and role.
- *Close-ended items*: These survey items are formulated in form of direct questions to be responded according to a 5-points Likert scale measuring the trainee's agreement from a minimum of "Not at all" (1) to a maximum of "Very much" (5). Questions 1-4 concern the perceived "immersivity" and the overall satisfaction of the trainee with the experience, the provided devices and the eventual occurrence of uncomfortable states or motion sickness symptoms. Questions 5-10 evaluate the "contents' effectiveness" both in achieving a plausible reproduction of the planned construction site environment and in supporting the scenario exploration with dedicated virtual objects (e.g., direction arrows, risk placeholders, interaction triggers, etc.). Questions 11-14 quantify the perceived "training contents' effectiveness" in support of hazard identification and in relation to the trainee's field experience. Eventually, questions 15-16 gauge the trainee's expectation towards the possible introduction of two features (i.e., ambient sounds, grasping site objects) not implemented in the experienced version of the VR training.
- *Open-ended item*: An open text field is provided at the end to collect spontaneous trainees' suggestions.

The survey responses are collected and treated anonymously and used only for the evaluation of the training experience. Trainees' demographic and organizational data enable the clustering of the results and gain insights that can be used to tailor the VR training future implementations based on the recipient age group, role, type of job and organization.


TRAINING METADATA – SESSION

Session Data

Training experience:

Date:

TRAINING METADATA – TRAINEE

User Data

ID:

Age:

Company:

Role/Job:

CLOSE-ENDED ITEMS

Questionnaire Not at all - Very much

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 CONTENTS' 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

OPEN-ENDED ITEM

Suggestions

Figure 3: Implemented post experience evaluation questionnaire.

5.2. Collection and visualization of trainee's spatial track

The collection and visualization of trainee's spatial track is performed with the approach and algorithms developed and demonstrated by the authors in their previous work (Getuli et al., 2020b). During the execution of the safety training application execution, a dedicated routine records the position of the trainee (i.e., 3D coordinates of the avatar's centroid) in the VR environment every second. At the end of the experience, the sequence of 3D points is saved and stored locally on the deployed mobile device and subsequently transferred to a dedicated server repository along with all the other track recordings of the training session. The collected tracks are then imported and processed with dedicated algorithms (i.e., Autodesk Dynamo) and visualized in a BIM environment (i.e., Autodesk Revit) in form of both a polyline connecting the recorded positions (track) and a heatmap (position prevalence) overlayed in plan views of the site model correspondent to the phase of interest. Afterwards, the plan views are exported in dedicated sheets (see example in Figure 4) and are eventually stored together with the questionnaires reporting the correspondent trainee's subjective feedback.

The visualization of the trainee's track enables controlling that the training experience was correctly and completely executed and that no relevant training areas have been left out or overlooked by the trainee. Moreover, the temporary passage of the trainee in areas exposed to specific risks (e.g., fall from height, struck, etc.) or with forbidden access can be easily identified and highlighted. In turn this occurrence, can stress either a deficiency in the planned and implemented site configuration, which could be later addressed updating the scenario, or a lack of understanding on the trainee's side which could lead to scheduling follow up training sessions.

Furthermore, the recorded trainee's positions are referred to the cells of a spatial grid overlayed on the construction site plan view and rendered with a coloured heatmap which synthesize the prevalence of time spent in different locations of the scenario, normalized to the value of the cell with the higher point count. This visualization enables the objective identification of the training tasks or locations of the scenario that were perceived by the trainee as more salient or that may present technical issues in the execution. The duration of the training experience and a blank space for trainer's notes complete the sheet.

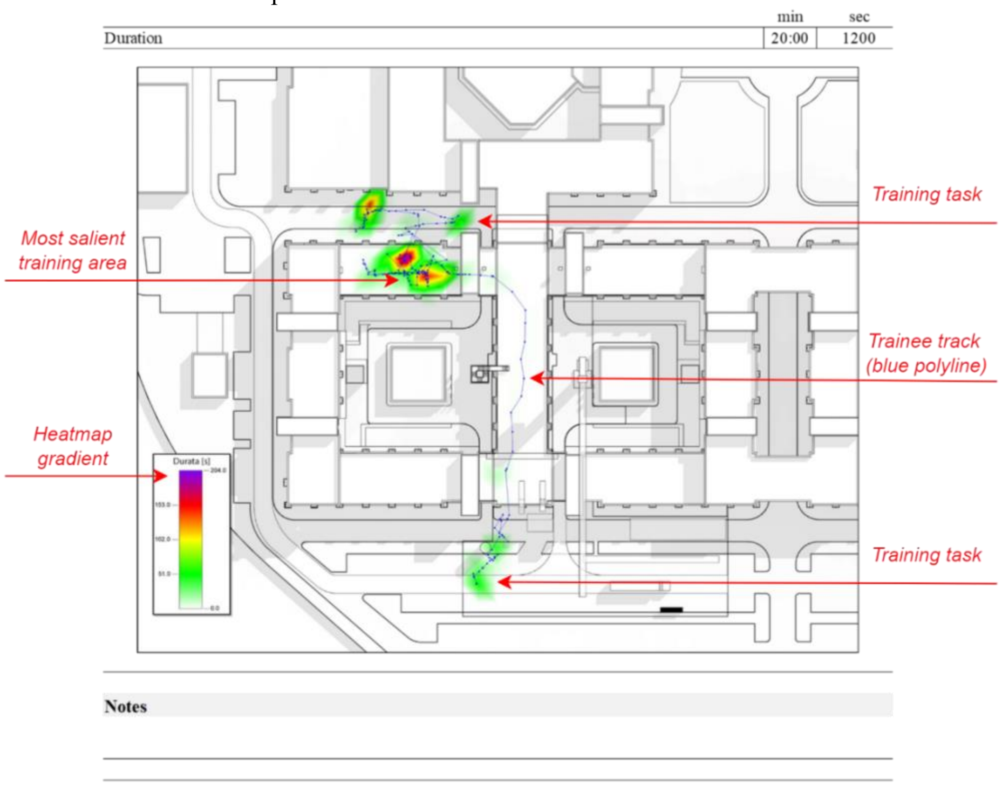


Figure 4: Example of trainee's spatial track evaluation sheet – Track and heatmap overlayed to the plan view of the construction site layout correspondent to the training experience.

6. DEMONSTRATION

6.1. Case study

The evaluation approach discussed in this paper was implemented in a pilot project regarding the construction of a new complex of three one-storey buildings with cross-laminated timber (CLT) structure atop an existing office facility in the city of Pisa, Italy, for which a BIM-based VR safety training campaign had previously been developed by the authors according to the implementation protocol described in Getuli et al., (2020a). A set of VR training sessions are used in the validation of the approach and its capacity to leverage both subjective and objective trainees' data to identify training's strengths and weaknesses and to inform further developments.

As showed in Figure 5, 12 post-experience questionnaires and spatial tracks were collected from 12 construction workers (i.e., trainees) during three VR safety training sessions. This comprised the implementation of a total of six VR training experiences administered in three different days according with the progress of the construction schedule. The first training session involved a crew of four workers employed by the contractor and appointed to the construction site installation (i.e., site facilities, plants, fences, signs, etc.). Each trainee had to navigate the VR construction site, getting familiar with its completed configuration and surrounding constraints, and witness the reproduction of the different phases of the procedure for the installation of the planned tower crane. The second training session regarded the installation of the main three CLT structural elements of the project, namely: wall panel, beam, and roof panel. Three VR experiences were administered to five specialized workers employed by the sub-contractor appointed for the construction of the CLT structure. Each experience was focused on the specific installation sequence and safety procedures to be followed for one type of element. Eventually, the last training session focused on the installation of two SKID system units on two distinct roof areas of the building. The existing site constraints determined different lifting sequences and safety procedures, therefore two training experiences were implemented and administered to the contractor's crew appointed for their installation.

All the training experiences implemented the same features (e.g., graphic detail, interaction, progress logic, etc.) and were deployed and administered on the same devices (e.g., mobile VR, Google Cardboard). Although the VR environment could be experienced directly by just one trainee at time, the members of the construction crew who were not directly involved in the training could witness the projected VR scenario (see Figure 5) and share their opinion with the trainee and the trainer, making the sessions collaborative. To reduce the recall bias, the post-experience questionnaire had been administered to each trainee at the end of their individual sessions by an assistant trainer.

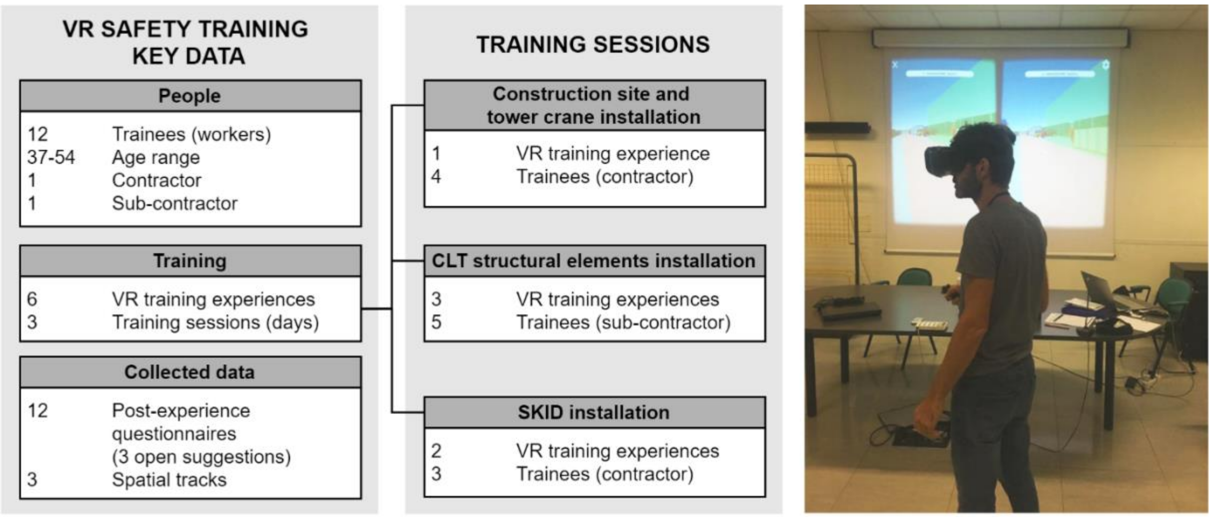


Figure 5: Case study VR safety training campaign: key data (left), training sessions (center), trainee during a VR training experience (right).

6.2. Questionnaire results evaluation

In this paragraph the analysis of the responses collected through the post-experience questionnaire previously discussed (see Figure 3) are reported.

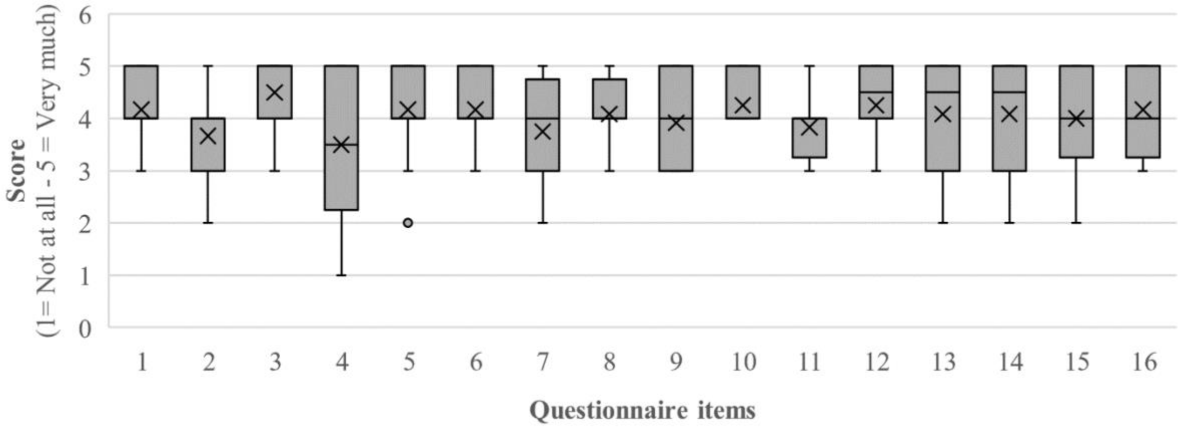


Figure 6: Post experience questionnaire: Response score distribution per item (boxplot, X representing mean value).

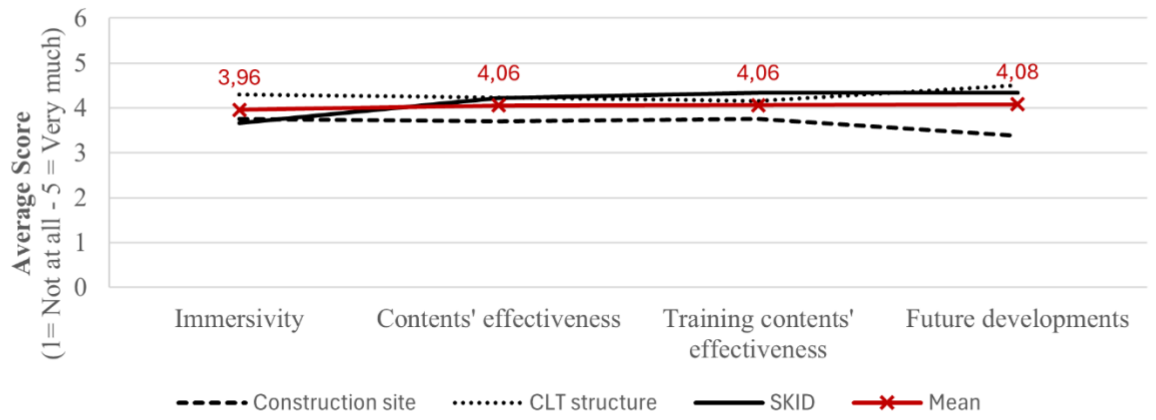


Figure 7: Post experience questionnaire: Training type average response score per inquiry area.

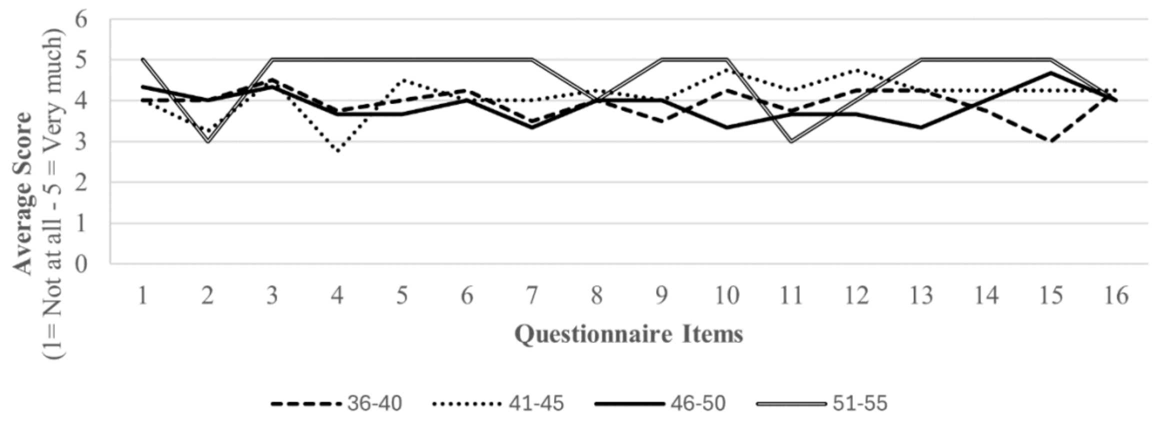


Figure 8: Post experience questionnaire: Age group average response score per item.

The aggregated response score distribution for each questionnaire item (Figure 6) and the mean score per inquiry area (Figure 7) confirms the expression of a general satisfaction for the VR training experiences, with an average responses comprised between 3,96 and 4,08 in the adopted 5-point agreement Likert scale.

In relation to the training *immersivity* (items 1-4), the experiences were perceived as engaging and easy to perform despite the trainees' lack of familiarity with VR technologies. Interestingly, a clear indication regarding the ability to see first-person the reproduction of once own body in the VR environment (not currently implemented) did not emerge (item 4). On one hand, this confirms the validity of training experiences based on the VR scenario exploration. Conversely, the preference for a more embodied experience leaning towards the direct execution of tasks by the trainees in a more sensory-rich environment returns also in the *future developments* area (items 15-16) with an average preference for the introduction of the acoustic dimension (e.g., sounds and noises) to the scenario and the ability to grasp and use worksite objects and (not currently implemented).

Concerning the evaluation of the virtual elements reproducing the construction site scenario and activities - *contents' effectiveness* (items 5-10) – the trainees' perceived the objects (i.e., arrows) used to guide the navigation useful and the construction site reproduction credible despite the graphical limitations of the adopted devices and the approximative geometries and materials derived from construction site BIM objects. Moreover, the reproduction of the activities (e.g., CLT wall panel installation) in their different macro-phases, the visualization of the planned workspaces (i.e., using transparent coloured volumes), and the signalling of specific risks by mean of dedicated virtual placeholders was considered correct and effective by the trainees in anticipating the real construction site work conditions. This evidence suggests that the implementation of virtual object in the training experience is not a detrimental distraction but supports the autonomous navigation of the scenario and enhance the transfer of safety contents to the trainees.

Most importantly, a positive outcome was achieved also in the key inquiry area related to *training contents' effectiveness* (items 11-14). While the experience was perceived useful for identifying and understanding the hazards present at the worksite, a slightly stronger agreement on this item is observed when the training is intended for an inexperienced worker. In this regard, a possible expert bias should be considered since all the trainees that participated in the study had more than a decade of work experience. Nonetheless, to better reproduce the construction site working conditions, a preference for a more dynamic scenario including moving people and machines (not currently implemented) was expressed and represents valuable feedback for further implementations.

Aggregating the results by training session and inquiry area (Figure 7), although with minimal deviations from the mean average score, emerges how the training related to the construction site and tower crane installation underperformed respect to both sessions related to installation of the CLT structure and SKID units. This reflects the more "static" nature of the first training session and suggests that experiences where the trainees get to be closer to specific construction activities perceived as more salient for the project outcome results as more engaging.

Moreover, given the lack of familiarity with VR technologies and immersive training experiences of all the participants to the study, the possible impact of the trainees' age was investigated analysing the distribution of the responses according to four age groups – 36-40, 41-45, 46-50, 51-55 - as showed in Figure 8. Especially, leaving out the last age group (51-55) which accounted for just one participant, no significant difference (minor than 1 point on average) can be noticed throughout the questionnaire's items.

Eventually, the following four open-ended suggestions were collected from four different trainees, all addressing aspects of the experience which were not explicitly considered in the inquired items:

- reduction of the walking speed of the trainee avatar in the VR scenario;
- implementation of a simpler, smoother, and clearer transition between previous and following phases of the represented construction activities, currently instantly switching at the activation of a dedicated VR trigger-object;
- introduction of more animated entities (e.g., machines, workers) and dynamic interaction with the site objects;
- introduction of the possibility to experience or visualize the outcomes and damage caused by incorrect operations or ignoring safety procedures (e.g., fall from height).

All these suggestions provide valuable insights which the authors will considered to reduce possible trainees' discomfort (i.e., walking speed) and frustration (i.e., disorienting training phase switch), and enhance their engagement (i.e., more interactive VR environment) in further developments.

6.3. Spatial tracks and heatmaps evaluation

In this paragraph the insights provided by the interpretation of the collected trainees' spatial tracks and heatmap visualizations are discussed. In Figure 9, a sample of the results of one training experience for each training session is reported. From the analysis and visualization of the collected spatial tracks emerged that, despite different training experiences focusing on different tasks and areas of the scenario, all the trainees were able to identify and avoid entering areas exposed to specific risk or for which they did not had have access clearance. In this regard the adoption of dedicated virtual objects (e.g., risk placeholders) proved to be effective in conveying the safety information, easy to spot and understand, and supportive to the scenario navigation. Moreover, the contextualization of the track within the construction site plan resulted useful to identify unforeseen shortcuts taken by the trainees in the navigation of the scenario and evaluate their solution where it was deemed necessary.

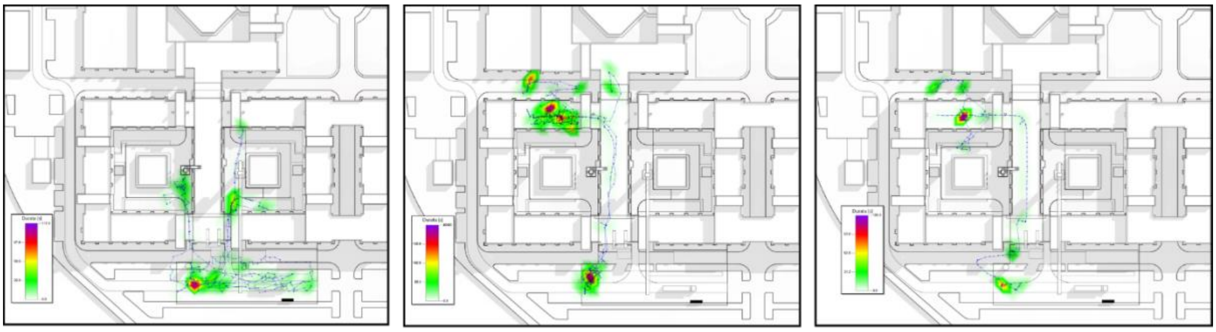


Figure 9: Trainees' spatial tracks and heatmaps samples: (left) construction site and tower crane installation; (center) CLT beam installation; (right) SKID system unit installation for Block A.

However, for longer training experiences with a large quantity of acquired trainee's positions, the visualization of the spatial tracks alone, especially in areas with a high density of points (i.e., longer trainee's permanence), results difficult to interpret. For this reason, the list of collected trainees' positions are further processed into a heatmap visualization which renders the cells of a grid distribution of 1,00 x 1,00 meters according to a normalized color gradient (e.g., from transparent for cells with no points to purple for the cells with highest point count). The comparison of all the different heatmaps generated after the training experiences confirmed a coherent distribution of the time spent by the trainees in the areas of the scenario with more salient training contents (e.g., training task). Furthermore, the presence of areas with minor (green to yellow) and major (yellow to purple) observed saliency suggests that the trainees tend to focus on the most salient task of the training experience, paying less attention to the remaining construction site configuration and side activity exploration. In turn, this should be considered for further developments of the tested VR training experiences, especially for those intended to make the trainees aware of the construction site planned configuration.

Nonetheless, the relatively high amount of time spent by the trainees staying still or slightly moving from the starting position of each training experience while getting used to the VR environment and movement control system tended to equal and sometimes exceed the time spent in salient training locations, affecting the quality and reliability of the generated heatmap. Further developments should provide the possibility to record or process the trainees' positions such as to identify and filter different phases (e.g., tutorial, first task, etc.) of the experience and consider the generation of one or more heatmaps accordingly. Moreover, from the generated heatmaps was not possible to understand what the focus of the trainee attention in a certain location was. In this regard, the recording of the trainees' gaze orientation vector besides their coordinates or the adoption of more sophisticated VR head-mounted devices (HMD) with eye-tracking capabilities should be considered to gain a more granular understanding of the trainees' attention allocation during the experience.

6.4. Informed development actions

Both the results of the quantitative analysis of the subjective feedback provided by the trainees via the developed survey and the spatial track and heatmap visualizations points highlight a twofold positive outcome: first, the prototypical BIM-based VR experiences implemented in the case study safety training campaign effectively engaged the trainees and transferred the intended safety contents; second, the evaluation approach proposed in this work proved to be effective in the collection and integration of trainees' subjective and objective data and provide useful insights on the current weaknesses and areas of improvement. In this regard, a list of informed development actions is provided below:

- *Trainee embodiment and experience immersivity:* A greater correspondence between the actual physical sensation perceived by the trainee and the virtual environment should be pursued. The trainees would prefer a greater interaction with the VR scenario and its element (e.g., possibility to grasp objects) and the exposure to realistic auditorial stimuli characterizing the noise environment of a real construction site (e.g., machine noise, activity noise, etc.). This in turn is expected to raise the experience immersivity and the trainees' involvement in the training, hence benefiting the safety contents' transfer. In the same light, the delivery of a livelier and more dynamic scenario, with more animated entities (e.g., machines, workers, etc.), together with streamlined controls and logics to progress in the experience are expected to have a positive impact on the trainees' engagement.
- *Virtual support objects:* The introduction of virtual objects (not present in the real construction site) in support of the execution of the training experience proved to be beneficial for transferring safety contents and for increasing trainees' autonomy in the experience navigation (e.g., visualization of risk via placeholders, visualization of hazardous or restricted areas via coloured volumes, etc.). This result encourages the further development of this support objects (e.g., for triggering the execution of training events or the access to safety contents).
- *Spatial tracking and attention allocation discovery:* While the spatial tracking and heatmap visualizations proved to be beneficial and provided useful insights on the trainees' spatial understanding of the environment and attention allocation during the experience, further development should focus of a more granular tracking of the trainees' posture or attention via additional wearable sensors or eye-tracking enabled VR HMD. Moreover, the possibility to better handle the collected spatial track data (i.e., filtering out or grouping parts of the experience) should be implemented to increase the reliability and quality of the information showed in the heatmaps.

7. CONCLUSIONS

This paper presents the case study implementation and validation of a novel approach for the evaluation of the effectiveness of immersive VR-enabled safety training experiences for construction workers based on the integration of trainees' subjective feedback, collected through a post-experience evaluation questionnaire, and objective tracking of their positions in the virtual scenario during the training experience. The approach was applied in the context of a broader framework for the development and administration of VR safety training to construction workers developed and presented by the authors in previous works. The evaluation regarded a training campaign that involved the implementation of six VR training experiences, administered in three sessions for the training of a total of 12 construction workers employed in a case study project related to the construction of a new complex of three one-storey buildings with CLT structure atop an existing office facility in the city of Pisa, Italy.

The proposed approach proved to be effective for the evaluation of VR safety training experiences, providing useful and coherent insights from the integration of subjective -survey responses- and objective -VR spatial track and heatmaps- trainees' data, and informing the improvement of the prototypical experiences with future development actions in three main areas, namely: trainee embodiment and experience immersivity; virtual support objects; and spatial tracking and attention allocation discovery.

However, despite the encouraging results, further research efforts are required to overcome the limitations of the present study. First, the proposed evaluation approach should further validated within to a broader VR safety training campaign comprising of: a larger and more diverse set of participants in terms of work experience and familiarity with VR technologies; different typologies of case study projects and, hence, construction site characteristics and activities (i.e., buildings, infrastructures, earthworks, etc.); different VR devices and typologies of training, from exploration-oriented to activity-oriented; different VR features implemented (e.g., acoustic contents, movement control, interaction with virtual environment, etc.). The implementation of the approach in a more extensive campaign is foreseen to confirm its effectiveness, bridging the gap related to a lack of acknowledged evaluation methods that could be suitable for a large-scale adoption in the industry and, therefore, fostering the spread of VR technologies for construction workers' safety training.

Furthermore, the discussion of the results pointed out the opportunity to improve the quality of the insights obtainable from the trainees' VR spatial track and heatmap visualization with the acquisition of further trainees' data, such as their body orientation (i.e., proxy for their cone of attention), the position of their body parts (e.g., with the introduction of dedicated wearable sensors) to analyze their posture during simulated construction activities, and eye-tracking HMDs for the granular analysis of the trainees' gaze direction over time and hence attention allocation. All the mentioned improvements are currently being considered by the authors and the results of their adoption will be object of future contributions.

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