Innovative systems for OSH training: VR Tour case study for LOTO procedure

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Abstract

Occupational safety and health (OSH) training is fundamental to reduce risks and ensure workers' well-being. In digital transformation context, virtual reality (VR) represents a tool able of simulating hazardous scenarios in which learning-by-doing, through an experiential learning model, is possible without being exposed to risk situations. The literature shows that a systematic approach to the design of OSH training interventions using VR is still lacking. This work presents the first investigation conducted as part of the Fereo project - Organizational Training and Resilience Engineering with New Enabling Technologies (Bric Inail 2022- ID63), namely the study and the evaluation protocols. In fact, one of the project objectives is to develop, implement and evaluate the effectiveness of a VR Tour on the LOTO (Lockout Tagout) procedure for the maintenance of machines and plants. The training modules have been implemented following the Skill-Rule-Knowledge framework to determine the appropriate display of information for workers to understand and operate systems while considering factors such as attention, response time, memory, and hand-eye coordination. The VR Tour was developed in three scenarios: "Trial & Error", "LOTO & Variability", "Supervisor Training". An evaluation protocol, including control groups and questionnaires, assesses the experience, effectiveness, and usability of the solution, focusing on Cybersickness, Presence and Task-Load. Future steps will involve extending the scenarios to include the role of supervisors with the opportunity to verify that operators are performing activities correctly and customizing the scenario. This experimentation in VR technology is expected to provide a broader perspective and enable organizations to improve the training and the management of workers' health and safety. The purpose of this study is to outline clear suggestions for the VR solutions design and implementation according to the quality, effectiveness and both technical and methodological specificity required by OSH training.

1 Introduction and background

The introduction of digital technologies has generated new opportunities and challenges for occupational safety and health (OSH). Particularly, emerging risks and unforeseen contingencies are increasingly evident, stemming from the complex interplay between human agents, machines, technological systems, and environmental factors [1], [2]. To mitigate the potential for injuries and accidents, organizations must strategically invest in education and training initiatives [1]. However, traditional training methodologies have proven inadequate for the demands of a digitally transforming work environment [3], [4]. The current literature emphasizes the necessity for innovation in both training content and delivery tools to align with the rapid technological advancements and safeguard employees across all organizational levels, from senior management to frontline staff [5], [6], [7].

Theoretical and empirical research underscores that experiential learning, particularly through direct engagement with realistic scenarios, fosters a deeper comprehension of critical events, enhances the mastery of practical skills, and promotes the development of complex problem-solving and other essential soft skills [2], [6]. Consequently, in the context of increasingly complex tasks and emergent risks, immersive training programs, notably those employing Virtual Reality (VR), show significant promise. VR has been validated as a robust training modality across diverse fields [8], [9] offering the unique benefits of environmental flexibility, scenario reproducibility, and safe exposure to risk-laden situations, which collectively render it highly effective for OSH training [10]. VR-based training enables workers to engage in learning-by-doing experiences within an immersive and risk-free virtual environment. This approach facilitates simultaneous training for multiple individuals and allows for customization based on the specific characteristics, prior experiences, needs, and roles of the workers within the organization.

Despite its potential, the literature indicates a gap in systematic approaches for designing VR-enhanced OSH training interventions [11]. Addressing this gap, within the Fereo project (Organizational Training and Resilience Engineering with New Enabling Technologies, Bric Inail 2022- ID63) an innovative solution has been designed. The latter refers to the development of a VR training solution on the Lockout Tagout (LOTO) procedure for the maintenance of machines and plants, that simulates various scenarios, mirroring real-world situations operators may encounter, thus not only innovating the training tools but also the content and overall approach to OSH management. The training framework leverages the Skill-Rule-Knowledge model [12], [13] and incorporates Safety II principles to advance the handling of OSH issues. Furthermore, protocols have been established to assess the efficacy and usability of the VR training solution. This research presents the study's preliminary findings, including the study protocol and the evaluation protocol designed to assess different aspects of their VR experience, i.e., cybersickness, mental workload, presence and usability. These preliminary results are the starting point for testing the developed solution in an initial operational setting and, later, at large industrial scale.

2 The study protocol

2.1 The reference procedure (LOTO)

The application context and scenarios focus on maintenance procedures, specifically the LOTO procedure. The selection of LOTO procedures as the foundation for developing a VR training solution is based on substantial evidence from the European Agency for Safety and Health at Work (EU-OSHA) [14], which identifies maintenance activities as a critical area prone to occupational accidents. Maintenance tasks inherently involve complex risk factors and potential exposure to dangerous energy sources. Consequently, LOTO procedures are of significant relevance, serving as a well-documented method to ensure worker safety by effectively managing and mitigating hazards during equipment servicing and maintenance. Beside manufacturing, some other production contexts are strongly impacted by improper LOTO application, e.g. construction [15], and oil and gas industry [16]. Research indicates that many accidents are linked to inadequate, unauthorized, or improper use of LOTO practices, highlighting a persistent gap between established safety standards and their practical implementation in the workplace [17], [18] .

The LOTO procedure is a multi-step safety protocol designed to isolate and secure hazardous energy sources before equipment maintenance begins [19]. It typically consists of six phases: (1) preparation for machine shutdown, (2) machine shutdown, (3) isolation of energy sources, (4) application of locking devices and warning tags, (5) dissipation of residual energy, and (6) verification of isolation. This structured approach ensures that machinery cannot be reactivated inadvertently, providing a critical layer of protection for workers. Despite the procedural rigor, training remains a pivotal component. The effectiveness of LOTO protocols depends not just on the operator's understanding and execution of these steps but also on their situational awareness and ability to recognize and mitigate potential hazards. Many incidents have been linked to unsafe operating conditions and a lack of risk awareness [17]. Serious accidents continue to occur due to lapses in LOTO applications, highlighting perceptual, comprehension, and projection challenges faced by operators during different phases of LOTO processes. During maintenance activities operators, driven by the pressure of time-sensitive tasks and productivity demands, may undervalue or bypass safety measures. This negligence is exacerbated by communication barriers, resource constraints, and conflicting priorities among stakeholders. As maintenance workers grapple with these operational complexities, the need for robust and immersive training becomes even more essential.

The VR-training solution selected the maintenance of an industrial compressor. The selected procedure involves managing three distinct energy sources (i.e., electrical, pneumatic, and thermal) and navigating hazards such as electric shocks, rotating machinery, and high-pressure air. The process requires various locking devices and tags to ensure comprehensive energy isolation. Figure 1 illustrates an image of the virtual environment, which aims to replicate this maintenance context realistically.

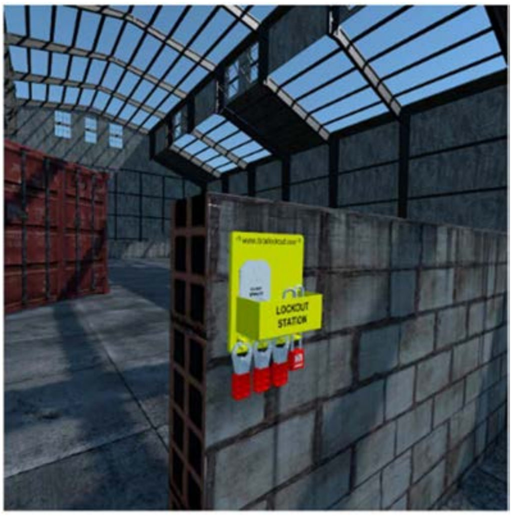

Fig. 1- Padlocks for the LOTO procedure completion in the virtual environment.

The procedure requires the worker to secure themselves and the compressor before conducting the maintenance activity. After simulating it, the same worker has to return the system to its initial state, i.e. the operational state. These steps require the worker to equip themselves with the personal protective equipment (PPE) needed to carry out the maintenance and to inform the operators present in the plant of the maintenance activity they intend to carry out. At this point, following the LOTO procedure, they shut down the compressor and switch off the power sources via the electrical panel, applying padlocks to provide evidence. Only after these steps have been completed the worker can perform maintenance on the compressor. As outlined in Section 2.1, what has been illustrated is the basic procedure. This procedure is then tailored to three scenarios that have different training objectives and potential users.

2.2 The reference framework (SRK) and VR scenarios

The Skill-Rule-Knowledge (SRK) framework is chosen to enhance the VR-based training from a Safety-II perspective. Namely, safety management based on Safety-II shifts focus from merely preventing failures, as seen in Safety-I, to enhancing an organization's ability to succeed across a range of conditions, thus promoting high levels of safety performance [20]. At the heart of Safety-II is systems thinking [21], which encourages understanding the complexities and interdependencies within systems. Rather than attributing safety to individual components, this approach considers safety as emerging from interactions within the system, promoting an awareness of how changes in one part of the system can impact the system as a whole. Resilience engineering is another foundational element in Safety-II [22]. It emphasizes a system's ability to function effectively during both anticipated and unexpected conditions. Resilience engineering aims to bolster the system's ability to adapt, learn, and recover from disruptions, maintaining safety through its capacity to absorb and respond to various challenges. Proactivity further distinguishes Safety-II from Safety-I [23]. Rather than reacting to incidents after they occur, Safety-II calls for a forward-looking stance. This proactive approach involves anticipating potential issues and preparing for them in advance,

thereby reducing the likelihood of accidents or failures. Continuous learning and adaptability are also central to Safety-II, which advocates for ongoing learning from both successful and unsuccessful outcomes. This principle encourages organizations to refine their safety practices based on insights gained from everyday operations as well as from broader industry developments [24]. Finally, Safety-II recognizes human performance variability as an asset [25], in contrast to Safety-I's tendency to view human variability as a source of error. Safety-II appreciates human adaptability and variability in performance as critical resources that enhance system resilience and promote safety under changing conditions. In sum, Safety-II fosters an approach to safety management that values adaptability, proactive planning, continuous learning, and human resilience, thereby creating systems that are better prepared to maintain safety across a wide range of operating conditions.
These principles are incorporated into the design of the VR solution by defining different scenarios. Specifically, scenario 1 and scenario 2 reflect different situations that the trainee might encounter in practice. The first (scenario 1) is a situation where everything goes as it should. This means that the application of the knowledge gained in training is sufficient to pass the test and complete the maintenance task without incident or the possibility of an incident. Scenario 2, on the other hand, places the worker in unexpected situations, and the mere application of known procedures is not sufficient to successfully complete the test. In this sense, scenarios 1 and 2 reflect different levels of learning and behavior that can be linked back to the SRK framework. Such a framework, developed by Jens Rasmussen, is a cognitive model used to categorize human behavior and decision-making into three distinct levels [13]. As depicted in Figure 2, and detailed after on, each level reflects different types of situations the worker is faced with, and therefore the cognitive level involved in coping with the scenario.

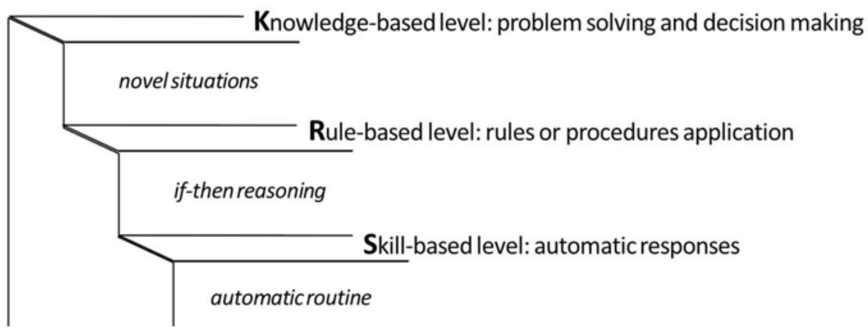

Fig 2 – Categorization of human behavior into three cognitive levels according to the SRK framework.

Specifically, a third scenario, in which a new user of the VR solution serves as the differentiating factor, is now being developed after two others have been established.

- Scenario 1 - Trail & Error (skill-and rule-based training): the goal is to ensure that workers internalize the LOTO steps and can execute them automatically. If participants make errors, such as missing a step in the procedure, they receive immediate feedback and must restart the process. As such, this scenario reflects a behavior governed by learned rules and procedures. Individuals apply specific “if-then” rules to manage routine but non-automatic situations. This is often used when safety protocols need to be followed, such as adhering to steps in a LOTO procedure.

- Scenario 2 - LOTO & Variability (knowledge-based training): this scenario builds on the previous training but introduces elements of unpredictability. Participants must use procedural knowledge and adapt to unexpected variables, such as communication challenges or emergent hazards. The VR environment requires operators to combine procedural adherence with situational assessment and decision-making. They must interact with avatars and use observation and initiative to ensure safety. At this level, the highest level of cognitive processing is used when individuals encounter novel or unpredictable situations that cannot be addressed through existing skills or rules. As such, it involves problem-solving, analysis, and the application of theoretical knowledge. Workers must assess the situation, draw on their broader understanding, and develop a new solution.
- Scenario 3 - the “Supervisor Training” will incorporate the role of supervisors, who will serve as experts overseeing the maintenance activities. Supervisors will verify procedural compliance and offer guidance within the VR simulation, ensuring that operators perform tasks correctly. This scenario will also allow for the review and potential updating of existing safety procedures, providing a comprehensive approach to continuous safety improvement.

3 The evaluation protocol

The evaluation protocol sets out the guidelines for carrying out the experiment and for the initial phases of results evaluation. For the VR training experiment, the Meta Quest Pro headset, equipped with an integrated eye tracker, has been selected, because of its advanced features that are critical for an immersive and high-quality VR experience. These features include a 4K high-resolution display (2048 x 2048 pixels per eye), a 120 Hz refresh rate, 3D spatial audio, and six degrees of freedom (6DoF) tracking. Together with its ergonomic design for lasting comfort and a robust processing system, the device ensures minimal impact on the learning process, allowing the focus to remain on training rather than on potential technological limitations. Specifically, the evaluation protocol consists of the following four steps.

- Phase 1 - recruitment and training: participants are first recruited and introduced to VR technology, gaining familiarity with how to interact within the virtual environment.

- Phase 2 - testing phase: participants test specific features of the VR system, ensuring they are comfortable and prepared for the full experiment.

- Phase 3 - experiment execution: participants engage in the core VR training experience, during which various data points, such as eye gaze, movements, and actions, are collected to analyze user interactions and learning outcomes.

- Phase 4 - questionnaire administration: participants complete a subjective questionnaire designed to assess different aspects of their VR experience.

The subjective questionnaire aims to assess on a 7-level Likert scale cybersickness, mental workload, presence, and usability of the VR training solution. Before assessing such aspects, participants complete a personal data section which includes information on gender, age, educational background, nationality, industry sector, computer literacy, prior experience with VR technology - both in general and as a training tool, level of confidence in using VR, and the specific contexts in which they have used VR previously. This information is crucial for contextualizing the results and understanding the diverse participant profiles.
Cybersickness is tested through the Cybersickness in Virtual Reality Questionnaire (CSQ-VR) [26], which measures symptoms related to cybersickness, a form of discomfort resulting from sensory conflicts in VR. Participants should rate the whole range of cybersickness symptoms, including nausea, disorientation, and oculomotor symptoms.
Mental workload is analyzed through the NASA-Task Load Index (NASA-TLX) [27], used to evaluate the mental effort required during the VR task, which is crucial as excessive mental workload can impair learning. This section consists of six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants rate each dimension, providing a comprehensive measure of mental workload.
Presence, a critical factor in immersive training effectiveness, is assessed though the Presence Questionnaire (PQ) [28] to evaluate the extent to which participants perceived the movement and interaction as natural, and felt involved in the experience; furthermore, how long it took them to get used to the experience by focusing on the task at hand rather than the mechanisms used to accomplish it, and whether they noticed any latency between their own actions and the virtual movements.
Finally, usability is detected by the System Usability Scale (SUS) [29] to assess the ease of use of the VR system, whether the training experience is complex, self-paced, or requires technical support, and to evaluate the integration of various features.
This questionnaire should be administered immediately after the VR experience to maximize the accuracy and relevance of participants' response.

4 Conclusion and future work

The VR training solution proposed aims to provide a realistic, engaging, and adaptive training environment that enhances workers' abilities across all three cognitive levels, i.e., skill-, rule-,–knowledge-based, preparing the user to handle both routine and unforeseen safety challenges effectively. As such, the solution aims to improve workers’ ability to act appropriately under varying conditions by aligning training objectives with the different cognitive demands of skill, rule, and knowledge levels. The designed experiment will first be tested in a laboratory environment to verify its usability, and all aspects defined in step 4 of the evaluation protocol. Once the technological solution and its content have been approved and optimized, it will be tested in the operational environment to evaluate its effectiveness also from a training perspective. In this regard, an additional plan will be defined to compare the results of traditional and innovative training from the perspective of the tool used. Specifically, the following question will be answered: what aspect of training is improved (or worsened) by using an innovative, interactive technology solution?

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