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Participatory development and mixed-methods evaluation of immersive VR training for radiation protection and nuclear safeguards – KISS

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Abstract: The ongoing decommissioning of nuclear facilities in Germany requires a highly qualified workforce, yet the sector faces a growing shortage of trained personnel due to retirements, restricted facility access, and declining educational capacity. Immersive virtual reality (VR) provides an effective means of supporting competence development where safety or operational constraints limit real-world training. However, existing VR-based training applications for the nuclear power sector remain limited in scope and often lack participatory development involving domain experts. The present study reports on the participatory, design-based development of an immersive VR training system and presents findings from an evaluation with experienced nuclear professionals. Using a convergent mixed-methods design, quantitative data from standardized questionnaires were combined with qualitative insights from semi-structured interviews. Thirteen radiation-protection workers and project engineers tested two radiation-protection and two safeguards scenarios. Participants reported consistently high enjoyment, clear task structures, and substantial perceived didactic value. Spatial presence was rated at a moderate level. The VR training was perceived as particularly beneficial for novices, supporting conceptual understanding, procedural awareness, and safety culture. Qualitative findings also identified several areas for refinement, including enhanced preparatory guidance, improved interaction fidelity, richer contextual information, and the potential introduction of multi-user modes. Overall, the results indicate that immersive VR can serve as an accessible, engaging, and instructionally meaningful complement to existing training practices in the nuclear sector.

The study provides empirically grounded design exemplars for site-independent VR training and highlights future directions for expanding scenario fidelity, validating learning outcomes, and embedding VR within structured training procedures.

Keywords: mobile training; virtual reality; training; decommissioning; onboarding

1 Introduction

The safe and efficient decommissioning of nuclear facilities is a long-term undertaking that requires highly specialized expertise in radiation protection, decommissioning operations, and regulatory compliance. Following Germany's nuclear phase-out in 2023, this need has intensified. A substantial proportion of nuclear professionals will retire in the coming years while educational programs in nuclear engineering and radiation protection have declined significantly (Kettler et al. 2025). As a result, a growing gap is emerging between the expertise needed for safe decommissioning and the availability of qualified personnel. National strategies therefore highlight the necessity of modern, scalable approaches to competence development, including innovative teaching methods and strengthened knowledge preservation (BMWK and BMUV 2020).

Traditional training for radiation protection and nuclear safeguards faces structural challenges due to restricted access to controlled areas, dose limits, and operational constraints. While mock-ups and simulator-based exercises are recommended for high-dose environments (OECD NEA 2009), such training environments often cannot replicate the spatial complexity, dynamic radiation fields, or embodied interactions characteristic of real facilities. The IAEA's systematic approach to training (SAT) emphasizes the importance of aligning instructional design with task criticality and risk profiles (IAEA 2021), further underlining the need for flexible, high-fidelity training solutions.

Virtual reality (VR) offers such potential. Research across educational and technical domains shows that VR can enhance motivation, presence, engagement, and, in specific contexts, learning outcomes (e.g., Parong 2021). VR is

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particularly advantageous for radiation protection, as it enables the safe exploration of otherwise unobservable phenomena, such as scattered radiation, shielding effects, and dose distribution (e.g., Nishi et al. 2022). Despite its strengths, VR training in the nuclear sector remains fragmented. Many systems rely on desktop VR, are site-specific, or lack empirically validated instructional design principles.

Responding to these sector-wide needs, the research and development project “Competence, Innovation, Safety, Radiation Protection” (Kompetenz, Innovation, Sicherheit, Strahlenschutz; K.I.S.S.) brings together seven partners from industry, research, and digital innovation to develop integrated solutions for knowledge management, licensing support, and immersive training in nuclear decommissioning. Within this broader initiative, one component focuses on creating an immersive mobile training station to support radiation-protection and safeguards training through VR experiences that can be deployed flexibly across sites and learning contexts.

Against this background, the present study investigates the participatory development and evaluation of immersive VR training scenarios for radiation protection and nuclear safeguards. The following section outlines the theoretical and didactic foundations that inform the design of VR learning environments and situates the study within existing research.

1.1 Promises and pitfalls of VR in education

VR refers to fully computer-generated environments that engage multiple sensory modalities and create the illusion of being physically present in an artificial world (Ni et al. 2006). Unlike augmented or mixed reality, which overlay digital elements onto the physical world (Milgram and Kishino 1994), VR separates the user from their real surroundings and provides an immersive representation through two-dimensional displays (“desktop VR”) or, more commonly, head-mounted displays (“immersive VR”). From a pedagogical perspective, VR offers the ability to simulate complex contexts, roles, and action sequences in a controlled learning environment, enabling contextualized, practice-oriented learning processes and facilitating theory-practice transfer (Köhler et al. 2013). Meta-analyses and systematic reviews consistently report positive effects of VR on motivational variables (e.g., interest, enjoyment), affective involvement, presence, and satisfaction, with several studies also demonstrating improvements in knowledge acquisition and procedural performance (Howard et al. 2021; Parong 2021;

Qiu et al. 2024). However, the educational value of VR is not inherent to the medium. Rather, it depends on how its technological features interact with cognitive and affective learning processes.

The Cognitive-Affective Model of Immersive Learning (CAMIL; Makransky and Petersen 2021) provides a widely recognized theoretical account of how VR can support learning. According to CAMIL, three technological features – immersion, representational fidelity, and control factors – shape users’ sense of presence and agency. These psychological states influence cognitive (e.g., attention allocation, mental model construction, cognitive load) and affective mechanisms (e.g., interest, motivation, self-efficacy, embodiment), which in turn determine learning outcomes across factual, conceptual, and procedural domains.

CAMIL highlights an important dualism: Although higher presence and agency can support engagement, self-efficacy, and learning, they can also induce distraction, emotional overactivation, or increased extraneous cognitive load. Thus, immersive VR can both facilitate and hinder learning depending on the alignment of its design with instructional goals. Recent syntheses reinforce CAMIL’s premise that VR is most effective when paired with generative learning activities that prompt mental organization, elaboration, or enactment (Mayer et al. 2023). These reviews emphasize that more immersion does not automatically produce better learning. Instead, VR environments must be instructionally coherent, cognitively manageable, and specifically designed to direct attention toward essential learning content rather than perceptual novelty. The Meaningful iVR Learning (M-iVR-L) framework (Mulders et al. 2020) operationalizes these implications for instructional design. It stresses the need to balance immersion with structured guidance and to incorporate supportive elements such as pre-training, signaling, segmentation, and scaffolding. The framework identifies specific conditions under which immersive VR is pedagogically advantageous, such as tasks requiring embodied interaction, spatial reasoning, or exposure to hazardous situations, while also warning against the potential for cognitive overload when immersive environments lack instructional alignment.

Taken together, these frameworks suggest that effective VR learning environments must be deliberately designed to leverage immersion while supporting cognitive processing and avoiding distraction. This perspective is particularly relevant for professional training contexts that rely on authentic, spatially complex, or safety-critical operations.

1.2 Virtual reality applications for nuclear training

Practical training in nuclear facilities and radiological work environments is often constrained by safety regulations, restricted accessibility, and the presence of ionizing radiation. VR can alleviate these limitations by enabling realistic, repeatable, and risk-free simulations of work processes and hazardous situations (Bailenson et al. 2008). In recent years, VR has evolved from isolated prototypes to a more established training technology within the nuclear sector, accompanied by a growing – yet still relatively limited – body of empirical research (Pakarinen et al. 2024).

A recent literature review identified four major application domains for VR-based training in nuclear operations (e.g., for nuclear power plant personnel): Incident and accident management, work-process planning, general safety, and radiation visualization and estimation (Pakarinen et al. 2021). Across these domains, VR has been consistently perceived as beneficial, often showing advantages compared to conventional training formats in terms of engagement and conceptual understanding. In nuclear engineering education, for instance, VR-enhanced reactor simulations have been shown to strengthen students' comprehension of complex dynamic phenomena by allowing self-paced experimentation (Prasad et al. 2024). Complementary evidence from medical and radiation physics further suggests that immersive technologies can enhance engagement, conceptual learning, and procedural skill acquisition (Tene et al. 2024). VR's ability to represent phenomena that cannot be directly observed in real environments (Jensen and Konradsen 2018) is particularly advantageous in radiation protection training, where immersive visualization techniques have been linked to improved understanding of dose distribution, shielding behavior, and exposure reduction strategies (e.g., Mól et al. 2009; Nishi et al. 2022; Szőke et al. 2014).

Despite these promising developments, several limitations characterize the current state of VR research in the nuclear domain. Most existing studies rely on desktop VR rather than immersive VR, limiting the generalizability of conclusions about embodied interaction and presence. Additionally, openly available, curriculum-level documentation is scarce – for instance regarding VR training for nuclear safeguards (Goncalves et al. 2010) and regulatory training – and as a result, systematic benchmarking of VR systems for nuclear training remains difficult. Empirical studies that rigorously evaluate the instructional design of VR applications are still limited in number, particularly in the context of immersive systems. Furthermore, recent

reviews emphasize that learning effectiveness depends not merely on the use of VR itself but on the degree to which technological affordances are aligned with learning goals, cognitive design principles, and the needs of target user groups (Pakarinen et al. 2024). This alignment requires close collaboration between engineers, instructional designers, trainers, and domain experts (Koskinen et al. 2024) – an aspect that is often acknowledged but insufficiently implemented in practice. Against this backdrop, the present study investigates the participatory development and evaluation of immersive VR training scenarios for radiation protection and nuclear safeguards within the research and development project “K.I.S.S.”.

1.3 Goals of the present research

In light of the conceptual and empirical gaps outlined above, the present study seeks to systematically examine how immersive VR can be designed and evaluated for training in radiation protection and nuclear safeguards. To this end, the study is guided by the following research questions (RQ):

- *RQ1:* How can virtual reality-based training scenarios for radiation protection and nuclear safeguards be designed and iteratively developed through a participatory process involving experienced nuclear professionals?
- *RQ2:* How do experienced nuclear professionals experience the VR training scenario in terms of usability, immersion, emotional engagement, and task interaction?
- *RQ3:* How do experienced nuclear professionals assess the didactic design of the VR training scenario, and to what extent do they perceive it as instructionally valuable for training themselves and prospective personnel in the nuclear sector?

2 Methods

2.1 Development and implementation of the VR-based training

The VR-based training component of the “K.I.S.S.” project was developed as a mobile demonstrator designed to enable realistic, technology-supported instruction in radiation protection and nuclear safeguards. Its development followed an iterative Design-Based Research (DBR) approach, which connects educational theory with real-world practice by designing, implementing, evaluating, and refining interventions in authentic settings through repeated cycles (Koppel 2017).

Following this framework, development began with a comprehensive requirements analysis involving trainers, safeguards experts, and decommissioning practitioners. This initial phase identified the pedagogical objectives, technical constraints, and key usability criteria. Building on these insights, a participatory development process was established that brought together software developers, scientific specialists, instructional designers, and work and educational psychologists. Subsequent development cycles focused on refining interaction design, scenario logic, and system stability, informed by formative tests conducted in authentic training settings. In line with the DBR approach, this iterative process ultimately resulted in a functional, mobile VR-based training system tailored to safety-critical contexts, as well as initial design principles for creating accessible, site-independent VR training solutions (Kosłowski et al. 2024).

2.1.1 System architecture and virtual environment

To meet the identified requirements for portability, simplicity, and maintainability, the consortium selected commercially available off-the-shelf hardware. The resulting prototype integrates a Meta Quest 3 headset, operated in a tethered configuration with a notebook to ensure stable performance and high visual fidelity. The notebook simultaneously serves as an instructor unit, enabling real-time observation, scenario control, and feedback. Both components are stored in a portable case that allows the system to be transported and deployed across different training sites.

The VR application was implemented using the Unity 3D engine, which supports real-time rendering and modular integration of multiple training scenarios. When launching the application, learners first enter their name and receive short on-screen information about correct device usage and essential safety instructions. They then select one of the four available scenarios, which are outlined in the subsequent section.

The virtual environment was designed to represent a realistic yet generic nuclear facility, including controlled zones, laboratory areas, and an interim storage hall. Rather than replicating a specific plant, the aim was to create a representative training setting that reflects common operational structures and enables the demonstration of key procedures relevant across different nuclear facility types.

2.1.2 Training scenarios

At the current stage of development, the system includes two radiation-protection scenarios and two safeguards scenarios, each aligned with defined learning objectives. All

scenarios were intentionally designed with simple navigation and interaction mechanics to ensure that learners can focus on the instructional content rather than on mastering complex controls. The guiding design principle was that, after a brief familiarization period, users should be able to operate the system independently and direct their attention fully to the task environment.

2.1.2.1 Scenario 1: radiation protection training

The first radiation-protection scenario was designed to familiarize newcomers and career changers with fundamental work processes in radiological environments. Insights from preliminary interviews with radiation-protection personnel indicated that immersive VR is particularly suitable for preparing learners for their first assignments in controlled areas, as it allows them to combine theoretical knowledge with safe, practice-oriented experience. Based on these findings, two central learning goals were defined: understanding the practical handling of radiation sources and strengthening nuclear safety culture and situational awareness.

The learning content focuses on core procedural skills relevant to radiation protection, including dose-rate measurements, contamination checks, decontamination steps, proper waste handling, and essential preparatory actions. The scenario takes place in a virtual laboratory that provides a simplified but realistic environment for practising these tasks. Learners are expected to carry out the procedures as they would under real conditions, maintaining safe distances, avoiding contamination spread, and following established safety protocols.

Hotspot research and shielding (Scenario 1A). In this scenario, learners practice locating and safely removing three radioactive items – a test tube, a screw, and a nut – within the virtual laboratory. Because the hotspots are not visible to the naked eye, they must be identified using a dosimeter lance by interpreting the dose-rate readings displayed in $\mu\text{Sv/h}$. Once the objects are located, the trainee opens the disposal container, uses the grabber tool to transfer each radioactive item into the bin, and then securely closes the container. The scenario concludes with procedural steps designed to prevent further contamination and ensure safe completion of the task. Selected learner actions from this scenario are illustrated in Figure 1.

Liquid contamination and decontamination (Scenario 1B). The second radiation-protection scenario focuses on responding to a liquid contamination event in the virtual laboratory. Before entering the contaminated area, learners must correctly select the required working tools (Kontamat, mop, and wipetest pads) as well as the appropriate personal protective equipment (protective suit, gloves, mask, shoe

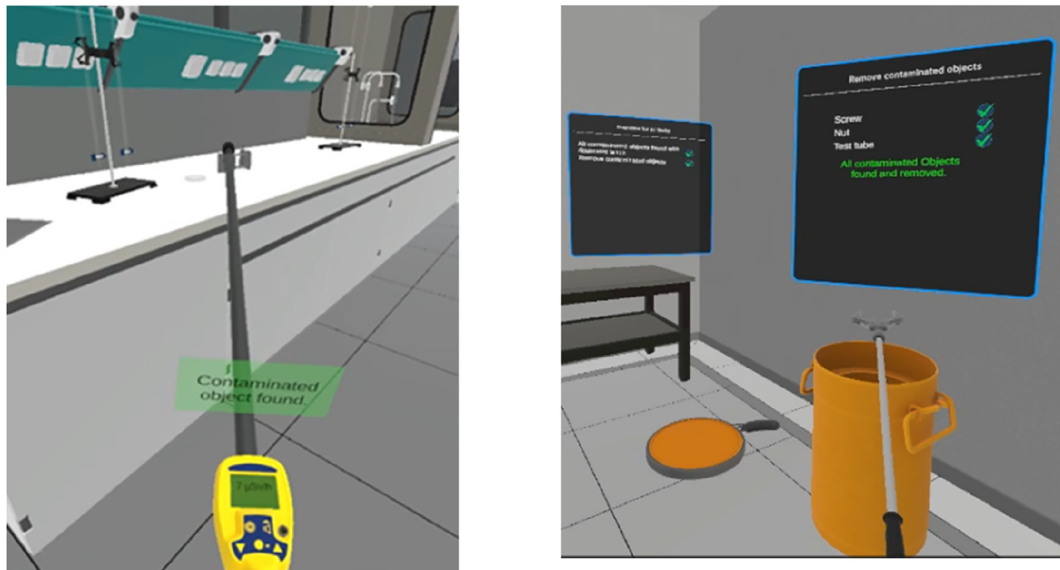


Figure 1: Selected interactive learner actions in Scenario 1A, showing hotspot localization with a dosimeter lance (left) and safe disposal of radioactive items using a grabber tool (right).

covers, and dosimeter) from a set of available items on a preparation table. Upon entering the room, the trainee performs an initial contamination measurement with the Kontamat and subsequently begins decontamination using a mop. The liquid must be scrubbed until no visible residue remains, after which the contaminated mop head cover must be removed and disposed of without spreading the contamination. A wipe test is then carried out using a pad and an alpha-beta monitor. Because the first wipe test is designed to return a positive result, the trainee must repeat the decontamination process – scrubbing, disposing of the mop cover, and conducting another wipe test. After the second cycle, the trainee performs a final measurement and disposes of all used personal protective equipment in the designated bin for flammable radioactive waste. Selected learner actions from this scenario are illustrated in Figure 2.

2.1.2.2 Nuclear safeguards scenario

Nuclear safeguards are technical measures ensuring that nuclear materials and activities are used solely for peaceful purposes, in line with international agreements such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and regulations from the International Atomic Energy Agency (IAEA) and European Atomic Energy Community (EURATOM). Through, for example, inspections and continuous monitoring, these measures aim to detect and deter the misuse or diversion of nuclear materials and technologies. A key element is the application of seals on CASTOR® casks used for transporting and storing spent fuel.

For states under integrated safeguards, including Germany, the IAEA requires continuity of knowledge during transport and long-term storage. Due to the inaccessibility of nuclear material during interim dry storage, these CASTOR® casks, once loaded with spent fuel, must be under dual containment and surveillance. To meet this requirement, the IAEA and EURATOM implement two independent sealing systems, alongside continuous surveillance. Loading and transferring CASTOR® casks is complex, as the CASTOR® casks require a drying process before sealing, with varying times. To prevent inspectors from remaining on site, the IAEA and EURATOM developed a procedure that allows German operators to apply seals in their absence (Aymanns et al. 2017). The subsequently presented training scenarios equip operators and inspectors with the skills needed to apply and verify active and passive seals – based on EOSS and COBRA designs.

Application of passive and active seals on CASTOR® casks by nuclear facility operations professionals in the reactor hall (Scenario 2A). The learning objective of this scenario is to train nuclear facility operators in the correct application of both passive and active seals on CASTOR® casks within the reactor hall (see Figure 3).

This training is designed to ensure that operators can accurately identify different types of seals and apply them in the correct manner. Trainees will begin by selecting the appropriate tools for the sealing process, ensuring they understand which tools are needed for each type of seal. They will then proceed to apply the seals in the proper sequence, starting with the correct positioning of the seals on the

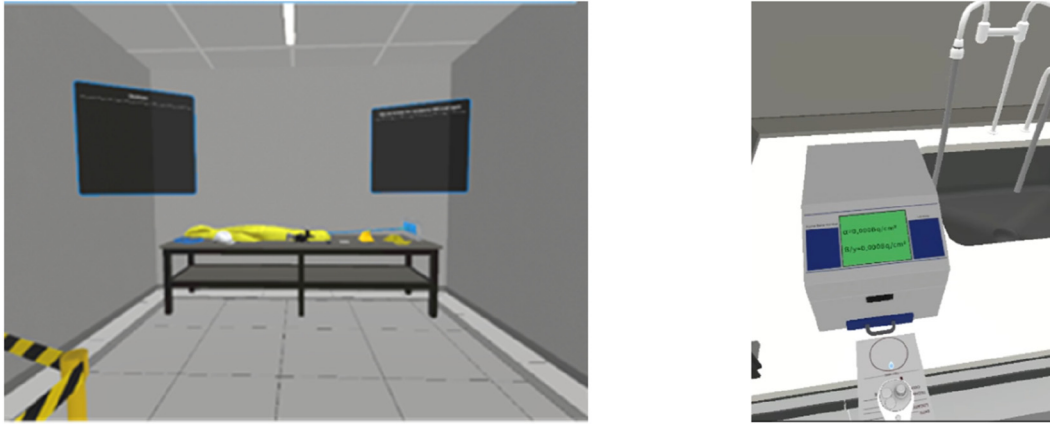


Figure 2: Selected interactive learner actions in Scenario 1B, including the selection of required tools and protective equipment (left), and the performance of a wipe test using an alpha-beta monitor (right).



Figure 3: Reactor hall shown in the VR training. The trainee stands in front of the CASTOR® cask.

CASTOR® cask lid. The scenario emphasizes the importance of maintaining the integrity of the seals during the transfer of the CASTOR® casks, ensuring they remain securely in place throughout transport to the interim storage facility.

Seal verification and replacement on the CASTOR® cask by an inspector in the interim storage facility (Scenario 2B). The objective of this scenario is to train inspectors in the process of verifying the integrity of passive and active seals on CASTOR® casks and performing seal replacement in the interim storage facility. The trainee begins by moving through the facility, entering the meeting room to simulate collecting documents and completing the initial coordination with the operator. They then proceed to the locker room to select and equip the required personal protective equipment (PPE). Once prepared, the trainee enters the technical room to choose the correct tools for verifying the seals and replacing the active seal with a passive one. Before accessing the transport area and storage hall, they perform a hand-foot contamination check as part of standard safety protocols. The articulated working platform is positioned near the CASTOR® cask and raises to the correct height, allowing the

trainee to access the cask lid (see Figure 4). The trainee first verifies the integrity of the seals, then removes the active seal using the proper procedures. They then install a new passive seal, following the established steps from Scenario 2A with the correct tools and installation sequence. After completing the task, the trainee leaves the storage hall, performs a hand-foot contamination check, returns the PPE in the locker room, and exits the building via the meeting room and entrance area.

2.1.3 Didactic concept

The learning scenarios supported by the VR-enhanced training are embedded within a structured training procedure. From an educational science perspective, VR is particularly suitable for enabling learners to apply previously acquired theoretical knowledge in a practical context. For this reason, a (1) preparatory phase is essential to establish the conceptual foundations that learners will later draw upon in the VR environment. This is followed by an (2) application phase in which learners actively engage with the

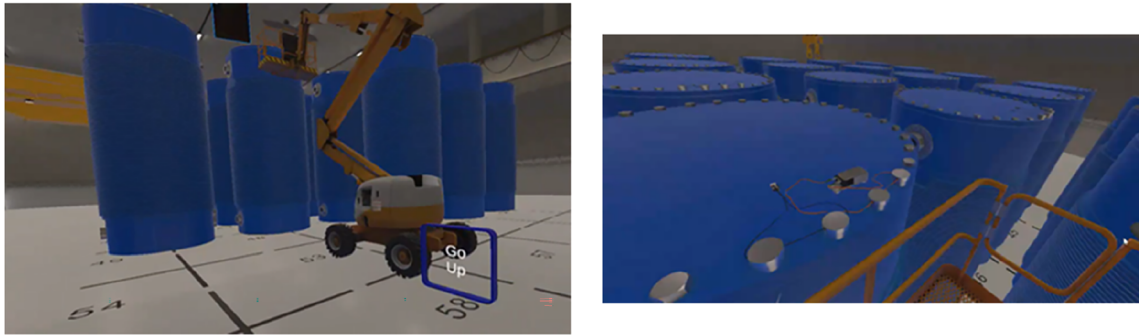


Figure 4: Safeguards seal handling scenario, showing (left) the elevated work platform used in the storage hall and (right) a passive seal to be inspected.

VR-based training scenario and apply the theoretical content in a situated, practice-oriented manner. A subsequent reflection phase will further support learning by helping participants articulate implicitly acquired insights and by addressing aspects that could not be represented within the VR scenario due to technical or didactic constraints. The three phases and their core didactic components are summarized in Table 1.

This training procedure is currently under development and has not yet been fully implemented in practice. At the current stage, the primary objective was to test the VR training prototype and its application phase with experienced personnel, such as project engineers and radiation protection workers, to gather initial insights into user experience and the perceived didactic value of the system in

a nuclear-technical context. The evaluation also serves to identify aspects that may need to be addressed outside the VR environment due to technical, organizational, or didactic constraints.

2.2 Research design

A convergent mixed methods design (Creswell and Creswell 2023) was employed in this study, combining primarily quantitative data from standardized questionnaires using predominantly closed-ended and a small number of open-ended items with qualitative data from in-depth semi-structured interviews conducted to further explore and contextualize participants' responses. Although both quantitative and qualitative components were collected within the same overall data collection phase, they were analyzed separately and subsequently integrated to provide a more comprehensive understanding of participants' perspectives. This design was chosen because it allows measurable response patterns to be examined alongside participants' detailed explanations, supports the triangulation of findings across methods, and increases the robustness and interpretive depth of the conclusions.

2.2.1 Research environment

The training sessions were conducted at two operational nuclear industry sites: the facilities of Jülicher Entsorgungsgesellschaft für Nuklearanlagen mbH, a specialized company responsible for the decommissioning and waste management of nuclear installations, and Advanced Nuclear Fuels GmbH (Framatome), a manufacturer of nuclear fuel assemblies operating within a high-reliability, safety-critical industrial environment. At both sites, the radiation-protection training scenarios were tested with specialized personnel from the respective organizations. The VR-enhanced training setup was installed in dedicated

Table 1: Structured training procedure integrating the VR-based scenarios.

#	Phase	Content
1	Preparatory phase	Learners are prepared for the subsequent application phase or prepare themselves, depending on the implementation context – either within an in-company training setting or as part of a formal qualification program. Preparation may include expert-led briefings and/or self-directed study using appropriate learning materials, such as instructional videos, web-based training, or handouts.
2	Application phase	Learners apply previously acquired theoretical knowledge within the VR learning scenario.
3	Reflection phase	Learners review and reflect upon the VR scenario, engage in follow-up learning activities, and may document or further elaborate on outcomes from the application phase. This reflection is supported by experienced trainers or by structured materials, such as guiding questions. The reflection phase also addresses elements that could not be represented in VR for technical or didactic reasons, including organization-specific procedures or contextual knowledge.

conference rooms at each location, allowing multiple mobile units – consisting of Meta Quest 3 headsets with controllers, notebooks, and connection cables – to be placed side by side to ensure comparable test conditions. The previously described prototypes were executed on the notebooks as tethered VR applications. This configuration provided a controlled yet contextually authentic environment for systematically assessing user experience, as well as the instructional added value and suitability of the VR training system, while accommodating the logistical constraints of active nuclear industry sites.

2.2.2 Measures

2.2.2.1 Questionnaire

Sociodemographic variables. Participants' age, perceived gender, qualification, current role within the company, tenure, and years since qualification in nuclear engineering or radiation protection were assessed using five targeted items. Age was measured with the open-ended question "In which year were you born?". Perceived gender was captured with the question "Which gender do you identify yourself with?" offering the response options female, male, diverse, and other. Participants' current role within their company was assessed using the open-ended question "What is your current role within your company?". Tenure and years since qualification in nuclear engineering or radiation protection were measured using the questions "For how many years have you been employed at your company?" and "How many years ago did you complete your professional qualification in nuclear engineering/radiation protection?", respectively, requiring an open numeric response.

Prior VR experience. Since no validated questionnaire exists for assessing prior experience with VR technologies, the study employed an ad-hoc item previously developed and used by Dyrna et al. (2025). Participants were asked: "How frequently have you used virtual reality (VR) technologies (e.g., Meta Quest, PlayStation VR, or 360° VR experiences in museums/exhibitions) prior to today's tests?" Responses were recorded on a 5-point Likert scale ranging from "very rarely" to "very often", with an additional option "never" to capture participants without any prior exposure.

Domain-specific knowledge. Participants' prior knowledge in domains relevant to the VR training was assessed using a self-report question asking them to rate their experience or knowledge prior to completing the VR scenarios. Three topic areas were evaluated: (1) radiation measurement, (2) decontamination, and (3) nuclear waste management. For each topic, participants indicated their perceived level of prior knowledge on a 5-point Likert scale ranging from "very low" to "very high."

Perceived didactic task design and overall didactic value.

As no standardized instruments are available for assessing perceptions of didactic task design and overall didactic value of the VR-based training, three ad-hoc items were developed for this study. The items addressed (1) the clarity of the task and procedural flow ("The task and procedure were clear to me at all times."), (2) the perceived didactic added value of the mobile training station ("I see added didactic value in using the mobile training station."), and (3) participants' willingness to recommend the system ("I would recommend the mobile training station to others."). Participants indicated their agreement on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree."

Enjoyment. Learners' enjoyment during the training, conceptualized as an affective component of the user experience, was measured using the Interest/Enjoyment subscale of the Intrinsic Motivation Inventory (IMI; Ryan 1982). The subscale originally included seven items. However, one item was excluded from the analysis because its inclusion resulted in unacceptable reliability. The remaining items ($\alpha = 0.64$) included statements such as "I enjoyed doing this activity very much." All items were rated on a 5-point Likert scale ranging from "does not apply at all" to "fully applies."

Spatial presence. Spatial presence, conceptualized as a cognitive component of the user experience, was assessed using the spatial presence subscale of the Temple Presence Inventory (TPI; Lombard et al. 2009). The subscale originally consisted of seven items. However, one item was removed from the analysis because its inclusion resulted in unacceptable reliability. The remaining items ($\alpha = 0.80$) included statements such as "To what extent did you experience a sense of being there inside the environment you saw/heard?" All items were rated on a 5-point Likert scale ranging from "not at all" to "very much."

Perceived individual training effectiveness. As no standardized scale was available to assess participants' perceptions of the VR training's effectiveness for their own professional performance, a set of four ad-hoc items was developed for this study. The items addressed the extent to which participants considered the training to improve their job performance ("The use of the training improves my job performance."), increase their productivity ("The use of the training increases my productivity at work."), enhance their effectiveness ("The use of the training enhances my effectiveness at work."), and be useful for their work ("I find the training useful for my work."). Internal consistency of the four-item scale was high ($\alpha = 0.92$). All items were rated on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree."

Perceived training effectiveness for prospective professionals. Since no standardized measures existed to assess

perceptions of the VR training's effectiveness for individuals entering the profession, a parallel four-item ad-hoc scale was developed. The items evaluated the extent to which participants believed the training would improve the job performance ("The use of the training improves the job performance of prospective professionals."), increase the productivity ("The use of the training increases the productivity of prospective professionals at work."), enhance the effectiveness ("The use of the training enhances the effectiveness of prospective professionals at work."), and be useful for their work ("I find the training useful for the work of prospective professionals."). Internal consistency of this scale was excellent ($\alpha = 0.95$). All items were rated on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree."

Perceived learning for prospective professionals. Since no standardized measures existed to assess participants' perceptions of the learning gains that prospective professionals might derive from the VR training, a set of four ad-hoc items was developed. The items captured the extent to which participants believed the training would (1) substantially improve prospective professionals' understanding of the topics covered ("The training significantly improves prospective professionals' understanding of the topics addressed."), (2) enhance their knowledge and understanding of radiation protection ("The training significantly improves prospective professionals' knowledge and understanding of radiation protection."), (3) strengthen their understanding of the operational procedures involved ("The training significantly improves prospective professionals' understanding of the procedures addressed."), and (4) deepen their grasp of key concepts and definitions ("The training significantly improves prospective professionals' understanding of concepts and definitions."). Internal consistency of the four-item scale was high ($\alpha = 0.91$). All items were rated on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree."

2.2.2.2 Semi-structured interview guide

To complement the questionnaire data, semi-structured interviews were conducted using a structured interview guide developed specifically for this study. The guide comprised three thematic areas – general perception, hedonic reactions, and perceived didactic value – and included pre-defined guiding questions to ensure comparability across interviews while allowing participants to elaborate freely. In the section on general perception, participants were invited to describe their overall impressions of the VR training ("How did you experience the VR training?") and to reflect on the degree to which they felt present in the virtual environments ("To what extent did you feel as if you were

actually present in the virtual rooms?"). The section on hedonic reactions focused on emotional responses, perceived positive and negative aspects, interest, and stressors. Participants were asked what they noticed positively ("What stood out to you positively?"), what they found exciting or interesting ("What did you find exciting or interesting?"), what they noticed negatively ("What stood out to you negatively?"), what they found uninteresting ("What did you find uninteresting?"), and which stressors they experienced ("Which stressors did you experience?"). The section on perceived didactic value prompted participants to reflect on how well the VR scenarios related to their own work ("To what extent do the scenarios shown in the VR application correspond to your work tasks?") and how they evaluated the added value of the training compared with existing training approaches ("How do you assess the added value of the VR training compared to previous training approaches?"). Participants were also encouraged to mention any important aspects not yet addressed ("Which additional important aspects became apparent to you while using the VR application?").

2.2.3 Procedure

The VR training scenarios were tested with specialized personnel from the respective organizations. At the beginning of each test phase, participants were informed about the objectives and background of the research project and the intended use of the VR training. They were then briefed on safety procedures and data protection, provided informed consent, and received a short introduction to the operation of the VR training and the VR headset. This was followed by a 30–40 min training phase in which participants independently completed the VR training scenarios under instructor supervision. Each training station was supervised by a dedicated instructor, enabling individual guidance, continuous exchange, and the collection of immediate feedback, while ensuring safe and intuitive use of the system. No test phase had to be terminated prematurely.

Immediately after completing the VR training, participants filled out the structured questionnaire described above. In a subsequent step, selected participants took part in brief semi-structured follow-up interviews based on the previously described interview guide. Depending on the participants' depth of responses, the interviews lasted between 5 and 15 min. Both the questionnaire-based measures and the interview procedures were implemented identically at both test sites, ensuring direct comparability of the resulting data.

2.2.4 Sample

In total, 13 experienced nuclear personnel participated in the evaluation of the VR training, including radiation-protection workers, technical specialists, and project engineers. These professional groups were selected because they routinely perform radiologically relevant tasks, follow strict procedural and safety requirements, and therefore possess the practical and domain-specific expertise required to meaningfully evaluate the user experience, didactic design and value, and perceived effectiveness of the VR scenarios. Based on the occupational information provided, participants' professional backgrounds fell into three groups: radiation protection personnel ($n = 5$; including radiation-protection workers, radiation-protection specialists, and radiation-protection officers), technical and operational specialists ($n = 4$; including decontamination staff, nuclear technical workers, and dismantling personnel), and engineering and planning personnel ($n = 4$; including planning engineers, project engineers, and safety engineers).

Participants were on average 44.08 years old ($SD = 9.95$; median = 42; range: 31–60). Regarding gender, 85 % identified as male ($n = 11$) and 15 % as female ($n = 2$), with no participant identifying as diverse. The sample covered a broad range of professional experience, with an average tenure of 10.73 years at the current company ($SD = 13.69$; median = 3; range: 0.5–35). Participants had completed their professional qualification in nuclear engineering or radiation protection an average of 13.46 years prior to the study ($SD = 13.11$; median = 6; range: 3–35). Self-assessed domain-specific knowledge was highest in the area of radioactive waste management ($M = 4.15$; $SD = 0.99$; range: 2–5), followed by radiation measurement ($M = 4.00$; $SD = 1.00$; range: 2–5) and decontamination procedures ($M = 3.85$; $SD = 0.99$; range: 2–5), indicating consistently high levels of expertise across all three domains.

Regarding prior experience with VR technologies, 53.8 % of participants reported having used VR before the study ($n = 7$), whereas 46.2 % had no previous contact with VR systems ($n = 6$). Among those with prior experience, the reported frequency of VR use was moderate ($M = 2.43$; $SD = 1.40$; median = 3; range: 1–4). This distribution aligns with findings indicating that overall VR familiarity in Germany remains relatively low (Dyrna et al. 2025), and such limited prior exposure can also reasonably be expected among professionals in the nuclear sector, where immersive technologies have only recently begun to be explored for training purposes.

2.2.5 Data analysis

All questionnaire data collected using paper-based instruments were digitized and prepared for analysis following standard data-cleaning procedures. This included checking for completeness, coding all item responses, and screening the dataset for input inconsistencies. The cleaned dataset was subsequently analyzed using IBM SPSS Statistics 30, with descriptive statistics (means, standard deviations, medians, ranges, and frequencies) computed for all variables. Scale scores were calculated according to the specifications of the respective instruments, and internal consistency was examined where applicable. The qualitative interview data were analyzed using a structured thematic analysis approach that combined both deductive and inductive elements. All interview responses were transcribed or transferred into a standardized tabular format and subjected to an initial review. Based on the interview material, a multi-level coding framework was developed that integrated concepts from user experience research, technology-enhanced learning, and the didactic objectives of the VR training scenarios (see Table 2). All interview segments were systematically coded, including multiple coding where statements addressed more than one thematic aspect. The coded material was then synthesized to identify recurring patterns and contrasting perspectives, thereby enriching and contextualizing the quantitative findings.

Following the separate analyses, quantitative and qualitative findings were integrated within a convergent mixed-methods framework. Response patterns and interview themes were systematically compared to identify convergence, complementarity, and divergence, thereby enabling a more comprehensive interpretation of the VR training's user experience and didactic value.

3 Results

3.1 Quantitative findings

Perceived Didactic Task Design and Overall Didactic Value. The clarity of the task and procedural flow was rated with a mean of 4.15 ($SD = 0.80$, median = 4.00, range = 3–5). All ratings fell into the moderately high (3.41–4.20) or high (4.21–5.00) value segments. Specifically, 23.1 % of the responses were in the moderately high range (value = 3), while 38.5 % were in the moderately high range (value = 4), and another 38.5 % in the high range (value = 5). No responses fell below

Table 2: Thematic coding structure used in the qualitative data analysis.

Main category	Subcategory	Description	Example quotation
User experience	General experience	Overall impressions of the VR training, including clarity, realism, orientation, and intuitive handling.	<i>“Overall, I experienced the VR training as clear and easy to navigate.”</i>
	Cognitive experience	Perceptions related to immersion, spatial presence, mental workload, and cognitive engagement.	<i>“The virtual environment felt quite immersive at times, almost like being on-site.”</i>
	Affective experience	Emotional reactions such as enjoyment, surprise, interest, or stress.	<i>“I was initially skeptical, but the training turned out to be surprisingly engaging.”</i>
	Behavioral experience	Interaction and control aspects, including handling objects, navigating the environment, and operating VR controls.	<i>“The controls felt unfamiliar at first, but I got used to them quickly.”</i>
Didactic value	Didactic clarity	Clarity of task instructions, workflow, objectives, and feedback within the VR scenario.	<i>“At times, I wasn’t sure why I was supposed to use certain tools.”</i>
	Didactic added value	Perceived learning benefits, improved understanding, or added instructional value compared to conventional training.	<i>“The training conveyed the basic principles very well.”</i>
	Work-task relevance/utility	Alignment between the VR scenario and actual job tasks or operational workflows.	<i>“For radiation protection staff, this type of scenario is highly relevant for everyday work.”</i>
	Transferability/applicability	Usefulness of the training for specific groups, particularly novices or trainees.	<i>“For newcomers, this kind of VR training would be extremely helpful.”</i>
	Limitations/missing elements	Aspects that VR cannot (yet) represent adequately, such as physical effort, procedural nuances, or plant-specific details.	<i>“Some parts of the scenario are less relevant in real labs, where source locations are already known.”</i>
Utility and optimization potential	Optimization needs	Improvement suggestions, missing features, or desired refinements of the VR training.	<i>“A more detailed introduction to the task would make the training even more effective.”</i>

the moderately high segment. *Participants’ perceived added value of using the VR training* showed a mean of 4.62 (SD = 0.65, median = 5.00, range = 3–5). Ratings were concentrated in the highest segments of the scale. One response (7.7 %) fell in the moderately high category (value = 3), 23.1 % in the moderately high category (value = 4), and 69.2 % in the highest category (value = 5). No values were reported below 3. The *intention to recommend the VR training* was rated with a mean of 4.54 (SD = 0.66, median = 5.00, range = 3–5). Distribution across quintile categories showed that 7.7 % of participants reported moderately high values (value = 3), 30.8 % reported moderately high values (value = 4), and 61.5 % fell into the high value segment (value = 5). No responses were in the lower three value categories.

Enjoyment ratings were consistently located in the upper end of the scale. The mean enjoyment score was 4.46 (SD = 0.38, median = 4.50, range = 3.67–5.00), and all responses fell within the two highest value segments (4.21–5.00). Individual ratings ranged from 3.67 to 5.00, with the most frequent values being 4.67 (23.1 %) and 4.83 (15.4 %), indicating that all participants selected values within the “moderately high” to “high” range of the five-level segmentation.

Spatial presence showed a broader distribution across the scale. The mean was 3.24 (SD = 0.74, median = 3.33, range = 1.50–4.00). The frequency distribution covered all five quintile categories: 23.1 % of the ratings were in the very low to low range (1.00–2.60), 30.8 % in the moderate range (2.61–3.40), and 46.2 % in the moderately high range (3.41–4.20). No values were located in the highest segment (4.21–5.00). The individual responses ranged from 1.50 to 4.00.

Perceived individual training effectiveness showed values across the full range of the scale. The mean was 3.29 (SD = 1.03, median = 3.25, range = 1.50–5.00). Fifteen-point-four percent of responses fell into the very low segment (1.00–1.80), 7.7 % into the low segment (1.81–2.60), 30.8 % into the moderate segment (2.61–3.40), 30.8 % into the moderately high segment (3.41–4.20), and 15.4 % into the high segment (4.21–5.00). The values therefore spanned all five quintile categories.

Perceived training effectiveness for prospective professionals was rated more favorably. The mean was 3.88 (SD = 1.07, median = 4.25, range = 1.75–5.00). Most values were in the upper two quintile categories, with 30.8 % in the moderate range (2.61–3.40), 7.7 % in the moderately high range (3.41–4.20), and 53.8 % in the high range (4.21–5.00).

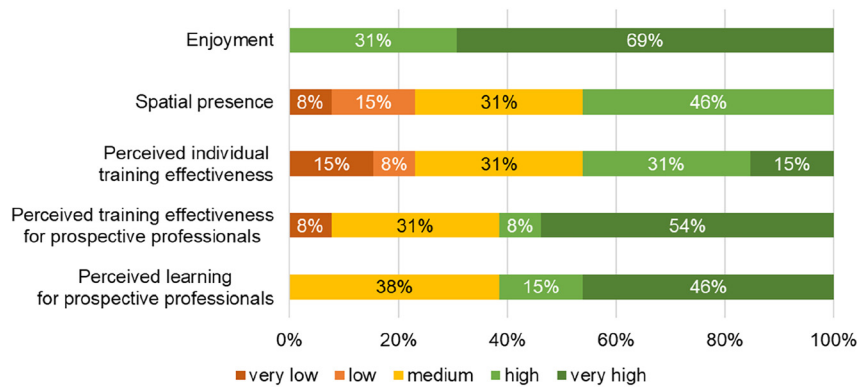


Figure 5: Percentage distribution of responses for enjoyment, spatial presence, and the three measures of perceived training effectiveness.

One rating (7.7 %) fell in the low range (1.81–2.60), and none in the very low segment.

Perceived learning for prospective professionals yielded a mean of 3.94 (SD = 0.82, median = 4.00, range = 2.75–5.00). No ratings were located in the very low or low value segments. Instead, 30.8 % of values fell within the moderate range (2.61–3.40), 30.8 % within the moderately high range (3.41–4.20), and 38.5 % within the high range (4.21–5.00). The ratings therefore clustered in the upper three quintile categories. Figure 5 summarizes the five key quantitative measures by showing the distribution of responses across the full range from very low to very high.

3.2 Qualitative findings

3.2.1 User experience

General Experience. Across participants, the VR training was generally described as coherent and easy to follow. Several users highlighted that the scenario felt well-structured and intuitive, noting that “the training was very well put together and easy to understand” (P10). Others emphasized the overall usability and completeness of the experience, referring to it as a “super simulation” (P4). These comments indicate that participants perceived the basic workflow and navigational structure as straightforward, even when interacting with VR technology for the first time.

Cognitive Experience. Participants’ cognitive responses centered on immersion, realism, and task difficulty. Some described parts of the environment as convincingly realistic – “certain sections felt like being in an actual controlled area” (P6) – while others pointed out fluctuations in immersion, observing that it was “limited in some areas” (P6). Cognitive challenge also emerged as a theme. Especially tasks involving the identification of contaminated objects were described as demanding, with one participant remarking that “finding the contaminated test tube was really difficult” (P7).

These reflections show that cognitive engagement varied across tasks and depended on both scenario complexity and VR fidelity.

Affective Experience. Affective reactions were consistently positive. Many participants reported that the training elicited a stronger emotional engagement than anticipated. One participant explained that they “were skeptical at first, but then really positively surprised” (P4), while another described that it “became fun once I got into it” (P10). The search tasks were perceived as engaging and stimulating – “the search for the source was genuinely interesting” (P7) – suggesting that the VR format successfully supported affective involvement, which can be an important precursor to motivation and attention in training contexts.

Behavioral Experience. Participants also reflected on the physical and interactive aspects of the VR sessions. Some reported an initial adaptation phase – “the controls were unfamiliar at first, but you get used to them quickly” (P10) – followed by increasing fluency as the session progressed. Others mentioned awkward or physically demanding postures, such as having to lean or twist the body to read measurement values, commenting that they “sometimes had to take on uncomfortable postures” (P3). These responses capture the learning curve and physicality of interacting with VR interfaces and point to areas where interaction design could be optimized.

3.2.2 Didactic value

Didactic Clarity. Participants expressed a need for clearer instructional support in certain parts of the training. This included both task explanations and contextual information. As one participant noted, “I didn’t always know why I was supposed to use certain tools” (P6). Another highlighted the usefulness of additional scenario details, such as specifying the type of spilled substance: “It would help to know which liquid had leaked” (P7). Suggestions for enhancing the introductory phase were also common, with participants

indicating that a more structured briefing could improve understanding of the task flow.

Didactic Added Value. Participants widely acknowledged that the VR training effectively conveyed fundamental principles relevant to radiation protection. Statements such as “the basic principles are conveyed well” (P10) illustrate this perception. Several interviewees also emphasized that the system could support the teaching of procedural and safety-related competencies. One participant noted that the application could “train safety-relevant procedures quite effectively” (P12). These accounts underline the educational potential of VR as a tool for conceptual and procedural learning in controlled environments.

Work-Task Relevance/Utility. The relevance of the VR scenarios to real work tasks was highlighted, particularly by participants in radiation protection roles. For example, one participant stated that “for radiation protection workers, this training is very useful” (P10). At the same time, some participants with different job profiles pointed out contextual limitations for instance, that in well-equipped laboratories, sources do not need to be located because their positions are known, making certain VR tasks “less relevant in that setting” (P6). Overall, the perceived utility was strongly tied to the proximity between VR tasks and the participants’ actual responsibilities.

Transferability/Applicability. A recurring theme was the strong suitability of the VR training for newcomers, trainees, or students. Participants described the system as “a great thing for newcomers” (P9) and emphasized that the scenarios could be applied in various training contexts, including formal qualification settings such as state-recognized vocational examinations. Others noted that the VR system could be beneficial for groups without access to controlled areas, for instance, “students or apprentices could work with this very well” (P12). These statements suggest a wide perceived applicability for early-stage competency development.

3.2.3 Utility and optimization potential

Participants also offered specific suggestions for improving the training experience. These included providing a more detailed introduction, adding contextual details, refining interaction mechanics, and expanding the range of available scenarios. A particularly important suggestion concerned collaborative training. One participant emphasized that many radiation-protection tasks are typically carried out by two-person teams and that the VR system should reflect this. That participant stated that “it would be good if the training could also be done in pairs” (P10). This point highlights a key

opportunity for increasing ecological validity and supporting the development of teamwork-related competencies.

3.3 Mixed methods integration

The integration of quantitative and qualitative findings reveals a coherent overall pattern regarding the user experience and instructional value of the VR training. Across constructs, convergence, complementarity, and divergence can be systematically identified (see Table 3). High quantitative enjoyment ratings were strongly corroborated by interview data describing the training as engaging and positively surprising, indicating robust affective involvement. Spatial presence showed greater variability in the quantitative data, which was mirrored in qualitative accounts of fluctuating immersion depending on scenario realism and interaction fidelity. Task clarity and perceived didactic added value were rated highly and confirmed qualitatively, although interview data provided additional nuance by identifying specific areas where clearer instructions or contextual information would enhance learning.

A differentiated pattern emerged regarding training effectiveness. While perceived personal effectiveness varied substantially, ratings for prospective professionals were consistently higher. This divergence was explained qualitatively through role-dependent relevance: experienced staff evaluated usefulness in relation to their specific work context, whereas novices were perceived as benefiting substantially from structured exposure to core procedures and safety principles. Finally, qualitative insights extended beyond the scope of the quantitative measures by identifying concrete optimization opportunities, including enhanced onboarding guidance, improved interaction fidelity, and the potential integration of collaborative multi-user formats. Together, these findings indicate that the VR training is perceived as affectively engaging, instructionally coherent, and particularly effective for early-stage professional development, while also highlighting targeted pathways for refinement.

4 Discussion

The present study investigated the participatory development and initial evaluation of immersive VR-based training scenarios for radiation protection and nuclear safeguards. By integrating quantitative and qualitative findings, the study provides insight into how experienced nuclear

Table 3: Integrated mixed-methods interpretation of the results.

Construct	Quantitative finding	Qualitative finding	Integrated interpretation
Enjoyment	Enjoyment ratings were consistently high across participants.	Participants described the training as engaging, surprising, and enjoyable (e.g., positively surprised, increased enjoyment over time).	Strong convergence: both strands indicate high affective engagement with the VR training.
Spatial presence	Spatial presence ratings showed substantial variability across participants.	Participants reported fluctuating immersion, with some moments feeling realistic and others less convincing.	Convergence with nuance: presence was experienced inconsistently, shaped by scenario realism and interaction design.
Task clarity	Task clarity was generally rated as high, with few critical responses.	Overall clarity was acknowledged, but participants noted specific instances where instructions or contextual information could be clearer.	Complementary: general clarity is confirmed, while qualitative data identify targeted areas for instructional refinement.
Didactic added value	Participants rated the learning value of the VR scenarios positively.	Interviewees emphasized that core principles and safety-related procedures were conveyed effectively.	Strong convergence: VR supports conceptual and procedural understanding.
Recommendation intention	Participants expressed strong willingness to recommend the VR training.	Interviews highlighted perceived usefulness and positive overall impressions of the training.	Reinforcing: high acceptance and perceived utility across both strands.
Training effectiveness (self)	Perceived personal training effectiveness varied considerably across participants.	Variability was explained by job-role differences and perceived relevance of scenarios to actual tasks.	Divergence explained: quantitative variability matches qualitative role-dependent relevance.
Training effectiveness (novices)	Participants rated the VR training as particularly useful for prospective professionals.	Interview data highlighted its suitability for newcomers and those without access to controlled environments.	Clear convergence: VR is particularly effective for early-stage training and onboarding.
Learning outcomes (novices)	Participants perceived strong learning benefits for novices.	Interviews described improved understanding of principles, procedures, and safety competencies.	Reinforcing: VR effectively supports novice learning across multiple domains.

professionals perceived the prototype in terms of user experience, instructional value, and contextual relevance.

could enhance agency and flow. Overall, the results suggest that the current level of immersion is sufficient to support engagement without overburdening users cognitively.

4.1 User experience

Across methods, participants experienced the VR training as accessible, engaging, and intuitive. High enjoyment ratings were reflected in interview accounts describing the training as motivating and positively surprising, even among participants with limited prior VR exposure. This aligns with research demonstrating the motivational benefits of immersive VR in educational contexts (Makransky et al. 2019; Yang et al. 2023). Spatial presence was experienced at a moderate level. Participants reported moments of convincing realism alongside limitations in interaction fidelity and environmental detail. These findings are consistent with immersive learning models (Makransky and Petersen 2021; Mulders et al. 2020), which emphasize that effective learning does not require maximal immersion but rather an appropriate balance between presence and cognitive manageability. User experience feedback further indicated that the interaction design was largely functional, though refinements in object handling and visual feedback

4.2 Perceived didactic design and instructional value

Both quantitative and qualitative data underscore the instructional coherence of the VR scenarios. Task sequences were perceived as structured and aligned with realistic operational workflows, and participants acknowledged clear didactic added value, particularly for early-stage training. Importantly, the findings reveal a differentiated perception of effectiveness. While experienced professionals evaluated usefulness in relation to their specific roles, the training was consistently regarded as highly beneficial for novices. This supports the assumption that immersive VR can serve as a safe, high-fidelity entry point into complex and safety-critical work domains. Qualitative insights further highlighted areas for refinement, particularly regarding instructional scaffolding. Participants suggested clearer explanations of task rationales and more explicit contextual framing. These recommendations resonate with

established immersive learning frameworks, which stress guided practice, structured onboarding, and reflective consolidation as critical components of effective VR-based instruction (Makransky and Petersen 2021; Mulders et al. 2020).

4.3 Opportunities for expansion and optimization

Beyond confirming the prototype's viability, participants identified targeted development pathways. Suggested improvements included enhanced preparatory guidance, refined interaction fidelity, expanded scenario variability, and the integration of collaborative multi-user functionality to reflect real-world team-based workflows. Incorporating such features could increase ecological validity and extend the instructional scope of the system. In particular, collaborative modes align with emerging research on immersive collaborative learning environments (Dyrna et al. 2023; Makransky and Petersen 2023), suggesting potential for fostering communication and coordinated problem-solving competencies in addition to procedural skills. Taken together, the findings indicate that immersive VR can function as an engaging and instructionally meaningful complement to conventional training in the nuclear sector, especially under conditions of limited facility access and increasing workforce transition.

5 Conclusions

This study examined the participatory development and initial evaluation of immersive VR-based training scenarios for radiation protection and nuclear safeguards. The findings indicate that the prototype is perceived as engaging, instructionally coherent, and particularly suitable for early-stage qualification. By enabling structured interaction with radiological procedures that are difficult to access in real facilities, immersive VR emerges as a meaningful complement to existing training formats in safety-critical environments.

5.1 Implications

From a practical perspective, these findings relate directly to broader structural challenges outlined in the introduction, including the shrinking availability of qualified personnel, declining training capacities, and restricted access to controlled areas (Kettler et al. 2025). In this context,

immersive VR represents one component within a wider digital transformation of nuclear competence development. As a portable and scalable medium, it can help compensate for reduced physical training infrastructure by enabling repeatable, risk-free rehearsal of complex procedures and supporting the onboarding of new personnel.

For implementation, the results underscore that VR should not function as a standalone solution but be embedded within structured qualification pathways that include preparation, guided application, and reflective consolidation. As decommissioning progresses and the need for efficient knowledge transfer grows, VR-based training environments may increasingly serve as a bridge between theoretical instruction, digitally supported learning processes, and supervised practice in operational settings, complementing other emerging tools such as digital learning platforms, AI-assisted guidance systems, and secure documentation technologies.

5.2 Limitations

Several limitations of this study should be considered when interpreting the results. First, the findings are based on a relatively small sample, which restricts the generalizability of the conclusions and calls for replication with larger and more diverse participant groups. Furthermore, only a prototype consisting of four scenarios covering two specific training topics was evaluated. This limited thematic scope constrains the extent to which the results can be generalized to other radiation-protection or safeguards tasks. The evaluation was also conducted at two individual organizations, meaning that local work practices or contextual conditions may have influenced participants' perceptions and may differ across other nuclear facilities.

Methodologically, some measurements relied on ad-hoc items developed specifically for this study. Although these scales exhibited very good internal consistency, their broader psychometric properties remain to be validated. In addition, the study focused on perceived instructional value, user experience, and subjective assessments rather than direct measures of learning. Consequently, no conclusions can be drawn regarding actual knowledge acquisition, procedural accuracy, or the transfer of skills to real operational environments.

5.3 Future directions

Future research should extend both the empirical scope and the practical breadth of VR-based training in the nuclear

domain. Controlled studies with novice learners are needed to examine measurable learning outcomes, procedural accuracy, and transfer to operational settings. Longitudinal and cross-site investigations would further clarify how immersive VR can be sustainably embedded within qualification systems. At the same time, development efforts should broaden the range of VR applications and explore additional radiological, operational, and safeguards-related scenarios. Their implementation may be guided by multidimensional frameworks for introducing VR into professional contexts, which account for didactic, organizational, technological, economic, and cultural factors (e.g., Fischer et al. 2021). Such work will help determine how immersive environments contribute to long-term knowledge preservation and competence development as demands on efficient knowledge transfer continue to increase.

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