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RESEARCH ARTICLE

Enhancing Occupational Safety and Health Training: A Guideline for Virtual Reality Integration

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ABSTRACT Training in the Occupational Safety and Health (OSH) sector is crucial for minimizing workplace hazards and ensuring employee well-being. Virtual Reality (VR) emerges as a training tool that can enhance learning outcomes and simulate hazardous scenarios safely. However, several aspects must be taken into consideration when implementing VR-based training solutions. The paper investigates how to effectively design, develop, integrate, and validate a VR OSH training tool. To this aim, a comprehensive guideline of 9 key elements articulated in 29 items is proposed. Every element and item is retrieved from analyzing the existing literature on the topic using a systematic approach. The result is a comprehensive guide to consider all these aspects from the outset of design, in a cohesive, complete, and tailored manner. This formalization is intended to facilitate the advancement of research and implementation of these solutions, which to date have been largely confined to prototypes or lack real practical application.

INDEX TERMS Immersive technologies, Industry 4.0, OSH, safety, training, VR.

I. INTRODUCTION

The advent of digital technologies presents new opportunities and challenges for Occupational Health and Safety (OSH). Emerging risks and unforeseen contingencies arise from the complex interactions between humans, machines, technology, and the environment [1], [2]. Historically, OSH has been a major concern in both public and private sectors [3], [4], [5]. Although compliance with safety procedures may seem self-evident, accidents and incidents, including fatal ones, frequently result from day-to-day non-compliance [6]. Whether erroneous, intentional, non-malevolent, or malevolent [7], safety violations can have significant consequences and require serious consideration. Every 15 seconds, 153 workers experience a work-related accident, with at least one worker dying from an occupational injury or illness [8]. This trend leads to over 2.3 million deaths annually. The human cost of these daily tragedies is devastating, and the economic burden of poor workplace safety practices is estimated at 4% of the world's gross domestic product each year [8]. Although workplace fatalities have decreased in recent years [9], statistics remain alarming. As of November 2023, the Italian National Institute for Insurance against Accidents at Work (INAIL) received 542,568 reports of work-related accidents, 968 of which were fatal [10].

To prevent injuries and accidents, organizations need to leverage education and training. Traditional training is insufficient in today's digitally transforming environment [11], [12]. Literature shows that in the new digital environment, both training content and tools must be innovative to keep

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up with technological evolution and protect employees at all levels, from management to operational staff [13], [14], [15]. Theoretical and empirical research indicates that firsthand experience of realistic situations leads to a deeper understanding of events, enhances the acquisition of practical skills, and stimulates elaborate responses, including the development of soft skills such as problem-solving [2], [14].

Thus, in this complex scenario characterized by procedural tasks and emerging risks, immersive training programs appear promising. Specifically, Virtual Reality (VR) has proven to be a powerful training tool in various fields [16], [17]. Its flexibility and reproducibility of environments and the safe management of risk scenarios make it a helpful tool for OSH training [18]. VR applications allow workers to experience learning-by-doing training through a comprehensive and risk-free experiential learning model. Additionally, the virtual environment allows for training people simultaneously, offering programs tailored to the process and the worker's specific characteristics, experiences, needs, and roles within the company.

Despite numerous studies investigating the use of VR for OSH training, there remains a lack of a systematic approach to the design of these interventions. To fill this gap, this research will address the following question: *how to effectively design, develop, implement, and validate a virtual reality tool for occupational health and safety training?*

To address this question, this research develops a comprehensive guideline to aid researchers and professionals involved in the use of VR training tools for OSH.

The remainder of the paper is organized as follows. Section II details the methodological approach used to elicit all the elements and options to consider in the guideline, and it presents details about the literature used. Section III then analyzes these elements and options to construct the guideline for VR solutions for OSH training in industrial contexts. Finally, Sections IV presents the final guideline as the research outcomes, reflecting critically on the field and possible future research paths. The conclusion summarizes the work and underlines the open research questions.

II. METHODOLOGY

The research methodology employed in this study starts with a systematic review of the literature, aimed at gathering a comprehensive stack of knowledge that forms the foundation for identifying all key elements necessary for the design, development, implementation, and validation of the VR tool for OSH training. Subsequently, each identified key element is rigorously analyzed within this knowledge base to delineate every decision that needs consideration. This thorough analysis converges into a final guideline, presented in Section IV.

A. PREFERRED REPORTING ITEMS FOR SYSTEMATIC REVIEWS AND META-ANALYSES

An extensive analysis of the literature systematically consolidates research findings to define the guideline for training in OSH with VR solutions. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method [19] was followed to carry out this systematic analysis of the literature. The PRISMA guidelines define a systematic process for the identification, screening, eligibility, and inclusion of studies [20]. PRISMA was adapted by integrating additional records identified through other sources and suggested as important references by a selected team of experts. The detail of the process followed is described in the workflow shown in FIGURE 1.

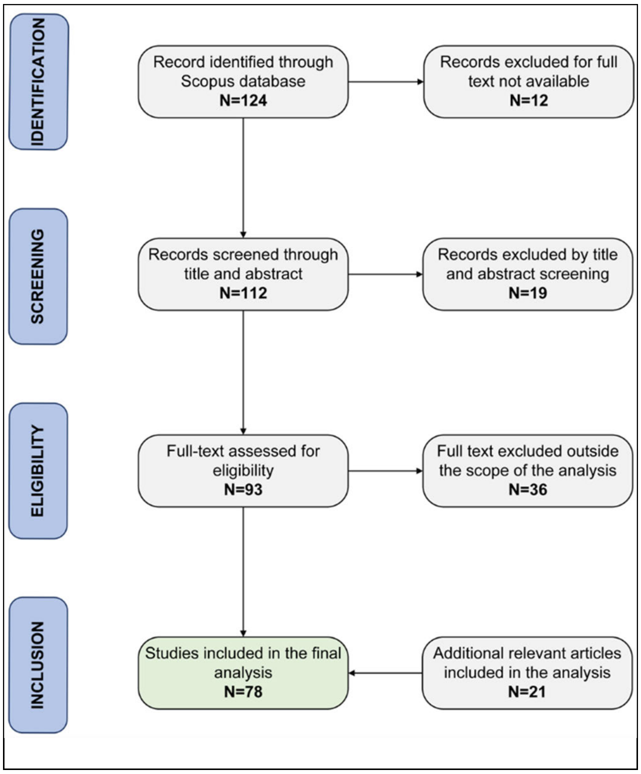

FIGURE 1. Prisma flowchart.

1) IDENTIFICATION

The review was conducted by searching the Scopus database for all papers indexed until 31 December 2023. The Scopus database was chosen based on its relevance in academia, with more than 90 million records in 29,000 journals from more than 7000 publishers [21]. The first step was to define the scope of the search query. An interdisciplinary team of experts with different backgrounds was set up. The team consisted of 10 people: four experts had a public research background in occupational safety and health, with expertise in training and education, innovation and communication, psychology, and law. Three experts have an academic and industrial background in manufacturing systems, with a focus on smart factories and industrial applications. Three experts have an academic background in virtual reality, focusing on telecommunications, digital signal and image processing, and immersive multimedia.

The selected search query looked for every article using "virtual reality" in association with "health and safety" or "occupational health" and with training or education or learning to broadly collect all the articles exploring the topic. However, to have broader inclusion criteria all the possible combinations of terms have been set to look both into Title, Abstract, and Keywords. The scope of the research was limited to articles, conference proceedings, and reviews published in English. In summary, the search query for the database was: (TITLE-ABS-KEY (("virtual reality" OR vr) AND ("health and safety" OR "occupat* health") AND (training OR educat* OR learn* OR teach*))) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English"))

The search query identified 124 articles; 12 articles have been excluded because the full text was not available. Therefore, the identification phase was concluded with 112 articles selected. Then, the team of experts identified additional 21 records, and the database-driven strategy was complemented resulting in a total of 133 articles.

2) SCREENING

In the screening phase, each article was screened in the title, abstract, and keywords to evaluate if its research was adherent to the objective of the review. Among 112 articles, 19 were excluded since they did not consider occupational health and safety or virtual reality.

3) ELIGIBILITY

During this phase, 93 articles were analyzed. The research team reviewed the full texts and 36 were rejected as they did not meet the inclusion criteria. They either did not focus on an education or training program or did not use virtual reality to enhance OSH training.

4) INCLUSION

A total of 78 articles were included for further analysis. The research team thoroughly reviewed these documents to extract data and synthesize information relevant to developing a guideline for VR solutions in industrial contexts for OSH training. The data is categorized using a framework that organizes information on citation details, abstracts, keywords, domains of application, and elements related to tool design, development, implementation, and validation.

The bibliometric analysis described in this section identified the quantitative aspects of the research sector.

The pie chart in FIGURE 2 shows a balanced ratio between journal articles and conference proceedings, with journal articles making up approximately 50.88% of the total. Additionally, review articles constitute a small portion, at only 12.28%.

Regarding the evolution of publications over time, FIGURE 3 illustrates a growing trend in the number of documents related to OSH training and VR. This increase is likely due to the spread of the technology, as well as a rising interest and concern in improving training tools and approaches.

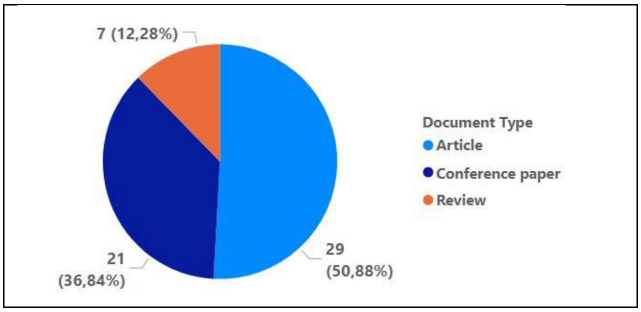

FIGURE 2. Document type.

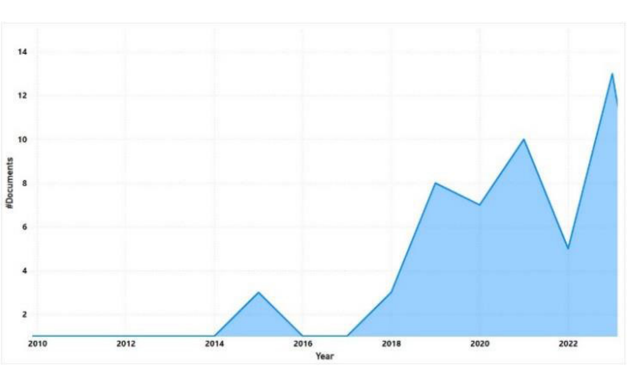

FIGURE 3. Evolution of documents over the years.

III. KEY ELEMENTS ANALYSIS

This paragraph discusses all the key elements that emerge from the PRISMA analysis, for the design, development, implementation, and validation of VR training for OSH. The authors propose a guideline to bridge the gap between advanced VR capabilities and the practical requirements of effective and immersive training programs.

The proposed guideline of Section IV is based on contributions identified through the literature review and analyzed by a multidisciplinary team of experts.

The guideline follows a systematic approach that begins with identifying the core objectives, expected learning outcomes, and target audience. Subsequently, it details the technical and content-related considerations for designing VR solutions. This involves selecting appropriate VR technology, creating content that aligns with learning objectives, and using interactive modalities to enhance user engagement and knowledge retention.

The development phase of the guideline also addresses best practices for creating immersive and interactive VR environments. The implementation guidance provides strategies for integrating VR training into existing OSH programs. This includes technical setup, user onboarding, and addressing potential barriers to adoption.

Additionally, the guideline outlines effective methods for validating the VR solution's effectiveness. This involves designing experiments to test the VR training against traditional methods, analyzing data to assess learning outcomes, and gathering user feedback to identify areas for improvement.

A. CONTEXT ANALYSIS AND TOOL DESIGN

The Context Analysis and Tool Design phase aims to investigate the learner's needs, the learning objective and the targeted context. This requires defining the primary target audience for the VR training system and the learning objectives the system is intended to achieve. This definition needs to specify the criteria that will be used for the assessment, such as the physical and organizational constraints of the target audience, considering the environment in which the course will be consumed.

1) PRIMARY TARGET AUDIENCE

The target audience refers to the primary users of the VR training system. The VR system for H&S training may find application in specific industrial sectors (e.g. construction, aeronautics).

The construction and building sectors are the most popular targets for VR OSH training solutions [16], [22], [23]. These solutions often address specific tasks essential to the construction industry, such as working at heights [24], [25], [26], excavation protocols [27], effective communication [28], adherence to social distancing guidelines [29], human-drone interaction [25], [30]. Additionally, they cover general health and safety practices, emphasizing risk identification and recognition [31], [32], [33], [34], [35], risk-taking behaviors [36], accident reporting [37], emergency management [38], fear arousal safety training [39], and long-term health risks [40]. Some solutions also help to reduce cognitive load by simplifying complex procedures [41]. Other solutions are more generalized and not tied to a specific industry, positioning themselves as broadly applicable to various sectors. Moreover, beyond construction, VR-based safety training has also been adopted in the Energy [51], [52], Oil & Gas [16], [25], [51], [52], [53], Chemical [54], [55], and Metallurgical sectors [56], as well as solutions designed for the Police [57], Schools [58], [59], Confined Spaces [60], and Transport sectors [61]. These results are in FIGURE 4.

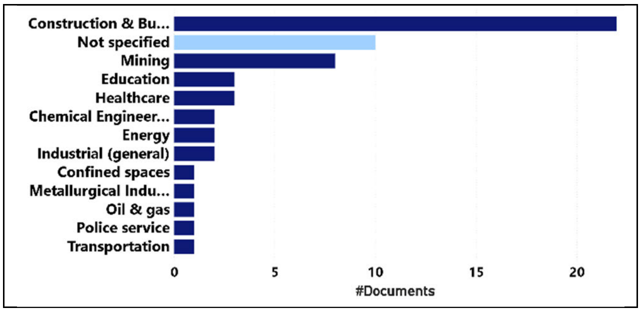

FIGURE 4. **Target industry.**

The choice of a valid test sample is also crucial. The target audience may include domain experts seeking to expand their knowledge or newcomers taking their first steps (FIGURE 5).

Shared characteristics among the target audience significantly influence the VR system's learning efficiency. Analyzing the personnel categories targeted by VR OSH training systems reveals that many documents lack specific information, often testing on a generic group, typically students with different backgrounds: graduate and post-graduate engineering students [40], [46], [58] students with experience in the industry [27], health students [49], [62], vocational and technical students [59].

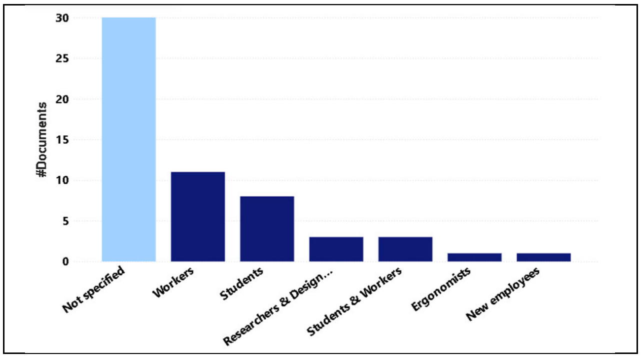

FIGURE 5. **Target audience.**

Among the documents that do specify this information, most solutions are designed for employees [32], [34], [39], [41], [51], [63], followed by engineers and designers [27], [54], [64], [65], new employees [44], [55], and technicians [60]. Solutions aimed at trainers and ergonomists [31], are less common. The choice of a valid test sample is essential for minimizing bias and enhancing generalizability. OSH training often involves evaluating the system with employees, workers, or students directly facing the addressed safety issues. For instance, in [34], 120 workers from eight Finnish construction companies participated in a study adopting a holistic perspective, addressing various roles in the construction industry and comparing four training methods. Participants needed at least two years of construction sector experience. In [39], the impact of fear arousal on correct habits in construction sites was studied in two sessions: one with contractors and officers on-site, and one with employees at headquarters, most having over eight years of industry experience. In [58], a VR safety training application was tested on seven undergraduate chemical engineering students to enhance laboratory risk awareness. In [41], 3 participants with similar backgrounds ensured consistent results. Involving individuals with diverse expertise in initial testing stages enhances comprehensiveness and effectiveness. In [31], 18 employees, including 12 construction workers, three trainers, and three ergonomists, tested a proposed safety training application.

2) EXPECTED LEARNING OUTCOME

Before designing the VR training system, it is essential to establish the primary learning objectives.

This involves defining what the VR solution aims to teach, including the content it will impart to the learners. Addressing the well-known Rasmussen's framework [66], the content, as well as the level of performance of human behavior, can be classified into three levels: skill, rule, and knowledge. The skill-based level governs automatic responses, in rutinary contexts; the rule-based refers to the application of rules procedures, mainly exploiting if-then reasoning; the knowledge-based level comprises problem-solving and decision-making processes, and therefore applies mainly to thinking in unfamiliar situations. Since these levels are not alternatives, but constantly interact with each other, and therefore the boundaries are not always clear, depending on the level of training and attention of the person, the term ''knowledge'' is used below as an umbrella term, referring to all the facets defined in Rasmussen's framework.

In defining the primary learning objectives, it is crucial to unambiguously set these goals at the outset and describe them in detail, ensuring their measurability. These goals should be supported by measurements that describe in detail how the knowledge acquired by the learner will be assessed and how the effectiveness of the solution will be evaluated, as explained later.

Most VR training for OSH aims to improve hazard recognition and identification capabilities as a primary learning objective. This training serves various purposes, such as enhancing decision-making skills, increasing awareness of OSH, distinguishing hazardous from non-hazardous situations, and reducing the likelihood of exposure to hazards.

The second most common learning outcome among the contributions is the acquisition of knowledge and skills for different purposes. This acquisition aims to reduce the rate of injury and unsafe behavior, as well as to increase knowledge of specific risks that are particularly significant for the context of interest, or finally to remember practical safety steps. A further learning outcome is intended to minimize exposure to hazards or to enable people to acquire procedural safety measures. Further contributions aim to improve the use of Personal Protective Equipment (PPE), and generally follow safety measures, guidelines, and procedures. Moreover, the goal is to familiarize users with emergencies and risk scenarios. In some cases, users are placed in risky situations without performing actions to boost confidence in such scenarios. In other cases, users are called upon to perform actions to test their aptitudes and develop technical expertise. Finally, some contributions aim to get users familiar with technologies, both from a physical and interactive perspective, e.g. touching, handling, and using, as well as from a functional perspective, e.g. stimulating users to evaluate the efficiency and effectiveness of the technology. TABLE 1 displays the training gaps and some of the proposed contents in the literature for each identified learning objective.

The design of the tool incorporates also crucial elements about the establishment of knowledge assessment tools, specifically at the level of key performance indicators (KPIs) and learning objectives. The existing literature offers limited contributions that advocate for knowledge assessments before training to help in the definition of learning objectives or define a comprehensive set of KPIs useful for evaluating knowledge acquisition and retention. This is for instance the case of [27], [47], and [59] which assesses pre and post-training to identify knowledge levels, and pinpoint initial gaps and training competencies to better define the goal and contents of the training. Moreover, the formalization of protocols and KPIs, as illustrated in [67], is infrequent. This formalization entails defining intervention arms, learning topics, and corresponding training content. Consequently, a significant proportion of studies focus on a specific learning objective, evaluating it in isolation without a holistic formalization of the expected improvements or the establishment of practical performance metrics and evaluation criteria.

B. TOOL DEVELOPMENT

The rationale behind the use of immersive technologies for safety training is based on several reasons: i) the immersivity of the technology, ii) the senses involved during training, and iii) how the content is displayed to users.

1) IMMERSIVE TECHNOLOGY SELECTION

EXtended Reality (XR) is a general term for VR, Augmented Reality (AR), and Mixed Reality (MR) denoting a range of immersive technologies that integrate digital and physical worlds [69]. These technologies make it possible to simulate reality (VR), overlay digital information onto the real world (AR), or fuse real and virtual worlds to generate new environments where physical and digital objects coexist and interact in real-time (MR) [69]. By leveraging advanced sensors, wearable computing systems, and graphical processing, XR provides users with enhanced interactive experiences, finding applications in various fields such as entertainment, education, healthcare, and industrial design [70], [71], [72]. The appropriate integration of immersive technology in OSH training remains a complex and evolving topic, requiring a nuanced approach to ensure its effectiveness [23], [73]. Despite promising research outcomes, the transition from academic studies to widespread industry application remains limited [74], further underscoring the need for continued exploration and refinement of immersive technology in OSH training. While immersive technology offers clear advantages, such as improved retention of concepts, enhanced knowledge transfer [49], and greater participant engagement, its implementation is not without challenges. These include technical issues like display brightness and the need for effective communication between trainers and trainees [75].

TABLE 1. Learning objective.

Learning Objective 1:
Hazards recognition and identification

Specific goal	*Training content*	*References*
Enhance decision-making by understanding the implications of decisions and actions	Experiencing a real accident or dangerous situation in virtual reality.	[17], [37], [39], [55], [64]
Increase awareness of H&S	Human factors safety training program in construction industry workplaces. Training with a special focus on chronic health components (long-term health hazards and perceiving long-term health risks).	[34], [40]
Distinguish hazardous from non-hazardous conditions and classify them	Hazard identification, visually searching for hazards, and removing hazards in construction industry workplaces. Risk Spotting in Chemical Procedures.	[16], [35], [55], [58], [67]
Minimize exposure to hazards	Risk Minimization and risk elimination in Chemical Procedures and construction-related hazards.	[33], [55], [58]

Learning Objective 2: Acquisition of knowledge ~~and skills~~

Specific goal	*Training content*	*References*
Reduce injury rate and unsafe behavior	Capture the risk-taking behavior of workers, identify at-risk workers, and propose injury-prevention interventions on a virtual scenario on a building's roof. Acquisition and practice of the correct behavior by the miners in a training virtual environment for blasting works.	[36], [43]
Improve the knowledge about specific risks	Industrial scenario (prevent pedestrian movement in warehouse and production areas for forklift movement) to show correct practices and potential user failures.	[68]
Remember the practical safety step	Combination of theoretical and practical training for an improved understanding of the task procedure for formwork stabilization.	[31]

Learning Objective 3:
Improvement of PPEs use, respect of guidelines and procedures

Specific goal	*Training content*	*References*
Teach the correct PPEs use and optimize safety measures	List safety procedures, and appropriate safety equipment and safety instructions and actions that help prevent accidents during work in construction sites. PPE adoption with a game scenario.	[29], [65], [67]

TABLE 1. *(Continued.)* Learning objective.

Learning Objective 4:
Familiarize with emergencies and risky scenarios

Specific goal	*Training content*	*References*
Without performing actions, to assess workers' comfort/attitude and to boost confidence with real scenarios	Psychological first aid stress management and disaster site safety training to boost confidence and competence. Virtual training enables workers to experience heights and assess their comfort in standing and working in such conditions.	[26], [50]
Performing actions to develop technical expertise and manage complex situations	Hazard recognition and decision-making skills for critical tasks.	[17]

Learning Objective 4:
Familiarize with technologies

Specific goal	*Training content*	*References*
For physical and interactive purposes (Contact and manipulation)	Train workers to work safely with drones, and show them the health and safety risks associated, including physical risks, attentional costs, and psychological impacts.	[25]
For functional purposes (evaluate the effectiveness and efficiency of the technology)	Safety and training implications of human-drone interactions: identify critical factors and build a safe adoption of new technology.	[30]

Additionally, some studies suggest that immersive technologies can potentially distract from cognitive processing [75]. Furthermore, there is evidence indicating that only limited knowledge gained from immersive media-based training is retained and applied in the workplace three months after the session, highlighting a potential shortfall in its long-term impact [76].

Up to now, VR has been considered as the main immersive technology to develop OSH training procedures. For instance, VR can reproduce and simulate hazardous events in workplaces [70]. An example of an application that did not use VR for safety training procedures was proposed in [36] where workers of the construction sector were trained for safety procedures in roof building and maintenance in MR. The study showed that the MR did indeed elicit behavioral changes, suggesting that MR-based tool could be useful for developing targeted safety interventions in the construction industry [36].

A recent work [71] analyzed the impact of different XR technologies on the learning outcomes of 127 undergraduate students majoring in rail traffic signal and control. The authors demonstrated that there were no significant differences among types of XR in the knowledge test scores. This result is consistent with other findings in the literature [77]. Hence, it is reasonable to design safety training procedures on top of VR for modeling scenarios of hazardous events.

2) SENSES INVOLVED IN THE PROCESS

The development of immersive learning experiences should consider which senses are engaged during the training [78]. Effective learning should involve more than just the visual sense; exploiting auditory, tactile, and even olfactory cues can enhance the realism of the training environment [78]. Indeed, engaging multiple senses helps to create a more compelling and memorable learning experience, which can improve knowledge retention and transfer to real-world applications [78].

In the context of enhancing tactile sensation during learning processes, the use of active feedback mechanisms, such as force feedback gloves, is recognized as a standard [79]. With this approach, however, users are always connected to the gloves, even in the absence of tactile stimuli. This requirement can lead to an altered interaction experience and significantly affect various aspects of human-computer interaction, particularly by decreasing the user's sense of immersion [80]. In contrast, passive haptic feedback leverages actual, tangible objects. These physical elements are designed to replicate the sensations of touch and force, thereby augmenting the user's experience by incorporating the tangible presence of real objects [80]. Nevertheless, using these objects may limit the virtual experience, since they do not allow the same flexibility as active haptic feedback, whose behavior can be changed dynamically with respect to users' input. This drawback can impact the realism, the experience, and the efficacy of the safety procedure training.

The sense of smell is a powerful human sensory experience that plays a crucial role in memory, emotion, and even survival, enabling us to detect and interpret the complex world of scents and aromas around us [81]. In [82] an initial work regarding safety training simulating smell was proposed. The research included a pilot study where users participated in VR training sessions with and without olfactory stimulation to assess the impact of scent on the learning experience. The findings suggest that the inclusion of olfactory cues did not negatively affect the users' interaction with VR content, indicating the possibility of enhancing VR training with scent to improve engagement and learning outcomes.

Although improving the immersivity of these technologies by adding multimedia content that involves multiple senses may improve knowledge transfer [78], it is important to highlight that employing multiple sensorial cues may cause the users' loss of attention during the explanation of safety procedures [77]. To the best of our knowledge, this is an open research problem that could be addressed in the future.

3) LEARNING CONTENT VISUALIZATION

Learning content for immersive technologies should align with educational goals and leverage the strengths of the selected technology. Content should be interactive and engaging to maximize learning outcomes, including Quality of Experience (QoE). QUALINET defines QoE as "the degree of delight or annoyance of an application or service user. It results from the fulfillment of his or her expectations concerning the utility and / or enjoyment of the application or service in the light of the user's personality and curreHowent state" [83]. Therefore, content should also be tailored to the learner's needs, providing the right balance of theoretical knowledge and practical application opportunities. Effective content development requires a deep understanding of the subject matter and the technical capabilities of the immersive technology platform. This can be done by including experts in the related field in the design of the safety training procedure [84].

From the analysis of the query result, learning content can be categorized by:

- ***Rendering***. The learning content can be shown on traditional monitors or immersive displays, such as Head Mounted Displays (HMDs) (e.g., HTC Vive Focus 3, Oculus Quest 2 and 3, etc..) and 360° displays. In addition, low-cost hardware, such as Google Cardboard, has been employed for budget-friendly safety procedure training.
- ***Interaction level***. The user can be passive or active with respect to the content. If the user can/cannot interact with the learning content, it is defined as active/passive.
- ***Type of knowledge transfer***. The content can be organized as a single-player game, as an adversarial competition or only as a passive visualization of videos/slides.

Among the selected 57 papers, only 39 describe how learning content is displayed in their application. Specifically, 9 of them passively engaged the user by proposing theoretical lectures or observation of hazardous events using 360° videos or slides with HMDs. Generally, these works are about construction (7 out of 9) or mining sites (2 out of 9), where a sequence of safety measures is shown to the user through storytelling, i.e., the art of narrating events or experiences to engage and inform an audience.

Differently, the applications in which the user is active (30 out of 39) are more diversified. As stated in 1), several types of HMDs have been used in the literature, a relevant factor in developing an immersive safety training experience. Regarding the types of knowledge transfer, 13 out of 30 works organized the content by exploiting the concept of "serious games", which are games designed for purposes beyond entertainment, such as education, training, or problem-solving. Another frequent modality is "questioning" (12 out of 30), which involves participants facing questions in the presence of critical hazard scenarios. The rest of the works (5 out of 30) employed both modalities to leverage their strengths.

In the same direction, how the learning content is shown to the users is not a standard process in the context of VR OSH training. In fact, among all the selected papers, each application follows a procedure tailored to the target scenario. For instance, in [68] the aim was to increase the awareness of workers to follow security procedures, e.g., safely climbing the stairs. As stated by the author, the combination of first and third-person views was a key element for the success of the training, changing considerably the visualization of the learning content. This concept was also employed in [56] where the user had the possibility to experience an accident and to view it from a different point of view. As a counterexample, in [52] the users could directly inspect and interact with objects in a first-person view of the virtual scene for solar farm maintenance.

C. TOOL IMPLEMENTATION

The design of a OSH training program must address the definition of an adequate testing protocol. When conducting a subjective experiment, several factors must be considered to ensure the reliability, validity, and replicability of the results.

1) NUMBER OF PARTICIPANTS

Choosing an appropriate number of participants for the experiment is also of paramount importance to ensure the reliability of the obtained results and statistical power, which refers to the probability that a study will correctly reject the null hypothesis when it is false [85]. Among the selected studies, 43 articles specify the number of users involved in the study. Nonetheless, the sample size must be meticulously determined, balancing the need for sufficient data to detect meaningful effects when varying the conditions under analysis. To the best of our knowledge, there is no standard related to the required number of participants for assessing the efficacy of an OSH training application. However, we can draw insights from established guidelines, such as those provided by the ITU-T, particularly in relation to subjective assessments of audiovisual quality in multimedia services, since a specific standard for interactive VR applications has not been published yet. Although not explicitly tailored to OSH training applications, these recommendations offer valuable insights into determining sample sizes for subjective evaluations, providing a useful starting point for establishing participant numbers in the assessment of OSH training applications. ITU-T P.910 [86], which focuses on subjective video quality assessment methods for multimedia applications, suggests involving at least 24 and 35 subjects, for controlled and uncontrolled environments respectively. ITU-T P.915 [87], which concerns subjective assessment methods for 3D video quality, and ITU-T P.919 [88], which refers to subjective test methodologies for 360° video on head-mounted displays and is currently the only ITU-T recommendation specifically addressing the design of subjective experiments for VR applications, both suggest a minimum of 28 subjects in controlled environments. In pilot studies, a smaller sample size may be utilized, but it should be clearly stated that the study is in its preliminary phases.

2) EXPERIMENT DURATION

Another key element to consider is the duration of the experiment session. However, very few works specify the length of the training session (only 8 among the selected studies). This is strictly related to the device chosen for the training session. In [36] a CAVE system was used. In this study, the training session was designed to last 20 minutes.

In [40], the Igloo system, which exploits immersive displays, has been used to design a OSH training program in the context of hazard recognition for chemical production. In this case, the training sessions have been designed to consider 20 minutes of lecturing and 20 minutes of training practice. Considering ITU-T P.910, depending on the experimental design, it is suggested that the sessions should not last more than 30 minutes, when the experiment presents users' short stimuli (i.e., less than 1 minute long). When longer stimuli are involved, it is essential to carefully assess users' engagement throughout the entire experiment to ensure that the test duration does not compromise the results.

On the other hand, when HMDs are employed, the time interval of their usage must be limited, to hinder the onset of cybersickness symptoms and fatigue, which may hinder the adoption of this technology in the field of safety training [89]. In ITU-P.919, it is suggested that the whole subjective experiment session should not last more than 1.5 hours, and the HMD should not be used for more than 25 minutes consecutively. Therefore, for experimental settings requiring wearing the HMD for longer time intervals, breaks between sessions should be scheduled to ensure participants' comfort. As an example, in [32], the training session was designed to last for 20 minutes.

D. TOOL VALIDATION

The evaluation of the designed systems is challenging since it must tackle several aspects, ranging from the training efficacy in terms of knowledge gain to the usability of the proposed approach from a user experience point of view.

1) TRAINING EFFICACY

One critical component is the administration of a knowledge test to participants both before and after the training experience. For example, in [27], the knowledge test comprised multiple-choice questions addressing key hazards, while in [59], participants underwent a pre-test to gauge their understanding of basic fire safety or [47] proposes an assessment of trainees' characteristics, their competency and knowledge level before attending the training sessions. In [90], 53 students with no prior knowledge of OSH training were involved in the study. In this work, a VR solution for construction OSH training has been developed. The baseline information was obtained by allowing the participants to use the proposed system before the training session. Users were asked to identify hazards in a construction site rendered in the virtual environment and to propose adequate strategies to manage them. This first part of the training session allowed the authors to evaluate both a hazard recognition score and a hazard management score.

Another significant aspect is the evaluation of self-efficacy [27], which measures an individual's confidence in their ability to perform tasks or achieve outcomes, as discussed by [91]. This too is typically assessed pre- and post-training. Such pre-and post-training assessments are instrumental in identifying knowledge levels, ensuring uniformity in the sample analysis, and obtaining the baseline to evaluate how efficient the proposed solution is.

However, another fundamental aspect is the ability to retain the information acquired during the training over time. In this case, a follow-up test can be arranged with the trainees, as in [34], [92]. In [92], the participants were asked to perform a OSH knowledge test before training, immediately after training, and after one month. The authors analyzed immediate training efficacy by comparing the prior-training and post-training test results, and short-term training efficacy by comparing the prior-training and the results of the tests after one month. Moreover, recall, which refers to the ability to retrieve and remember information previously learned, was evaluated by comparing the post-training and one month after training test results. In [34], it has been proposed also to assess self-efficacy, which refers to the individual's perception of being able to perform a safety-related task. The results of the study highlighted that the proposed VR solution allowed to increase self-efficacy in identifying hazardous situations after a one-month follow-up.

2) ASSESSMENT OF HUMAN FACTORS' IMPACT

The evaluation of the proposed solution should also address issues related to the innovative technologies involved in the designed solution. On one hand, it should be noted that rendering devices are constantly evolving. Indeed, it is necessary to find a compromise between system portability (weight, integrated communication systems, battery, etc.) and rendering quality (optics, viewer resolution, contrast, computational capacity, etc.) [93]. On the other hand, individuals often lack familiarity with VR systems. This absence of personal benchmarks can make it challenging for people to evaluate their experience in these simulated environments [94]. One of the visible consequences is the so-called wow effect, due to which the judgment of a user's experience is due more to the novelty than the experience itself [95].

All these factors have an impact on the assessment of the designed OSH training solutions, thus emphasizing the necessity for developing new evaluation methodologies and frameworks in this evolving technological landscape.

Therefore, several key factors can be considered for evaluating the designed training application. To this aim, subjective questionnaires are usually provided to the trainees.

From the performed analysis, some factors play a significant role in the evaluation process:

- Cybersickness is a complex phenomenon that can be described, in general terms, as a form of discomfort experienced by users while using immersive technologies. This occurs because of a mismatch between the visual stimuli received by the brain and the body's vestibular system, which senses movement and balance [96]. The discrepancy between what the eyes see and what the body perceives can cause sensory conflict, leading to discomfort or sickness. Among the studies analyzed, the Simulator Sickness Questionnaire (SSQ) [84] has been used to assess the onset of cybersickness symptoms. In this questionnaire, users are asked to rate the level of perception of 16 different symptoms, including, for example, nausea, dizziness, and headache. To this aim, they are given options ranging from none to severe to indicate the intensity of their perception. Although it was not used in the selected studies, it is worth mentioning that ITU-T P.919 suggests the use of the Vertigo Score Rating (VSR) [97] scale for fast cybersickness self-assessment, since it consists of only one question asking users to rate their feeling of discomfort on a 5-point Likert scale.
- Mental load refers to the amount of mental effort or cognitive resources to perform a task or process information [98]. Measuring mental load is of paramount importance, since it can significantly hinder the learning process [99]. One of the most used questionnaires is the NASA-Task Load Index (NASA-TLX) [100]. In this questionnaire, the mental load is defined through six components: mental demand, physical demand, temporal demand, performance, effort, and frustration. These components are evaluated on a 0-100 scale. Another frequently used method for mental load assessment is the Subjective Workload Assessment Technique (SWAT) [101], which considers three workload dimensions, namely time load, mental effort, and psychological stress load. The participants can provide a rate from 1 to 3.
- Presence refers to both the sensation of being physically present in the virtual environment and the sense of capability to engage within it [95], [102]. In [59], the Presence Questionnaire (PQ) [103] has been used to assess the level of presence perceived by the users in the VR environment. This questionnaire consists of 19 to 32 items, depending on the specific version and the research context in which it is used. The questions tackle different aspects of presence, such as the sense of being there, the sense of realism, and the sense of interaction within the virtual environment. The users are asked to assess these features on a 7-point Likert scale. In [39], users were asked to rate their feeling of presence and embodiment in the VR environment on a scale from 0 to 100. Another frequently employed questionnaire is the Slater-Usoh-Steed

presence questionnaire [104], used in [105]. In this case, users are asked 5 different questions on the extent to which users perceived the virtual experience as real. Ratings are given on a scale from 1 to 7. In [77], the perceived feeling of presence was measured using the Igroup Presence Questionnaire (IPQ) [106]. This questionnaire is composed of 14 items, among which there are questions from the PQ and the Slater-Usoh-Steed questionnaire.

- Usability of the system refers to the participant's perception of the extent to which the tool under design is easy to use to achieve the desired goal [107]. Among others, the most used assessment tools are the System Usability Scale (SUS) [108], which contains 10 items on a 5-point Likert scale. The calculated SUS score can range from 0 to 100, wherein values above 68 are desirable to show good usability. This questionnaire has been used in [43], [52], and [62]. The Usefulness, Satisfaction, and Ease of Use (USE) questionnaire [111], used in [112], is also related to usability, tackling through 30 items the aspects of usefulness, ease of use, ease of learning, and satisfaction.
- Technology acceptance is defined as the willingness or readiness of individuals to adopt and use a technology. Among the studies analyzed, the models that are mostly employed are the Technology Acceptance Model (TAM) [109] and the Unified Theory of Acceptance and Use of Technology (UTAUT) [113]. TAM is a theoretical model developed to understand the cognitive processes behind the acceptance of a technology. According to the TAM, the acceptance of technology is influenced by several factors, including perceived ease of use and usefulness [110]. The decision to adopt the technology involves weighing its perceived benefits against the perceived effort needed to use it. The UTAUT model seeks to consolidate the theoretical framework underlying technology acceptance by defining it across four primary dimensions: performance expectancy, effort expectancy, social influence, and facilitating conditions. This model incorporates and validates constructs from prior technology acceptance models, including TAM. To apply the UTAUT model, researchers can exploit the validated items to measure users' attitudes toward a new technology based on the defined dimensions. In [57], an end-user acceptance questionnaire was provided to the study participants. In this test, users were asked to rate on a 5-point scale different factors, related to both knowledge and technical aspects.
- Other factors related to QoE may be considered when evaluating the proposed solution. As a final remark, the analysis points out that the measurement of QoE is a very challenging task due to its inherent relation to the subject's perception of an event. However, in ITU-T P.910 [86], Absolute Category Rating (ACR) is proposed to tackle this issue. More specifically, users can be asked to rate their perceived QoE on a 5-point Likert scale.

TABLE 2. **Subjective questionnaires.**

Factors to be measured	*Questionnaires*	*References*
Knowledge gain	Subject to the specific use case	[22], [26], [28], [42], [58], [62], [71], [72], [77], [90], [92], [105], [117], [118], [119], [120], [121], [122]
Self-efficacy	Subject to the specific use case	[28], [112], [120]
Cybersickness	SSQ, VSR	[22], [42], [51], [54], [122], [123]
Mental load	NASA-TLX, SWAT	[23], [37], [52], [54], [118]
Presence	PQ, sense of presence, presence and feeling of embodiment scale	[58], [105], [112], [120], [122]
Usability	SUS, USE	[42], [51], [53], [54], [61], [63], [72]
Acceptance	TAM, UTAUT, end-user acceptance questionnaire	[40], [57], [64]
QoE	GEQ, ACR, on-purpose questionnaire	[28], [61], [71], [72], [120]

The Game Experience Questionnaire (GEQ) tackles the problem of QoE assessment by considering several factors simultaneously, namely immersion, flow, competence, positive and negative affect, tension, and challenge [114]. The primary objective of the GEQ is to assess player experiences. Notably, it has been applied in various non-recreational contexts, such as training, where the designs implemented followed the framework of serious games [115]. The questionnaire was developed considering different modules, among which the in-game module was used in [61]. In [72], users' engagement was measured using GEQ, while users' satisfaction was evaluated using the corresponding section of the USE questionnaire, while in [112], self-reporting on engagement was employed.

Table 2 presents a summary of the questionnaires and the references to the studies where they have been employed. The selection of a standardized questionnaire to assess the relevant factors ensures reliable results, as these tools have been validated and widely used in numerous studies. However, it is important to avoid excessively long questionnaires to prevent participant fatigue, which may lead to random or careless responses [116]. Therefore, if certain questions are not directly applicable to the study, it is preferable to omit them. For instance, the PQ includes questions on haptic or auditory feedback; if the study does not involve these features or their evaluation is not relevant, these questions may be

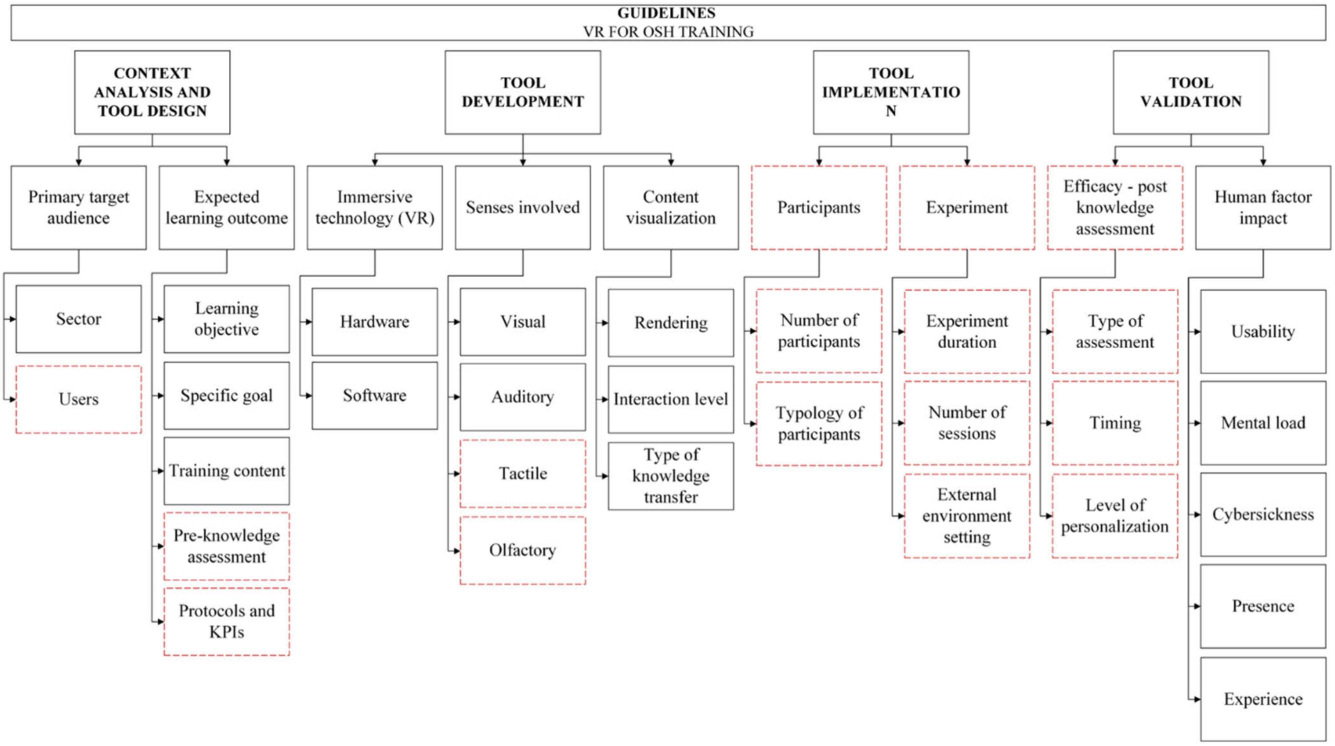

FIGURE 6. Guideline for the design, development, implementation and validation of OSH training VR solution.

excluded to reduce the questionnaire's length. Additionally, it is advisable not to attempt to assess all the human factors mentioned simultaneously, as doing so would result in overly long questionnaires, further increasing the risk of participants' fatigue. Therefore, the factors to evaluate should be carefully chosen based on the specific aim of the research, balancing the need for sufficient data to provide significant analysis and the length of the overall questionnaire to provide to the participants.

IV. RESULTING GUIDELINE AND DISCUSSION

Researchers are actively exploring ways to enhance VR training effectiveness for OSH by addressing existing protocol limitations. A growing number of articles reflect this trend, likely driven by VR technology's widespread adoption and the push to improve training methods. However, research remains nascent, mostly theoretical, or focused on specific aspects. The literature suggests the need to simultaneously consider multiple aspects. Moreover, the design process should integrate practical considerations for application-oriented outcomes. Overlooking certain aspects at the design stage could lead to ineffective or unsuitable tools. To tackle this fragmentation, FIGURE 6 presents a guideline offering a comprehensive overview of the critical aspects to consider and analyze throughout the VR tool's design, development, implementation, and validation phases for OSH training.

For each phase (at the first level), the aspects to be analyzed and the decisions to be made (at the second) are provided, with a further level of detail on the main facets relating to each. As anticipated, these elements are the direct result of the analysis of practical and theoretical solutions found in the literature. The red boxes highlight the aspects that are currently most underestimated, as well as those that require further investigation.

Regarding the primary target audience, to date the main users are students or generic people selected for prototype solutions [16], [27], [40], [59], [62]. However, many authors do not specify the target users of VR tools, which may reflect a lack of initial definition of this target. This tendency risks producing tools that are incomplete or of poor practical usefulness. Pre-knowledge assessments are infrequent, both regarding OSH and VR knowledge. So, the initial conditions are underestimated, which in turn could lead to the inability to design accurate and tailored solutions. As such, a lack of initial knowledge assessment can undermine the ability to evaluate the effectiveness of the training solution by not knowing the learners' initial level of knowledge. It also does not ensure that learners start from the same level of knowledge, which can lead to the design of tools that are not calibrated to actual training needs. This is also evident in the lack of protocols and KPIs to be analyzed and monitored during the implementation and validation phases. Some research suggests that integrating additional senses, such as tactile and olfactory, could enhance the overall experience. Further studies are required to assess the potential benefits and drawbacks of integrating additional senses into the learning experience. While such integration could enhance the realism of the experience, it could also act as a disruptive factor and detract from the learning objectives.

The most evident signal of the immaturity of such solutions is observed in the aspects related to the implementation phase. It is uncommon for solutions to be implemented or tested. There is a widespread absence of testing protocols. Furthermore, no reasoning concerning the availability of physical space necessary to carry out the tests is provided, although it's a fundamental and critical aspect. Similarly, research reports lack information on the number of sessions and the duration of experiments. No standards for post-knowledge assessment, and the absence of control groups during tests, are further evidence of the solutions' application immaturity. This should include, for example, reasoning on the frequency of administration, and the extent of tests' customization.

The guideline provides a practical and theoretical contribution to the field. From a theoretical standpoint, it offers an overview of the issues addressed in the literature, emphasizing the most oft-overlooked aspects. In this direction, further research is needed to close the current gaps.

From a practical standpoint, the guideline assists researchers and implementers in the design of comprehensive and tailored solutions, that are context-specific and aligned with the specific objectives. It is therefore important to define this requirement from the outset. This guideline also outlines the challenge in designing and implementing solutions that are universally applicable, suitable, and effective. However, the meticulous attention to detail and suitability for the specific scenario are the hallmarks and strengths of these solutions.

As a result, the entire process of creating a VR solution for OSH training is inherently challenging and time-consuming, requiring the availability of physical resources, space and human expertise. This aspect raises questions about the real applicability of such solutions. Firstly, the identification of an accurate training need and the ability of the VR solution to meet that need is a prerequisite. Then there is the analysis of available resources, where the evaluation should consider both the short term and the medium to long term. This is because, even after the design and implementation of such a solution, the testing and possible recalibration phases are perhaps the most delicate and necessary to generate tools in line with what has been planned and conceived.

V. CONCLUSION AND FUTURE WORK

The integration of VR technology into OSH training, offering firsthand experience of realistic situations, is crucial for improving OSH procedures in complex modern work environments where traditional methods often fall short. However, research still lacks comprehensive guidelines to define which aspects to consider when designing solutions. An in-depth analysis of the works presented in the literature identified the key elements to consider during the different phases of tool design, development, implementation, and validation. These aspects have been reformulated and included within the proposed guideline, which provides a comprehensive overview to build a VR solution for OSH training. It has emerged that most of the presented works do not consider detailed aspects in all these phases, while they should be considered together from the outset. It emerges an underestimation in identifying the target audience, in its training requirements and in the definition of clear learning objectives. Those aspects should be also aligned with the choice of VR hardware and software, since they highly influence training results, and they should be based on training requirements and cost. Also, the training content must be adapted to the VR structure, and the type of interaction required must be considered during the design phase. At the same time, the user interface must be intuitive, and the interaction well-planned regarding objects, menus, and controls.

Real-time feedback mechanisms can be further explored to guide participants. Finally, evaluation methods must be designed both to measure learning outcomes and to assess the human factor impact of the VR training system.

The most neglected features in the current literature are the definition of the space required for the subject to move during training, and the employment of tests to assess participants' familiarity with VR or their initial knowledge of OSH. Also, control groups to validate the test results, and the estimation of training intensity and duration. Finally, the assessment of progressive cognitive overload: on the one hand, it increases training load and promotes improvement; on the other hand, it leads to fatigue and hinders progress. It is therefore necessary to provide recovery and rest times. A variety of exercises offered in training can also avoid monotony.

The limitations of this study pertain to the analysis of industrial sectors. It would be beneficial to investigate whether any useful insights or reports in other fields of application could be employed to enhance the guideline. Furthermore, the guideline must be used for the creation of actual training solutions to obtain feedback from designers and developers. Future work will consider the implementation of an OSH VR-based training module, which will be developed adhering to the guidelines provided in this paper. Moreover, each element of the guideline can serve as a subject for in-depth research, exploring current and potential future options. For instance, investigating the selection of senses involved can help assess the impact that touch and smell have on training outcomes. Another potential area of future research lies in efficacy assessment, particularly in considering the "Type of assessment," which could become a specific research focus aimed at overcoming current, less effective methods of efficacy evaluation. An additional future development could involve integrating project management methods into the guideline, and proposing a detailed project plan that includes specific objectives, timelines, required resources, and project indicators. Furthermore, applying the guideline could lead to instantiations that consider specific contexts or accidents for training purposes.

ACRONYMS

AI	Artificial Intelligence.
AR	Augmented Reality.
ACR	Absolute Category Rating.

GEQ	Game Experience Questionnaire.
COTS	Commercial-Off-the-Shelf.
MR	Mixed Reality.
MMSM	Mulsemedia Multiple Sensorial Media.
QoE	Quality of Experience.
VR	Virtual Reality.
XR	eXtended Reality.
ITU-T	International Telecommunication Union Telecommunication Standardization Sector.
HMD	Head Mounted Display.
TAM	Technology Acceptance Model.
SSQ	Simulator Sickness Questionnaire.
VSR	Vertigo Score Rating.
PQ	Presence Questionnaire.
NASA-TLX	NASA-Task Load Index.
SWAT	Subjective Workload Assessment Technique.
SUS	System Usability Scale.
OSH	Occupational Health and Safety.
UTAUT	Unified Theory of Acceptance and Use of Technology.

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