ACTA ELECTRONICA UNIVERSITATIS LAPPONIENSIS 430

Anu Lehikko

Synthesizing Sociocultural and Cognitivist Approaches to Learning in a Simulation-Based Model for Immersive Virtual Reality Safety Training

LAPIN YLIOPISTO
UNIVERSITY OF LAPLAND

Acta electronica Universitatis Lapponiensis 430

ANU LEHIKKO

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ACADEMIC DISSERTATION
to be publicly defended with permission
of the Faculty of Education at the University of Lapland
in Auditorium B127 on 6 February 2026 at 12 noon.

LAPIN YLIOPISTO
UNIVERSITY OF LAPLAND

Rovaniemi 2026

University of Lapland
Faculty of Education

Supervised by

Professor Heli Ruokamo, University of Lapland

Docent Hanna Vuojärvi, University of Lapland

Reviewed by

Professor Emeritus Kai Hakkarainen, University of Helsinki

Professor Raija Hämäläinen, University of Jyväskylä

Opponent

Professor Emeritus Kai Hakkarainen, University of Helsinki

Layout: Minna Komppa, Taittotalo PrintOne

Acta electronica Universitatis Lapponiensis 430

ISBN 978-952-337-530-7
ISSN 1796-6310

Permanent address of the publication:
https://urn.fi/URN:ISBN:978-952-337-530-7

All that you change changes you.

Octavia E. Butler

Abstract

Anu Lehikko
Synthesizing sociocultural and cognitivist approaches to learning
in a simulation-based model for immersive virtual reality safety training
Rovaniemi: University of Lapland 2026, 152 pages
Acta electronica Universitatis Lapponiensis 430
Doctoral Thesis: University of Lapland, Faculty of Education,
Media Education Hub
ISBN 978-952-337-530-7
ISSN 1796-6310

A simulation-based model for immersive virtual reality (IVR) safety training was developed in this study. Simulations offer an effective training method due to their strong contextualization and phasing, which reduces the cognitive load of learners and supports training transfer. IVR has specific advantages for occupational safety training because it provides a safe environment to train for possibly hazardous situations and supports training effectiveness by increasing learner interest and engagement that may contribute towards the achievement of safety learning goals and training transfer to work routines. However, IVR research has remained mostly disconnected from learning theories, and empirically grounded and practice-oriented models for the pedagogically viable application of IVR environments in safety training have not yet been proposed.

To address the research gap, the current study aimed to: (1) develop an ecologically valid and contextually sensitive model to guide the implementation of IVR in occupational safety training settings for the benefit of training practitioners in work organizations, enterprises, and educational institutions; (2) study the significance of learner–IVR interactivity for the learners' sense of agency, cognitive load, and safety learning outcomes, and provide recommendations for IVR training design based on these results; and (3) explore the role of individual learner factors for the learners' experience of the IVR training scenarios. To achieve this study's pragmatic and theoretical objectives, design-based research (DBR) was selected as the guiding paradigm. The expertise of the safety trainers in the participating work organizations was utilized in the conceptualization of the model, and the training interventions were planned in collaboration with them.

This dissertation draws on three sub-studies, each reported and published as a peer-reviewed international journal article. The initial conceptualization of the

model was based on research literature and the findings from semi-structured thematic interviews with 18 safety trainers in two work organizations to ensure a functional selection of the pedagogical practices and IVR learning design principles that support occupational safety training objectives and training transfer (Substudy I). A mixed-methods experimental approach was applied to study learner–IVR interactivity and the learners' experiences during the training interventions. A total of 22 training sessions were held for 68 participants in two work organizations (Substudies II and III).

The simulation-based model for IVR safety training introduces the key elements of IVR safety training design and delivery: learning objectives and outcomes, trainers' pre- and post-training activities, and trainer and learner actions during the four training phases—introduction, IVR briefing, IVR scenario, and debriefing. The empirical results indicate that the simulation-based model enables cognitive and affective safety learning outcomes. A high level of interactivity between the learners and the IVR environment is recommended as an important IVR design feature: It supports instructional designs that foster agency and involvement, and creates premises for learning outcomes and training transfer. IVR scenario designs involving high interactivity and familiar work procedures may support learners' generative cognitive processing. The learners' previous VR experiences should also be observed in IVR safety training design by implementing tutorials and practice sessions, as well as including attentional guidance and motivational elements in the scenario design. The simulation-based model is applicable across various industries and educational levels to provide more engaging and effective safety training. It is also adaptable to different topics in curricular contexts.

Keywords: immersive virtual reality, safety training, sociocultural approach, cognitivism, mixed-methods research, learning outcomes

Tiivistelmä

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Synthesizing sociocultural and cognitivist approaches to learning
in a simulation-based model for immersive virtual reality safety training
Rovaniemi: Lapin yliopisto 2025, 152 sivua
Acta electronica Universitatis Lapponiensis 430
Väitöskirja: Lapin yliopisto, Kasvatustieteiden tiedekunta, Media Education Hub
ISBN 978-952-337-530-7
ISSN 1796-6310

Tässä tutkimuksessa kehitettiin simulaatiokoulutukseen perustuva malli immersiivistä virtuaalitodellisuutta (IVR) hyödyntävälle työturvallisuuskoulutukselle. Simulaatioille on ominaista oppimisen vahva kontekstualisointi sekä vaiheistus, joka pienentää oppijoiden kognitiivista kuormitusta ja tukee opitun siirtymistä työtehtäviin. IVR-oppimisympäristöillä on erityisiä etuja työturvallisuuskoulutuksen näkökulmasta: ne tarjoavat oppijoille turvallisen ympäristön mahdollisten vaaratilanteiden harjoitteluun, ja ne voivat edistää oppimistavoitteiden saavuttamista ja koulutuksen siirtovaikutusta lisäämällä oppijoiden kiinnostusta ja sitoutumista koulutukseen. IVR-ympäristöjen tutkimus on kuitenkin jäänyt enimmäkseen irralliseksi oppimisteorioista, eikä tutkimukseen perustuvia malleja IVR:n pedagogisesti mielekkäälle soveltamiselle osana turvallisuuskoulutusta ole ollut tarjolla.

Tutkimuksen tavoitteena oli (1) kehittää kontekstiin sovitettu koulutusmalli tukemaan IVR-työturvallisuuskoulutuksen suunnittelua ja toteutusta työorganisaatioissa, yrityksissä ja oppilaitoksissa; (2) tutkia oppijan ja IVR:n välisen vuorovaikutteisuuden merkitystä oppijoiden toimijuuden tunteelle, kognitiiviselle kuormitukselle ja työturvallisuuteen liittyville oppimistuloksille sekä antaa tutkimuksen tuloksiin perustuvia suosituksia IVR-koulutusten suunnitteluun; ja (3) tutkia oppijoiden taustatekijöiden vaikutusta heidän kokemuksiinsa IVR-harjoitusten aikana. Tutkimusta ohjaavaksi paradigmaksi valittiin design-tutkimus (DBR). Yhteistyöorganisaatioissa työskentelevien turvallisuuskouluttajien asiantuntijuutta hyödynnettiin mallin konseptoinnissa, ja koulutusinterventiot suunniteltiin heidän kanssaan yhteistyössä.

Väitöskirja perustuu kolmeen osatutkimukseen, jotka on julkaistu vertaisarvioituina artikkeleina kansainvälisissä tieteellisissä julkaisuissa. Pedagogisen mallin konseptointi perustui tutkimuskirjallisuuteen ja kahden työorganisaation 18 turvallisuuskouluttajan puolistrukturoitujen teemahaastattelujen tuloksiin (osa-

tutkimus I). Haastattelut valottivat kouluttajien tavoitteita työturvallisuuskoulutukselle ja koulutuksen siirtovaikutusta tukevia pedagogisia käytäntöjä; löydökset viestiin osaksi konseptoitua mallia. Seuraavaksi mallia testattiin empiirisesti koulutusinterventioissa: yhteensä 22 koulutusryhmää, joissa oli 68 osallistujaa, osallistui turvallisuuskoulutuksiin (osatutkimukset II ja III). Oppijan ja IVR:n välistä vuorovaikutteisuutta sekä oppijoiden kokemuksia koulutuksesta tarkasteltiin monimenetelmätutkimuksen keinoin.

Tuloksissa esitellään koulutusmalli, joka sisältää IVR-turvallisuuskoulutuksen suunnittelun ja toteutuksen keskeiset elementit: oppimistavoitteet ja -tulokset, koulutusta edeltävät ja sen jälkeiset toimenpiteet sekä kouluttajien ja oppijoiden toimet neljässä koulutusvaiheessa: johdanto, IVR-perehdytys, IVR-harjoitus ja purkukeskustelu. Empiiriset tulokset viittaavat siihen, että koulutusmalli tukee kognitiivisten ja affektiivisten turvallisuusoppimistavoitteiden saavuttamista. Tulosten mukaan oppijan ja IVR-ympäristön välinen vuorovaikutteisuus mahdollistaa toimijuuden ja osallisuuden kokemukset ja luo edellytyksiä oppimistuloksille ja koulutuksen siirtovaikutukselle. Vuorovaikutteisuutta ja tuttuja työympäristöjä hyödyntävä skenaariosuunnittelu tukee oppimisen kannalta keskeistä kognitiivista prosessointia. Koulutussuunnittelussa tulisi huomioida erityisesti oppijat, joilla ei ole aikaisempaa IVR-kokemusta esimerkiksi järjestämällä riittävästi aikaa perehtymiseen ja harjoitteluun sekä sisällyttämällä skenaarioihin huomiokykyä ohjaavia ja motivoivia elementtejä. Koulutusmalli tukee vaikuttavamman ja mielekkäämmän työturvallisuuskoulutuksen suunnittelua ja toteutusta eri aloilla ja koulutusasteilla, ja se on sovitettavissa erilaisiin oppimiskonteksteihin ja opetussuunnitelmiin.

Asiasanat: immersiivinen virtuaalitodellisuus, työturvallisuuskoulutus, sosiokulttuurinen viitekehys, kognitivismi, oppimistulokset, monimenetelmätutkimus

Acknowledgements

First, I would like to express my gratitude to my supervisors, Professor Heli Ruokamo and Dr Hanna Vuojärvi. Heli, I likely would not have embarked on a PhD journey at all, had you not given me the initial push. I want to thank you for facilitating the development of my academic agency, acting as a dynamic role model and creating opportunities and space for me to grow during our collaborations. Hanna, thank you for your kind and patient guidance throughout this long process. Moreover, I want to thank my thesis pre-examiners, Professor Emeritus Kai Hakkarainen from the University of Helsinki and Professor Raija Hämäläinen from the University of Jyväskylä, for their constructive and helpful feedback. I am also very grateful to Dr Satu-Maarit Korte for her valuable comments on my thesis summary. Many thanks to my PhD seminar group, especially Dr Päivi Timonen, for creating a sense of belonging in the academic community and providing peer support. Päivi, I value your friendship and insights.

I am indebted to Dr Mikko Nykänen, M.Sc. (Tech) Kristian Lukander and Dr Maria Tiikkaja for their kindness and expertise during our shared research endeavors. Mikko, special thanks for stepping in to cover the audiovisual data collection in the field during my covid-19 quarantine, reading and commenting on this manuscript, and being a knowledgeable, trustworthy and constructive co-author in several research publications. I am grateful to Dr Josef Buchner, whose articulate and insightful mentorship I have accessed through the European Association for Research in Learning and Instruction. Josef, your guidance has enabled me to develop my professional skills and helped me to stay focused and motivated in the final years of my studies. I would like to thank Professor Jari Metsämuuronen from the University of Turku for providing academic and methodological guidance and for encouraging me to choose this career path. Lastly, I want to express my gratitude to the Finnish Work Environment Fund for funding this research, and to the University of Lapland for the Esko Riepula doctoral study grant.

This multidisciplinary study stems from my accumulated professional experiences in both public and private sectors, and long-held personal interests: my drive to understand human behavior and learning, fascination with scientific and technological advances—often first imagined and portrayed by science fiction authors and artists—and a long-term affinity towards computers as a medium for creativity and entertainment. Completing this study, however, would have been impossible without the numerous interactions and exchanges with my colleagues,

peers, teachers, collaborators, friends, loved ones, and their pets. Thank you for offering counterarguments, encouragement, compassion, companionship, and creative or humorous diversions that make life and research more meaningful. Thank you for being there.

I dedicate this work to the memory of my former teacher, Dr Jorma Vainionpää, whose example and expertise fostered my interest in computer-mediated learning research during my undergraduate years in Tampere. Teachers, use your power wisely.

List of Original Articles

The dissertation is based on the following original articles, which will be referred to in the text by the Roman numerals I, II, and III.

I. Lehikko, A., Nykänen, M., & Ruokamo, H. (2025). Conceptualizing a Pedagogical Model for Immersive Virtual Reality Safety Training: Pedagogical Practices in Trainer Interviews. *Educational Technology Research and Development, 73,* 2543–2565. https://doi.org/10.1007/s11423-025-10490-1

II. Lehikko, A., Nykänen, M., Lukander, K., Uusitalo, J., & Ruokamo, H. (2024). Exploring Interactivity Effects on Learners' Sense of Agency, Cognitive Load, and Learning Outcomes: A Mixed Methods Study. *Computers & Education: X Reality, 4,* 100066. https://doi.org/10.1016/j.cexr.2024.100066

III. Lehikko, A., & Nykänen, M, & Ruokamo, H. (2025). Previous VR Experience Increases Embodiment in Immersive VR Safety Training: An Exploratory Mixed-Methods Study. *Virtual Reality*, *29*, 126. https://doi.org/10.1007/s10055-025-01196-z

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List of Abbreviations

3D	three-dimensional
AR	augmented reality
DBR	design-based research
CLT	cognitive load theory
CTML	cognitive theory of multimedia learning
ECL	extraneous cognitive load
FIOH	Finnish Institute of Occupational Health
GCL	germane cognitive load
GDPR	general data protection regulation
HMD	head-mounted display
ICL	intrinsic cognitive load
IVR	immersive virtual reality
MR	mixed reality
O1	organization 1
O2	organization 2
PERF	primary ego reference frame
STRI	stimulated recall interview
T1	baseline questionnaire
T2A	short-term delayed questionnaire A
T2B	short-term delayed questionnaire B
T3	long-term delayed questionnaire
VR	virtual reality
XR	extended reality

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1 Introduction

Working cultures are determined by workers' attitudes and actions, which can either support and uphold or challenge and change the status quo. Ensuring the participants' engagement in training and learning activities is often considered a significant challenge in workplace learning (Evans et al., 2006). Safety training is a focal activity for improving occupational safety in work organizations across industries and is an integral part of many applied higher and vocational education curriculums. Training is the key method for improving workers' safety behaviors. In addition to increasing safety knowledge, it aims to inflict attitudinal and motivational change (Ricci et al., 2016; Robson et al., 2012). For safety training design, it is essential to consider the embodied—bodily and spatial—aspects of workplace learning experiences (Hyland, 2019; Somerville & Lloyd, 2006). Effective training enables learners to transfer their enhanced knowledge and skills to their work setting and motivates them to maintain the change (see Baldwin & Ford, 1988; de Jong et al., 2023; Pham et al., 2023).

According to the review studies by Casey et al. (2021) and Li et al. (2018), the engaging and emotion-inducing features of immersive virtual reality (IVR) suit the purposes of occupational safety training particularly well. The possibility of constructing artificial environments in which trainees can act and learn safely in situations that could pose an imminent threat to their well-being in real life is considered one of the main benefits of IVR as a safety training medium (Checa & Bustillo, 2020; Morélot et al., 2021). Experiential IVR learning events that may simulate dangerous working conditions offer interesting opportunities to increase safety training engagement and effectiveness while ensuring the overall safety of trainees. Recently, IVR has been combined with simulations in disciplines such as security and defense (e.g., Garcia Estrada et al., 2024).

The availability of consumer-level technologies that have enabled IVR's commercial, widespread application in educational settings increased during the 2010s, leading to a surge of interest from the research community (Checa & Bustillo, 2020; Jensen & Konradsen, 2018; Martín-Gutiérrez et al., 2017). However, well over a decade later, uncertainty surrounds the pedagogical viability of IVR in curricular training contexts (see Bödding et al., 2025; Harris et al., 2020). Empirical evidence has demonstrated small to medium effect sizes for the effectiveness of IVR as a safety training medium (Nykänen et al., 2020; Makransky & Klingenberg, 2022; Rey-Becerra et al., 2023). Several authors have noted the absence of IVR research grounded in learning theory (Radhakrishnan et al., 2021; Radianti et al., 2020). The methodological quality of the empirical comparison studies on IVR

learning has stirred concern as a possible cause for conflicting results—the main concern being that the instructional differences between the compared learning media conditions have not been controlled for (Buchner & Kerres, 2023; Lawson & Martella, 2023; Lawson et al., 2024; Mulders, 2023). The learning design principles for IVR environments are unclear (Çeken & Taskin, 2022), and the affective learning objectives and outcomes that are focal for safety training interventions (Burke et al., 2006a) remain under-researched, as observed by Hamilton et al. (2021) in their literature review on IVR as a pedagogical tool and confirmed by Bödding et al. (2025) for vocational and professional development contexts.

A research gap exists concerning the pedagogical validity of educational virtual reality (VR) use and its contextual appropriateness, both of which need to be confirmed to ensure training efficiency and transfer (e.g., Harris et al., 2020; Oje et al., 2023) and to address the ethical concerns expressed in the field (see Skulmowski, 2023). Methodologically, a stronger emphasis on intervention studies, mixed-methods approaches to outcome evaluation, and the implementation of standardized measurements of training outcomes and training transfer in IVR studies have been advised (Checa & Bustillo, 2020; Luo et al., 2021; Makransky & Klingenberg, 2022; Radianti et al., 2020). For vocational or professional contexts, research on IVR must be expanded from the laboratory to on-the-job settings (Bödding et al., 2025). Rather than waiting for the engineering sciences or other scientific communities in the multidisciplinary field to assume responsibility, it is the education researchers' task to use these pointers to assess and develop the pedagogical viability of novel learning technology implementations across learning contexts (see Lawson & Martella, 2023). The results should be accompanied by practical recommendations, grounded in frameworks and theories for learning, for the benefit of practitioners and the larger audience.

A conceptual distinction between safety *culture* and safety *climate* has been introduced into occupational safety research in the past; these constructs overlap in the literature (Casey et al., 2022). According to some sources, safety *culture* encompasses safety-related practices and behaviors in the workplace, whereas employees' values and beliefs on safety-related matters are considered to be partial to the safety *climate* (DeJoy, 1996). Other sources consider safety climate to encompass not only individual values but also other sociocultural factors, such as management and organizational practices, including communications and employee involvement (Neal et al., 2000). In this study, occupational safety learning is discussed using the terms and definitions of the sociocultural approach to workplace learning. The term *safety culture* is used in this study for the organizational sociocultural context of safety-related assumptions, beliefs, values, practices, and artifacts (Schein, 2004). Measuring or evaluating safety culture in the participant organizations is not included in the study objectives (cf. Casey et al., 2022).

This study introduces a learning theory-grounded, empirically tested simulation-based model for applying IVR practice scenarios as a part of safety training implementations. The study contributes to the educational research niches of educational technology and professional development. Developed in design-based research (DBR; e.g., Amiel & Reeves, 2008), the training model synthesizes earlier literature ranging from learning sciences to occupational safety research. Abiding by DBR principles, pragmatically driven (Campanella & Penuel, 2021; Creswell & Plano Clark, 2017) research was conducted in collaboration with the staff of two large Finnish work organizations in an intervention study. Encouraging the learners to assume proactive safety behavior was a main objective for the training interventions (see Lukander et al., 2025).

The results of the empirical study were used in both iterating the model and as a basis for design principles applicable to both IVR training scenario design and training implementation as a part of a curricular setting. The results will benefit the wider community in the form of increased understanding of pedagogically sound design and the application of educational IVR as a part of training and learning events. The simulation-based model for IVR safety training will benefit training practitioners and providers inside and outside the safety training field: it can be used as a starting point for designing engaging and effective training, modified to suit the purposes of educational institutions, and adapted to other training topics. In addition to these pragmatic aims, this study furthers IVR learning research into mature learners in the workplace learning context.

2 Immersive Virtual Reality as a Learning Medium

2.1 What is IVR?

There is a confusing variety of interpretations of the definition of IVR. This is evident even in the recent literature on virtual reality (VR) use in occupational safety training (e.g., Babalola et al., 2023). For this reason, Luo et al. (2021) recommended taking appropriate care to introduce the relevant terms and definitions. In this study, IVR is understood as a computer-generated three-dimensional (3D) environment that aims to provide its users with a convincing sensory illusion of being located in an artificial space (Cummings & Bailenson, 2016). Immersion is thought to be achieved by using suitable technology, such as a head-mounted display (HMD) and hand controllers, to access and control the virtual environment (see di Natale et al., 2020; Jensen & Konradsen, 2018; Scavarelli et al., 2021). Other extended reality (XR) technologies, such as augmented reality (AR) or mixed reality (MR), and desktop-operated VR applications are not considered fully immersive virtual environments and are thus excluded from the study scope.

Artificial 3D environments can be created using 3D modeling tools or photogrammetry, which employs sensors, geographical references, laser scanning, and stationary or drone-carried cameras. These methods can also be combined in IVR environment production (Nebel et al., 2020). To fully understand the nuances of immersive technology, a distinction should be made between, on the one hand, IVR environments designed to deliver an illusion of a 3D space that may mimic the affordances of a physical environment in terms of locomotion, and, on the other hand, 360° videos created to be accessed from one or more fixed locations in the artificial space, predetermined by the chosen camera placements. Of these, the 360° video is currently a more affordable option for educators, and is easier to produce without advanced programming skills (Di Natale et al., 2020).

The sensation of walking around in a 3D environment is very unlike that engendered by operating non-immersive VR on a desktop computer or mobile device because the user is surrounded by virtual space, and—especially in the wireless setups—free to roam the environment within the boundaries set by programming and the available physical space. Moving around in the virtual environment may cause some users to experience visually induced motion sickness, also known as simulator sickness or cybersickness, and often associated with the use of stereoscopic HMDs (de Winkel et al., 2022). Simulator sickness can be caused by the discrepancy between the user's visual and vestibular sensory inputs, such as a

stationary physical position vs. the illusion of movement in the virtual environment; both technological and individual factors are involved. The symptoms may include nausea, dizziness, and headache (Chang et al., 2020; Rebenitsch & Owen, 2016). Frame rate consistency and multimodality, that is, using other modalities, such as auditory and vestibular information, to complement visual information can reduce simulator sickness occurrence (Chang et al., 2020).

From the IVR training design perspective, the choice between stationary and locomotive approaches to the user's physical and spatial involvement in the interaction with the environment has practical implications for IVR scenario production. These should be weighed against the implications that adapting either of these approaches have on the resulting learning experience (see Checa & Bustillo, 2020). Further design choices, such as the inclusion of interactive elements, may create premises for both mentally and physically engaging learning experiences. Users may experience agency by performing intentional actions and perceiving their influence on virtual events and surroundings (see Bandura, 2006); they may also experience physical presence and body ownership in the virtual setting. These phenomena are understood to enhance the embodied and affective dimensions of learning (Johnson-Glenberg, 2017; Kilteni et al., 2012; Makransky & Petersen, 2021). The IVR learning environment[1] used in this study was capable of fostering embodied interactions through design and allowed the participants to explore the virtual training space by walking. The environment was designed to induce as little simulator sickness as possible by, for instance, including one-to-one mapping between the user's physical and virtual movements, multimodality, and a consistent frame rate in its design.

2.2 Interactivity Between Learner and IVR

Interactivity between the learner and the IVR environment is considered a key element in designing IVR training that fosters an experiential learning approach (Roussou, 2004; Slater, 2017). In this dissertation, interactivity is studied in terms of the degree to which learners can control and modify events in the virtual learning environment by their actions (Steuer, 1992). The term is thus not considered to mean social interaction, or the observation of actions between two or more human actors within the IVR environment. Interactivity supports the learner's perception of the IVR affordances: The dynamic interactions and relations between the learner and the virtual environment, often understood as the action opportunities provided to the learner by the environment (Dalgarno & Lee, 2010; Gibson, 2014; Petersen et al., 2022; Shin, 2017) that are essential for their agentic engagement. Instructional

1 The Virtuario™ learning environment is the intellectual property of the Finnish Institute of Occupational Health.

design for IVR should take advantage of the affordances particular to that medium to support the learners in sense making (see Dalgarno & Lee, 2010; Makransky & Petersen, 2021; Damşa et al., 2019).

The relational nature of affordances implies that not all users perceive and experience them in a similar manner in the same IVR environment (Gibson, 2014; Heeter, 2000; Krueger, 2023; Norman, 2013). Compared to physical reality, one may have to move around and gather significantly more sensory information to perceive the available affordances in IVR due to technological limitations, such as limited field of vision and lack of haptic information (Bhargava et al., 2020; Foglia & Wilson, 2013; Gibson, 2014; Harris et al., 2019; Heeter, 2000). Affordance perception can be supported by using visual or auditory signifiers that inform the user of the afforded actions (Castro-Alonso et al., 2024; Norman, 2013). For example, a pair of footprints on the virtual floor can be used to signify the correct standing location for the user, while the IVR equipment calibrates for the training area, and an auditory cue such as a simple instruction to walk to that location can be provided. Together, these signifiers communicate to the novice user that walking is an afforded and expected action in the IVR. Nevertheless, affordance perception may be influenced by sociocultural factors, such as norms and values (Parchoma, 2014).

Recent review studies on the learning benefits of IVR learning environments provide some insight into favorable pedagogical approaches. Di Natale et al. (2020) remarked on IVR's capacities to elicit learners' interest, support their motivation and engagement with learning content, and offer hands-on experiential learning opportunities. However, the same authors also noted that the studies included in their review had methodological deficits, such as small sample sizes, nonrandomized trials, and nonvalidated measures. Conrad et al. (2024), who included only studies using objective measures of declarative and procedural IVR learning outcomes in their systematic review, concluded that IVR environments requiring the learner's active involvement were associated with these learning outcomes more often than their more passive counterparts. Luo et al. (2021) reported trial and error as the most effective pedagogical approach, compared to collaborative, direct instruction and inquiry-based approaches, in their comprehensive meta-analysis of IVR research in K-12 and higher education spanning two decades. They also reported scaffolding provided by both computer and teacher as more effective in terms of learning outcomes than scaffolding provided by either of these alone.

2.3 Sense of Embodiment in IVR

The learners' observable physical actions, including movement, gaze, speech, and body position, represent the embodied interface between the IVR environment and the learner's cognition (see Heeter, 2000; Newen et al., 2018; Schilhab & Groth,

2024). According to Makransky and Petersen's cognitive affective model of immersive learning (Makransky & Petersen, 2021; Petersen et al., 2022), the immersion and interactivity provided by the environment enable learners to experience senses of agency and spatial presence. The learner's sense of agency arises from a perceived capability to initiate and control actions within the virtual environment (Braun et al., 2018; Farrer et al., 2013), and it can be diminished by IVR latency (Roth & Latoschik, 2020). The perception of agency has an implicit prereflective level and an explicit level at which the conscious judgment of one's agency is formed (Moore et al., 2012). Compared to positive or neutral outcomes, negative outcomes of learners' actions may negatively impact their sense of agency (Yoshie & Haggard, 2013). In terms of IVR learning, learners' agentic experiences may enable them to experience motivation and self-efficacy—belief in their capability to achieve a given attainment—in the learning process (Bandura, 1997, 2006; Makransky & Petersen, 2021; Ryan & Deci, 2000).

The immersive capabilities of IVR technology are considered focal in the creation of an illusion of presence in the virtual environment (Gibson, 2014; Heeter, 2000; Makransky & Petersen, 2021). A learner's perception of being spatially located "inside" the virtual environment is called *spatial presence* (Lee, 2004; Slater, 2003). Wirth et al. (2007) proposed that the sense of spatial presence that emerges through a process is initially founded on the learner's attention to the medium: involuntary attention, such as that evoked by automatic responses to visual stimuli (see Holcombe, 2023), and voluntary attention enhanced by the learner's situational interest. Attentional cues enable the learner to choose a primary ego reference frame (PERF) based either on the real world or the virtual world.

Choosing the mediated PERF means relying on the virtual sensory input at the expense of some of the sensory input that is grounded in the physical environment. The learner's imagination and suspension of disbelief may be essential for a sense of spatial presence (Slater & Wilbur, 1997; Wirth et al., 2007). The individual's inclination for absorption—i.e., their tendency toward intense engagement with attentional objects, such as media products—is considered to support the process (see Wild et al., 1995; Wirth et al., 2007). The sense of spatial presence may be associated with better spatial learning outcomes; it is influenced by distraction factors (Parong et al., 2020), but its meaning for learning is, in general, not yet fully understood. Recent empirical studies by, for instance, Khorasani et al. (2023), have cast doubt on the positive relationship between spatial presence and learning outcomes. Presence has also been considered to support learner engagement (e.g., Harris et al., 2021).

According to Kilteni et al. (2012), an individual's sense of *embodiment*—a feeling of bodily interaction with and within the IVR—has three components: body ownership, agency, and self-location. Roth and Latoschik's (2020) empirical study confirmed the correlation between body ownership and agency. *Body ownership*—

the learner's sensation of possessing a body within the IVR environment—has importance in training settings in which the learning objectives extend beyond declarative knowledge acquisition. For instance, Mal et al. (2023) illustrated that body ownership has a significant effect on behavior changes in exercise performance. Their study employed avatars (virtual, computer-generated body representations), although some empirical evidence has suggested that body ownership illusion is not dependent on having an avatar (see Ogawa et al., 2020). Nevertheless, the sense of embodiment is vulnerable to incongruencies between the learner's physical and virtual movements due to inadequate mapping in the IVR (Bovet et al., 2018; Pritchard et al., 2016; Roth & Latoschik, 2020). This means that it is also linked to the representational fidelity of the IVR environment (Harris et al., 2020; Makransky & Petersen, 2021; Petersen et al., 2022).

Embodiment is thought to have a beneficial influence on learning through several pathways, especially by advocates of the *embodied cognition theory*, which highlights the role of sensory and motor functions in cognition (e.g., Foglia & Wilson, 2013). For instance, Castro-Alonso et al. (2024) suggested that embodiment allows for the exercise of physical activity, generative learning, and offloaded cognition, all of which are considered to enhance learning. Ratcliffe et al. (2021) discovered that embodied actions increased language learners' performance in a memorization test; however, the effect was no longer significant in a one-week delayed test. In IVR safety training, embodiment may increase the learner's training engagement and attention to the learning tasks, and this may lead to better learning outcomes (see Casey et al., 2021; Gao et al., 2019) and enhanced learning retention (Johnson-Glenberg, 2017). In high-risk conditions, which may often be relevant in safety training simulations, embodiment may hinder the learner's task performance due to the perceived threat to one's virtual body representation and the increase in the risk perception. However, a greater perception of risk may be necessary in certain situations to prevent unsafe behaviors (Shin et al., 2021). Hence, embodiment is a focal construct for the current study.

3 Frameworks of Learning

3.1 Simulations as Situated Workplace Learning Activities

Simulations are coordinated activities that replicate real work procedures and surroundings but have a reduced level of risk to the participants, and similarly minimal consequences for their errors. They can be applied in education, with an emphasis on conceptual knowledge and basic skills, or in training for actual work tasks and procedures, and in performance or competency assessments (Gaba, 2004). Simulation training encompasses elements from several frameworks of learning, with Kolb's (1984) experiential learning model at its core, defining the training structure with its repeated cycles of activity and reflection (see also criticism by Miettinen, 2000). The situated and often collaborative nature of simulation training is aligned with a sociocultural approach to learning (Stocker et al., 2014). In addition, simulations are considered useful in creating and maintaining a safety-oriented organizational culture (Gaba, 2004).

In the sociocultural framework, learners and trainers are seen as situated in the social and cultural practices of the workplace. Social and individual dimensions of knowing, doing, and learning intertwine; social practices are transformed during social interaction, and so are the individuals who participate in them, gradually gaining fluency in the discourse and acquiring membership in the expert community. Practices are viewed as relational, recurrent, intentional, and socially sustained activities (see Gherardi, 2012). Physical and symbolic tools, *artifacts*, are thought to mediate the learning process; for instance, both abstract concepts and communication technology are used to construct and convey knowledge in discourses and exchanges (Boreham & Morgan, 2004; Sutherland et al., 2009; Tenenberg & Knobelsdorf, 2014; Vygotsky, 1978). Here, social practices aimed at shaping learners' educational development are considered pedagogical practices (Higgs, 2012). If aligned with Orlikowski's (2007) proposal, pedagogical practices are inherently sociomaterial in nature and enacted within the entangled social and material dimensions of the work organization.

Evans et al. (2006) suggested that sociocultural and constructivist approaches to workplace learning are important, not just for their emphasis on the contextual setting, but also for their acknowledgment of the power relations and the linkage of existing and new knowledge in the learning situation. The expanded concept of situated learning introduced by Evans et al. (2006) considers three dimensions of situatedness that are all important for learning to occur. Applied in the occupational

safety training context, *practically situated learning* could involve engaging the workers in safety practices and work groups, giving them access to safety programs, and providing them with time and space for learning. *Culturally situated learning* remains historically consistent with the safety culture in the organization, the area, and the working environment. *Socially situated learning* could be interpreted as shared responsibility for safety knowledge and skills development, adjusting the safety training contents and contexts to the learners' background and experiences, linking safety-related activities, resources and support for the learners, and acknowledging the social and affective dimensions of learning. The situatedness of simulations can also be viewed through the layers of a learning ecosystem—the individual learner, the systemic relationships, and the work community (see Markauskaite et al., 2023, 2024).

Safety-related knowledge and experiences do not exist only in the rules and regulations; they can be tacit, embodied, and very context-specific (e.g., Somerville & Lloyd, 2006). In a situational and sociocultural view of safety training, the development of single competences and skills may be regarded as a secondary concern compared to participation in the practices and discourses of a safety culture in which workers can develop their capacities through experience, acquiring shared safety-related values and beliefs in the process (Duryan et al., 2020; Mullen, 2004). The focus on situatedness may be perceived as juxtaposed with the study of learning transfer (e.g., Mason, 2007). Viewed through an ecological lens on learning, however, the relationship between the learners and the learning space—the immaterial space of action where the learners' knowing and doing emerge—is seen as both transformative and reciprocal. A learner's skill and agency are essential to the process of interpreting and reconstructing the learning spaces provided, configured, and facilitated by the work organization (see Damşa et al., 2019; Gherardi, 2012; Markauskaite et al., 2023). The transfer of learning to daily practices similarly implies agency and bodily engagement (Nicolini, 2012). Hence, designing and scaffolding the training to make it conducive to each learner's active, agentic role as a co-creator and participant in the safety culture is essential.

The safety trainer's role can be seen as that of an adviser, coach, or mediator in the social activity (see Evans et al., 2006). Adapting to the new role may be challenging for those accustomed to a more traditional teacher–student arrangement; the trainers themselves need training and support for their identity work in the transition from teachers to facilitators. Occupational safety training may challenge the identities and self-images of the participants and the trainers. The self-images of some members of the work community may clash with the employer's expectations for safe behaviors, for instance, because they associate risk taking with intentional displays of machismo (Mullen, 2004), leading to a deviation from safety practices and a power struggle in the community (see Evans et al., 2006; Schein, 2004). Hence, discussing and questioning existing safety-related individual assumptions

and interpretations of the preferable values and work practices, as well as those that align with the organizational efforts and guidelines to promote the safety of the work community, is an important part of the training activities. Situated, coordinated, and essentially experiential, simulations can provide a meaningful and relevant framework to address these challenges from both trainers' and learners' perspectives.

Training objectives reflect the learning purpose, addressing a gap identified in professional practices (Holdsworth et al., 2022). Simulations suit a range of learning objectives and activities. They have a long history of application and development, especially in the medical and health sciences, in which IVR training solutions have also gained the attention of researchers and practitioners (Checa & Bustillo, 2020; Wrzus et al., 2024). Examples of pedagogical models for teaching and learning in non-immersive VR simulations exist in the field of medical education (e.g., Keskitalo, 2015; Poikela et al., 2015). In simulations, the learners' attitudes, expectations, and prior knowledge can be addressed during prebriefing (Billett, 2013; Dieckmann, 2009; Gaba, 2004; Holdsworth et al., 2022), and the learners can be guided to reflect on the learning experience afterward (Kolb, 1984). See Figure 1.

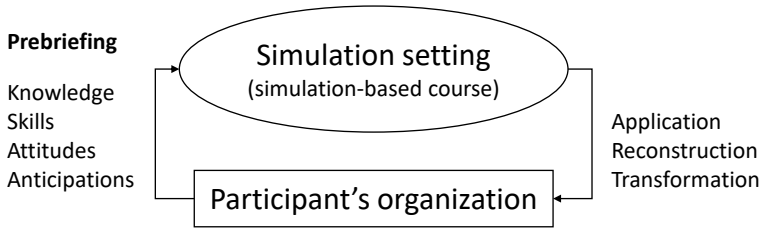

Figure 1. *Simulation Setting as an Off-the-job Setting (Dieckmann, 2009, p. 47)*

Facilitative actions, such as delivering necessary feedback while maintaining a positive, emotionally safe learning atmosphere (Decker et al., 2013; Dieckmann et al., 2007; Gaba, 2004; Rudolph et al., 2014), aim to support the simulation participants in the reconstruction and transformation of the learning experience for application in their daily work practices (Billett, 2013; Dieckmann, 2009; Sutherland et al., 2009). Creating an emotionally safe training environment is essential to encouraging learners to engage in the learning situation and reflect on their experiences openly (Dieckmann et al., 2007; Rudolph et al., 2014). Psychological safety facilitates change without the feeling of loss of integrity of membership in the group (Schein, 2004); it supports employee collaboration and openness to providing and receiving honest feedback (e.g., Newman et al., 2017). It may also persuade participants to willingly apply suspension of disbelief and buy-in during the simulation, contributing to training effectiveness (Dieckmann et al., 2007; Muckler, 2017).

Simulation training objectives should be defined in advance to enable successful training and outcome assessment (Anderson & Krathwohl, 2001; Dieckmann, 2009; Kraiger et al., 1993). See Table 1.

Table 1. *Examples of Training Objectives in Educational Simulations vs. Taxonomy of Learning Outcomes (adapted from Dieckmann, 2009, pp. 90–93; Kraiger et al., 1993, p. 323)*

Objectives	Examples	Learning Outcomes
Declarative Knowledge	Principles, knowledge of models, systemic understanding, metacognitive skills	Cognitive outcomes
Procedural Knowledge	Application of principles, performance of procedures, problem-solving skills	Cognitive and skill-based outcomes
Attitudes	Acceptance, insight, teamwork, self-confidence	Affective outcomes
Psychomotor Skills	Hand-eye coordination	Skill-based outcomes

Simulations can help learners develop systemic understanding and metacognitive skills, increase their performance across a variety of procedures and problem-solving tasks, undergo attitudinal change and learn teamwork skills, and develop hand-eye coordination (Dieckmann, 2009). Procedural and psychomotor objectives are often essential for vocational education (e.g., Hyland, 2019). High representational fidelity of the simulation learning environment may be necessary to achieve certain learning objectives (Nebel et al., 2020). Considering other design factors is also essential. In technology-mediated learning, appropriate learning goals should be selected according to technological affordances. For example, the exclusion of psychomotor learning objectives may be advisable in IVR setups that are operated using standard consumer-level hand controllers (e.g., Lehikko & Ruokamo, 2025).

Training transfer is influenced by motivational factors (see de Jong et al., 2023). According to Scott et al. (2014), supporting learners' autonomous motivation has more influence on their safety compliance than indirect safety culture interventions that attempt to influence their employees' values by using leadership as a proxy. Developing employees' safety-related motivation and self-efficacies by improving their personal safety expertise, for instance, is understood to reflect a change in their personal beliefs and attitudes (Anderson & Krathwohl, 2001; Kraiger et al., 1993; Krathwohl et al., 1973). Affective and cognitive learning outcomes are often intertwined, so learners' safety knowledge—that is, their understanding of safety-related instructions and procedures in the workplace—should also be considered. Neal et al. (2000) proposed that training interventions addressing both motivational and knowledge dimensions can be expected to be more effective in terms of safety performance outcomes.

In the current study, the IVR scenarios were scripted around specific training goals that were determined in collaboration with practitioners. The instructional content

provided guidance on safety knowledge, safety procedures, and attitudes related to the preferred safety behaviors, accompanied by safety-related tasks and actions to be performed during the scenario. The training goals included, for instance, identifying the value of one's personal safety actions and understanding how preventive actions promote occupational safety. The acknowledged situatedness of learning means that the representations of knowledge in training events must be designed for coherence with work practice (see Baldwin & Ford, 1988; Billett, 2021; Holdsworth et al., 2022; Tynjälä, 2013). Billett (1996, 1998) proposed combining sociocultural and cognitive learning theories to better understand the processes and goals of learning, as well as the relationship between social practices and individual behavior in the workplace.

3.2 Cognitivist Perspectives on Simulation-Based IVR Learning

Cognitivist educational research, as traditionally understood, considers learning to be changes in individual mental representations that can be measured and empirically studied. In this frame, the well-organized mental schemas of more advanced and experienced learners allow them to use their cognitive resources more efficiently in the learning situation (Billett, 1996, 1998; Kirschner et al., 2011; Mayer, 2024; Newen et al., 2018). Cognitive learning outcomes are subject to influence by motivational, affective, and situational factors (Mason, 2007; Makransky & Petersen, 2021; Mayer, 2014; Petersen et al., 2022). However, the learning context and the embodied aspects of learning may be regarded as secondary to the cognitive phenomenon under scrutiny (Billett, 1998; Foglia & Wilson, 2013).

The cognitive load theory (CLT; Sweller, 2020) and the cognitive theory of multimedia learning (CTML; Mayer, 2014, 2024) have been proposed as key theories that advance IVR learning research (Lawson & Martella, 2023; Lawson & Mayer, 2024; Makransky & Petersen, 2021; Oje et al., 2023). Both theories consider the role of *cognitive load*, a concept used to discuss how the different elements of the learning situation tax the learner's working memory and impact cognitive processing (Mayer, 2014). In some empirical studies, IVR environments have been found to inflict a higher cognitive load on learners than other learning media, which is disadvantageous for the learning process and outcomes (e.g., Makransky et al., 2019; Meyer et al., 2019; Parong & Mayer, 2021). Therefore, further study on how IVR relates to the learner's cognitive load has been advised to better understand the suitability of the learning medium for educational use (Lawson & Martella, 2023).

The cognitive load theory suggests that a virtual learning experience taxes the learner's cognitive processing in three ways: *intrinsic cognitive load* (ICL) is related to the complexity and learners' previous familiarity with the learning content, *extrinsic cognitive load* (ECL) is connected to design factors, such as the usability of

the control interface and the sources of auditory and visual sensory data provided by the IVR in general, and *germane cognitive load* (GCL) is linked to the processing and memorization of the learning content. Whereas ICL and ECL may have a negative effect on learning, GCL may indicate the learner's increased engagement and generative processing of the learning material (Lawson & Mayer, 2024; Skulmowski & Xu, 2022). Differentiation between the three types of cognitive load, as well as further studies on the strategies to address each type in IVR learning design, have been recommended. Distractions unrelated to the learning event are regarded as extraneous sources of cognitive load that should also be accounted for (see Lawson & Martella, 2023; Lawson & Mayer, 2024).

The CTML understands cognitive load not only in terms of the learner's working memory capacity but also in terms of the amount of cognitive and attentive control (*executive function*) that can be exercised in the learning process (Lawson & Mayer, 2024). The theory outlines three focal processes for meaningful learning to occur: selecting, organizing, and integrating. The learner is expected to address the presented learning content (selecting), arrange the material into coherent cognitive representations (organizing), and form connections between these representations and their former experiences stored in long-term memory (integrating). According to the CTML, the vivid sensory environment provided by IVR may distract the learner in the process of selecting the content for further processing. Thus, a learner's individual capacity to focus attention on the instructionally relevant material can influence the ability to experience meaningful learning in IVR (Lawson & Mayer, 2024; Mayer, 2024).

Alternative cognitivist approaches to studying cognition and learning have emerged from criticism of the segregation between the international representations of information and the sensorimotor system, also evident in the CLT and the CTML. Considering the importance of the agentic and embodied aspects of safety learning, it is essential to discuss these alternative frameworks. For instance, cognitive ecology studies cognitive phenomena in relation to context (Hutchins, 2010; Newen et al., 2018). Ecological theories of learning encompass not only sociocultural perspectives but also contemporary cognitivist approaches, such as the 4E theory—of embodied, enacted, embedded, and extended cognition—that emphasize the interconnectedness of the learner's higher cognitive processes and the sociomaterial environment (see Markauskaite et al., 2023).

The 4E theory assumes that (1) cognition is essentially embodied, and cognitive phenomena are closely related to physical and bodily changes; (2) cognition is enacted in and with the environment; (3) cognition is partially embedded in or dependent on the extrabodily processes in the environment and the situation; and (4) cognitive processes are extended through interaction with the sociomaterial environment (Newen et al., 2018; Schilhab & Groth, 2024). Applying 4E to the context of embodied IVR, one can assume that physical activity supports

cognitive processing, especially if it is meaningful and connected to the learning task at hand. Embeddedness implies that the training situation and the social context both influence learning. Generative actions, such as object manipulations and personal gestures, can support learners in making connections between their existing knowledge and the learning content. The possibility of offloading cognitive processing to one's body parts and the surrounding environment during, for instance, generative learning activities, reduces the strain inflicted on the working memory during the learning event (see Castro-Alonso et al., 2024; Foglia & Wilson, 2013; Korte & Körkkö, 2024; Schilhab & Groth, 2024).

Several notions of beneficial pedagogical practices for simulation-based IVR training can be found in the literature. The concept of pretraining to ease the learner's cognitive load has been demonstrated to be effective in IVR learning and has been recommended to improve learner performance (Checa & Bustillo, 2020; Meyer et al., 2019). In simulation learning, prepractice briefings are performed to reduce the learner's cognitive load during the actual simulation experience. Practices such as introducing the key concepts and procedures beforehand have been established to help learners make sense of their experiences (see Damşa et al., 2019; Dieckmann & Ringstedt, 2013). It is important for training design to acknowledge the difficulties that novice users may experience in adapting to the IVR hardware and software; making tutorials and instructional scaffolding available to learners has been recommended (e.g., Johnson-Glenberg, 2019; Laine et al., 2024).

In digital simulations, giving the learner a high degree of control over the learning experience in the simulation environment may support self-efficacy and learning transfer; offering feedback after the exercise has also been recommended (Gegenfurtner et al., 2014). Debriefing learners has been suggested as a scaffolding strategy that could enhance the outcomes of VR-based instruction in K-12 and higher education (Luo et al., 2021) and has featured in prior IVR safety training research. For example, Rey-Becerra et al. (2023) combined IVR training with debriefings in both lecture and IVR conditions in their study of construction safety. Similarly, Makransky and Klingenberg (2022) included a guided reflection condition in their empirical study on maritime-themed IVR safety training. Based on their empirical study of IVR pedestrian safety education for elementary school students, Feng et al. (2021) recommended a blended approach in which the IVR scenario provides the experiential training component. This is followed by debriefing and a second exposure to the same scenario to support knowledge acquisition and behavioral learning outcomes. Interestingly, the realism and representational fidelity of the virtual environment may not be a pivotal concern for learning when IVR is used in a blended setting. The inconsistencies between the virtual and real-life experiences may offer pedagogically valuable discussion points in simulation-based training when the learners are given the opportunity to reflect on their IVR training experiences with a trained facilitator (see Sellberg et al., 2024).

The simulation-based model introduced in this study builds on both cognitivist and sociocultural paradigms; the current study lends itself easily to reinterpretation through ecological perspectives focusing on the learner, the relationships, and the community. The model includes experiential IVR scenarios, used for practicing safety behaviors and as a basis for active guided reflection involving the aspects of the local sociomaterial environment, such as the safety-related practices, discourses, and artifacts relevant to the learners' work. A learner focus is evident in the research questions concerning the learners' perceptions and embodied experiences in IVR; systemic and relational perspectives are involved throughout the study. Learner–IVR interactivity is studied in the context of IVR scenarios and hypothesized to enable more agentic and autonomous learning experiences that help support the achievement of the affective and cognitive safety learning outcomes: proactive safety behavior self-efficacy and safety knowledge. The trainers' facilitative actions are geared towards upholding a psychologically safe learning environment that enables learners to build their agency, expertise, and membership in occupational safety-related practices and discourses in the workplace, supporting training transfer. This study also touches upon collective expectations and activities in its discussion of the sociomaterial aspects of the model's implementation.

4 Research Questions

The main research question for this doctoral study was, "How should the pre- and post-briefings and individual IVR training scenarios be designed and implemented in a simulation-based training model to support the achievement of safety training objectives in the sociocultural setting of the workplace?" The three substudies aimed to (1) conceptualize a pedagogical model for IVR safety training and increase its ecological validity and contextualization with the help of safety trainer interviews; (2) study the effects of learner–IVR interactivity for learners' sense of agency, germane cognitive load, and safety learning outcomes based on self-report measures and stimulated recall interviews of the learners, and provide recommendations for IVR scenario design; and (3) to explore the role of interactivity and learners' background characteristics for their IVR experience in terms of their sense of embodiment, sense of spatial presence and their extraneous cognitive load using a mixed-methods approach. The research questions for the substudies were as follows:

For substudy I:

1) "What kinds of pedagogical practices do trainers apply in safety training?" and
2) "How do trainers' pedagogical practices inform the sociocultural contextualization of the pedagogical model for IVR safety training?"

For substudy II:

1) "How does interactivity influence learners' sense of agency?" and
2) "How does interactivity influence learners' cognitive load and learning outcomes?"

For substudy III:

1) "Do learner–IVR interactivity or learner characteristics influence learners' perceptions of spatial presence, ECL, and embodiment in IVR safety training?" and
2) "What kinds of factors influence the learners' training experiences, and how can they be addressed in IVR safety training design?"

5 Methods

5.1 Research Design

Design-based research (DBR) was applied as the guiding methodological paradigm in this dissertation. Currently, one of the many recommended approaches to advancing research on educational IVR (see Luo et al., 2021), DBR supports the integration of technological and learning theoretical viewpoints. In educational settings, DBR is typically future-oriented, builds knowledge and theory on both learning and design, aims for usability, and relies on iteration (Campanella & Penuel, 2021). To ensure the practicality of the solutions found, the research is conducted using real learning situations rather than laboratory conditions; it is driven by the local context, but simultaneously aims to transcend it to enhance the wider applicability of its products. According to Barab and Squire (2004), DBR can be harnessed for systemic reform in addition to improving daily practices. The research method is characterized by careful structuring to achieve theoretical understanding and by its emphasis on researcher–practitioner collaboration (Amiel & Reeves, 2008; Hjalmarson et al., 2021; McKenney & Reeves, 2021; Moore et al., 2023).

Typically, diverse methods of data collection and analysis are encouraged in DBR (e.g., McKenney & Reeves, 2021); a mixed-methods approach calls for consideration of the epistemological and ontological frameworks of the research. In the current study, the sociocultural and cognitivist approaches to learning—rooted in constructivist and positivist epistemologies, respectively—were understood as complementary and essential for achieving the pragmatic goals of the training model development. The sociocultural framework of learning offered situated, contextually sensitive insight into IVR safety training development through examination of the trainers' safety training-related practices and beliefs (Billett, 1996, 2013), studied using qualitative methods. The cognitivist elements provided grounding for the mixed-methods study of learners' perceptions and experiences regarding IVR learning media.

This study demonstrates a future orientation in its aim to combine IVR technology, which is relatively little researched but promising, with the established and well-researched educational practices of simulation and safety training. The staff in the professional development and health and safety functions in the participating work organizations formed an important stakeholder group that the researchers sought to engage in the DBR from the start. See Figure 2.

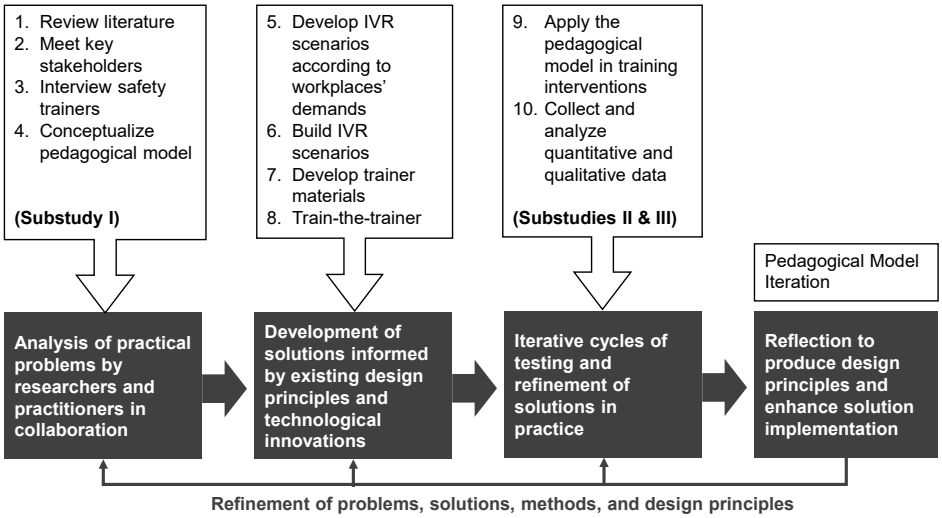

Figure 2. *Developing a Pedagogical Model in DBR (Adapted from Amiel & Reeves, 2008, p. 8)*

One DBR cycle was completed in this study. In Substudy I, the conceptualized model was informed by trainer interview findings in the initial design phase of DBR. See Table 2.

Table 2. *Research Design: Substudies I, II, and III*

Study	Research Aims	Methodology	Publication	Contribution
Substudy I: Conceptualizing a Pedagogical Model for Immersive Virtual Reality Safety Training: Pedagogical Practices in Trainer Interviews	To conceptualize a pedagogical model for IVR safety training by combining research literature and the findings on the pedagogical practices used by safety trainers.	Semistructured thematic interviews of safety trainers (n= 18) in two work organizations. Qualitative content analysis using NVivo software.	Lehikko et al. (2025a)	The study provided insight into the training context and the pedagogical practices preferred by the trainers. The findings were used in the development and conceptualization of the model prior to empirical testing.
Substudy II: Exploring Interactivity Effects on Learners' Sense of Agency, Cognitive Load, and Learning Outcomes: A Mixed Methods Study	To study the effect of IVR interactivity on the learners' sense of agency, cognitive load, safety knowledge and proactive safety behavior self-efficacy.	Empirical mixed-methods RCT study on IVR safety training (n=76) across two experimental conditions in two work organizations. Videography, observation, stimulated recall interviews (n=23). Quantitative analysis in SPSS. Qualitative content analysis of stimulated recall interview (STRI) data using NVivo.	Lehikko et al. (2024)	Learners' agency and cognitive load, as well as the two safety learning outcome measures, were studied by comparing high and limited IVR interactivity conditions. The findings had implications for the IVR scenario design in the iterated model.
Substudy III: Previous VR Experience Increases Embodiment in Immersive VR Safety Training: An Exploratory Mixed-Methods Study	To explore the effect of interactivity and learner characteristics on the learners' sense of embodiment, sense of spatial presence and extraneous cognitive load.	See Substudy II.	Lehikko et al. (2025b)	The influence of interactivity and the learners' background characteristics on their IVR learning experiences was studied. The results highlighted the role of attention and motivation in IVR learning and contributed to training model redesign.

In Substudies II and III, the model was subjected to empirical study that focused on the learners' experiences and perceptions of the training situation. Workshops were held for the work organizations' representatives to plan, prepare, and schedule organization-specific IVR scenario development and the training interventions that had to be performed sequentially due to limited development resources. Organization 1 (O1) chose to enter the process first.

The effects of high vs. limited learner–IVR interactivity on the learners' self-reported sense of agency, germane cognitive load, and safety learning outcomes (Substudy II), and their extraneous cognitive load, sense of spatial presence, and sense of embodiment (Substudy III) were studied empirically in the training interventions. The role of the learners' background characteristics was further explored in Substudy III. An experimental mixed-methods design with embedded qualitative data collection was applied in both substudies, with quantitative data used as the primary data type (Creswell & Plano Clark, 2017). Quantitative and qualitative data were collected before, during, and after the interventions. See Figure 3.

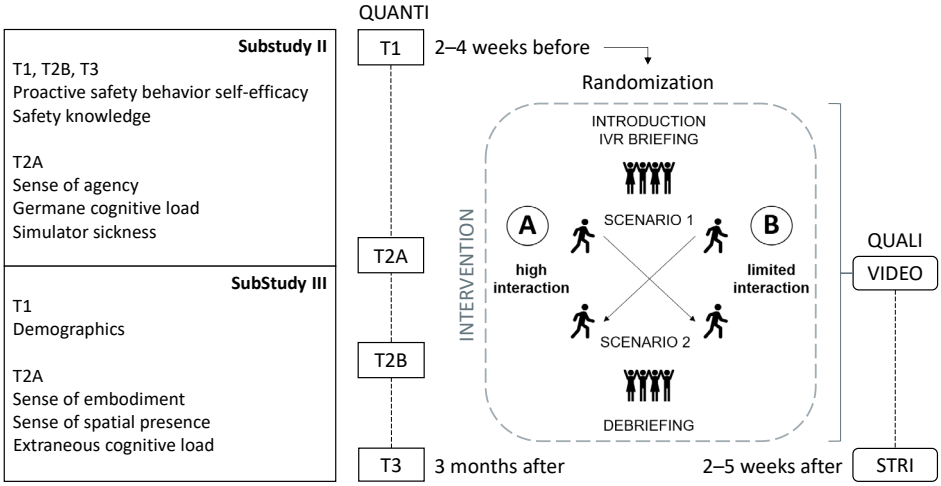

Figure 3. *Experiment Design and Data Collection for Substudies II and III*

Quantitative data collection was performed using questionnaires at baseline (T1) two to four weeks prior to the intervention, and during interventions directly after Scenario 1 (short-term delayed; T2A), after Scenario 2 (short-term delayed; T2B), and 3 months after intervention (long-term delayed; T3). Qualitative data collection was performed during interventions by videography, observations, and field notes, and 2–5 weeks after participants' training sessions in stimulated recall interviews (STRIs). The results from the data analyses were applied in the redesign of the simulation-based model for IVR safety training. Substudies II and III also informed the offered recommendations for IVR training scenario design and safety training design. In addition, analyses of the large qualitative and quantitative datasets collected during the interventions enabled several peer-reviewed publications not included in this study: a qualitative paper on trainers' perceptions of safety training goals (Lehikko & Ruokamo, 2025), a qualitative study on the discussion script used in training facilitation (Lehikko et al., 2023), and a quantitative examination of the self-reported safety training outcomes (Lukander et al., 2025).

In each substudy, the author participated in document preparation for funding acquisition, participant communications, and the ethical review. She performed literature reviews, collaborated with the contact persons and trainers in the target organizations, contributed to the design and preparation of interview protocols and materials, performed all interviews and qualitative content analyses, formulated the conclusions based on the findings, carried the main responsibility for preparing and editing the publication manuscripts, and participated in the dissemination of the research findings in scientific and public forums, such as conferences, lectures, seminars, and social media activities. Furthermore, the author contributed to translating the measuring instruments and selected the sense of embodiment measure

employed in Substudy III. She validated the statistical analyses and participated in their interpretation in Substudy II, and she performed and interpreted all the statistical analyses for Substudy III. She also participated in video data collection and performed field notes and trainer feedback collection in all training sessions during the training interventions for Substudies II and III.

5.2 Substudy I: Conceptual Development of the Pedagogical Model

A total of 18 safety trainers from two work organizations participated in semistructured thematic interviews (Creswell, 2009); 11 from O1 and 7 from O2. The trainer interviews were performed in December 2021 and January 2022 within a six-week period prior to the commencement of the IVR scenario design workshops. One contact person from each organization helped to locate interviewees involved in the design and delivery of safety training and onboarding. The author then approached these individuals to discuss the study and to interview them using the Microsoft Teams conference tool. The contact persons were included in the sample due to their organizational roles in safety training design and delivery.

A thematic interview protocol was prepared (see Lehikko et al., 2025a). The privacy notice, the research information leaflet, the interview questions, and the study participation agreement were emailed to the interviewees in advance. Their consent to the study was confirmed verbally and recorded at the start of the interview. Interviews were recorded on an external audio recording device, and a mobile phone was used as a backup. They took 25–40 minutes each and averaged 34 minutes in length. The recorded material totaled 10 h 9 min. Personal details and introductions were removed from the beginning of the audio recordings before they were sent out to an external transcription service provider. The transcriptions totaled 55,920 words and 143 pages (size A4, single-spaced). Before being subjected to content analysis, the transcripts were checked against the audio recordings for accuracy and corrected when necessary (e.g., Hsieh & Shannon, 2005).

Qualitative analysis requires moving beyond descriptions to patterns, abstractions, and interpretations of the data (Twining et al., 2017). To address the research questions, the interview data were submitted to content-driven analyses in NVivo (version 1.4, Lumivero, US). First, the transcriptions were read fully several times to form an understanding of their contents. An initial round of coding was performed. Each coherent thought or idea, expressed by one or more sentences, was applied as a unit of analysis. As the analysis progressed, the codes were edited and occasionally renamed or combined to ensure conceptual clarity. The codes were grouped into subcategories, which were then grouped into main categories. The codes and categories were then discussed in detail with another researcher—an experienced trainer—before the analysis was finalized. This step was essential for checking the

coding consistency and the contextual relevance of the identified categories. The results were reported as frequencies per category, with interview excerpts to illustrate the idea or thought condensed in the unit of analysis.

5.3 Substudy II: Empirical Testing in Training Interventions

5.3.1 Hypotheses and Measures

Five hypotheses were set in Substudy II. It was hypothesized that high interactivity in the IVR scenario is connected to stronger self-reported agency (H1) (Braun et al., 2018; Heeter, 2000; Kilteni et al., 2012; Norman, 2013; Steuer, 1992), and that it increases the learners' ECL (H2) and GCL (H3) (Albus et al., 2021; Frederiksen et al., 2020; Gibson, 2014; Sweller, 2020). It was also hypothesized that a high degree of interactivity has a beneficial effect on the learning outcomes of self-efficacy (H4) and safety knowledge (H5) (Bandura, 1997; Johnson-Glenberg, 2017; Metcalfe, 2017; Slater, 2017; Vygotsky, 1978).

All self-report measures used bipolar 7-point Likert scales ranging from "very little" (1) to "very much" (7) (see Kusmaryono et al., 2022). Sense of agency was measured using three items adapted and translated from Pritchard et al. (2016) ($\alpha = 0.79$). The cognitive load measure, which had two items for GCL ($r_{sb} = 0.84$), was translated from Klepsch et al. (2017). The proactive safety behavior self-efficacy measure included eight items: four items based on the concepts of safety participation (Neal et al., 2000) and safety citizenship (Hofmann et al., 2003), and another four items developed specifically for the study, which reflected the safety learning content in the organization-specific IVR practice scenarios. The alphas for the self-efficacy measure were 0.85 at T1, 0.76 at T2B, and 0.75 at T3. Safety knowledge was measured by three items adapted and translated from Neal et al. (2000). The reliability of the safety knowledge measure was 0.81 at T1, 0.83 at T2B, and 0.80 at T3.

5.3.2 IVR Scenario Themes and Interactivity Conditions

Three safety training scenario themes were used: (1) valve work on a busy street, (2) x-ray luggage inspection, and (3) assisting in a bridge crane lifting operation. See Figures 4-6.

Figure 4. *Screenshot of Learner View in the Valve Work Scenario (Courtesy of Finnish Institute of Occupational Health)*

Figure 5. *Screenshot of Learner View in the X-Ray Inspection Scenario (Courtesy of Finnish Institute of Occupational Health)*

Figure 6. *Screenshot of Learner View in the Lifting Operation Scenario (Courtesy of Finnish Institute of Occupational Health)*

The valve work scenario was selected from the IVR training developer's existing scenario library due to its limited relevance to the work tasks in either of the participating work organizations. The aim was to ensure that the training content was not very familiar to the learners in both organizations during the first safety learning scenario, minimizing the effect of previous familiarity on the studied constructs. The valve work scenario was performed by all learners during the training process (Scenario 1). Two organization-specific scenarios—luggage inspection and bridge crane lifting operation—were developed in collaboration with the personnel from each workplace. The scenario theme was selected according to the organizational safety training demands and scripted in collaboration with the process experts. During the intervention, either the luggage inspection or bridge crane lifting scenario was performed by the learners from the corresponding organization (Scenario 2).

For the experimental conditions, two versions of each of the three IVR scenarios were produced, each with either high or limited interactivity features enabled for the learner (Checa & Bustillo, 2020; Skulmowski & Rey, 2020). In both versions, the wireless VR equipment and the scenario design allowed the learner to move around the 4 × 4 m training area as they wished, and advance at their own pace with no time limits imposed. All scenario versions took 15–25 min to complete, depending on the learner's pace. Both versions followed a direct script with no branching storyline elements. Identical learning objectives and learning content were maintained in both versions.

In the limited interactivity versions, the learner progressed by using hand controllers to click on text boxes containing instructional content, and was presented with only the correct choices of action. In the high interactivity versions, in addition to the text box interaction, the learner could click on certain objects to perform actions and tasks. The script occasionally presented multiple choices of action, essentially providing them with the possibility to make errors and to get feedback on their actions (Metcalfe, 2017). The contents of the instructional text boxes and the accompanying voiceover reflected the interactivity level: All actions and events were presented in passive voice in the limited version, whereas in the high interactivity version, the learners received the instructions and feedback in second person singular to reflect the learning tasks. Thus, the learner's ability to control and modify the scenario events and perceive the consequences of their actions differed between the scenario versions (Steuer, 1992).

All scenario versions were preceded by a brief tutorial that could be completed in one to two minutes. The tutorial instructed the learner to walk to a certain location within the training area to calibrate the mapping of the virtual space with the physical training area before the scenario commenced. The tutorial also instructed learners how to use the hand controllers to interact with the instructional text boxes, for example, by advising them to step closer if they attempted to click the box from a distance outside the programmed specification (Chauvergne et al., 2023; Miguel-

Alonso et al., 2023). The scripted dialogues for the tutorials preceding the high and limited scenarios varied accordingly: the learner was informed whether they could interact with the objects and text boxes or with the text boxes only. The signaling principle was used to cue the learners on the afforded actions both in the tutorials and the training scenarios (Albus et al., 2021; Castro-Alonso et al., 2019; Norman, 2013).

5.3.3 Training Procedure and Trainer Collaboration

The pedagogical model for IVR safety training, conceptualized in Substudy I, was applied to the design of the training interventions and the support materials for the trainers. A discussion script for the introduction and debriefing phases of the training sessions was prepared in collaboration with two experienced trainers who had been selected to facilitate the training sessions in O1 (see Appendix A). This step was performed to increase shared understanding of the pedagogical model, to support the trainers in facilitating the sessions, and to consolidate the procedure as a quality control measure. The script included several questions and prompts intended to help the trainers maintain a learner-centric approach and support learner activity and agency while keeping the focus of the discussions on the topic. The document, intended to be kept at hand during facilitation, was presented as a checklist covering one A4-sized page per discussion, with a diagram of the training and data collection steps on one page to provide a visual aid to the trainers. The discussion script contents were modified in collaboration with one O2 trainer to suit the IVR scenario topic for that organization.

The safety training sessions were facilitated by one or two trainers from the corresponding organization, depending on their availability. Five persons in total participated in training facilitation, of whom three had participated in the design of the discussion scripts used during the introduction and debriefing phases, while all five had familiarized themselves with the IVR scenarios, the training procedure, and the discussion scripts before the interventions. To share the experiences of O1 and discuss any concerns, a meeting was arranged for the trainers from both organizations before the O2 intervention commenced. At least three members of the research team were present in all sessions to perform data collection and to provide IVR briefings and technical support.

The researchers offered a brief welcome and made introductions before the training session began. The learners were instructed not to discuss the questionnaires or other topics when filling out the online forms, and were asked to notify the researchers if they experienced any discomfort or difficulty during the training. Following the phases of the pedagogical model, the training process commenced with a facilitated introduction. Next, the learners were directed to the training space for the IVR briefing, which allowed them to familiarize themselves with the Oculus Quest 2 (Reality Labs, US) VR equipment. The learners were assisted in finding comfortable settings and instructed to begin the first tutorial and IVR scenario.

After finishing the scenario, the learners were directed to another room to fill out an online questionnaire; a laptop computer was provided for each participant for this purpose. The process was repeated for the second tutorial, scenario, and questionnaire. When all training group members had completed this process, a short break was taken before they returned to the group setting for debriefing. One training session usually took approximately two hours, but occasionally longer—usually due to active group discussions.

5.3.4 Participants and Data Collection

All research-related activities, including the training interventions, were performed during the participants' paid working hours at their work locations. They received no additional rewards in addition to their normal pay. The participants were recruited by the contact persons and trainers in the participating organizations. The aim was to recruit participants from worker roles pertinent to the work procedures included in the organization-specific IVR safety scenarios. Persons involved in the scenario scripting process as subject matter experts were excluded from the candidate pool. In O1 (n = 50), these principles were upheld successfully. In O2 (n = 26), administrative staff unexpectedly made up a substantial portion of the participant sample due to difficulties in participant recruitment. Demographically, the O1 sample consisted of 50% females and 50% males, whereas the O2 sample consisted of 20% females and 80% males. No participants selected "other" or "not willing to disclose" when asked about their gender. All participants were randomized to either condition A (perform high interactivity scenario version first) or condition B (perform limited interactivity scenario version first).

Quantitative data collection. A total of 76 learners filled out the baseline questionnaire (T1), which consisted of both single- and repeated-measure items. See Figure 7.

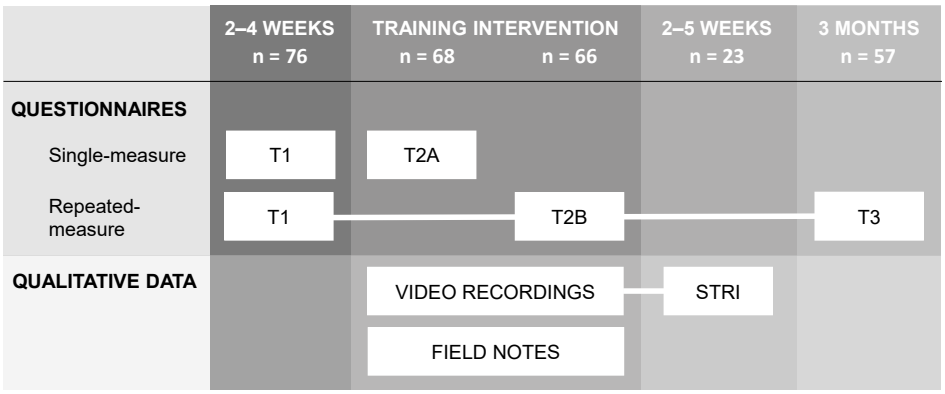

Figure 7. *Quantitative and Qualitative Data Collection on Intervention Participants*

Twenty-two safety training sessions (14 in O1 and 8 in O2) were held for groups of 2-4 learners. For reasons that included work shift conflicts and health concerns on the training day, only 68 persons participated in the training sessions and the short-term delayed questionnaires T2A and T2B administered after the completion of training scenarios 1 and 2, respectively. Two units of observation were discarded due to a data collection error in T2B, reducing the number of participants at this data collection point to 66. Fifty-seven persons filled out the long-term delayed questionnaire (T3) approximately three months after the training interventions. All questionnaires were administered using the Webropol online survey tool (Webropol Oy, FI).

Qualitative data collection. Each training session was observed by the researchers during the IVR briefing and IVR practice phases. Field notes were taken by hand on learner actions and various environmental factors, such as background noise, technical problems, and other distractions. Trainers were debriefed after each session, and their comments and the relayed learner feedback were recorded in the field notes. Afterwards, the field notes were transferred into a shared electronic file for the research group. Eight training groups (three groups in O1 and five in O2) were also video recorded and observed throughout all four training phases. The dates for video data collection were chosen on the basis of logistic arrangements, which led to the inclusion of the corresponding training groups in the sample. Five of the eight groups were observed through live video feed, and three with the researchers physically present in the training space due to technical issues during the O2 intervention. The 23 learners in these groups were video recorded in all training phases using external digital cameras, and their IVR performances were also recorded by the HMDs.

All learners from the video recorded groups participated in stimulated recall interviews (STRIs) two to five weeks after their training session. This variation was due to their shift arrangements and availability. Video clips of what appeared to be significant moments for learning, based on learner actions and vocalizations during the training session, were selected by the researchers. One to three video clips per learner were used in the STRIs (see Appendix B). The STRIs were held using Microsoft Teams, except for one interview, which had to be conducted over the telephone due to technical difficulties with the teleconference application. The interviewer verbally described the contents of their video clips to this interviewee, which may have influenced the participant's understanding, interpretation, or recollection of the events during the training session. Cameras were kept on or off during the interviews according to interviewee preference, but only audio was recorded on external digital devices. The stimulated recall interview recordings totaled 18 h 39 min and averaged just under 49 min in length. The introductions and personal job details discussed at the start of the interviews were cut to increase the anonymity of the audio files before they were sent to an external transcription

service provider. The transcriptions totaled 112,413 words and 285 pages (A4, 12 pt Times New Roman, single-spaced).

5.3.5 Data Analyses

Quantitative data analyses. Substudy II involved both between-group and within-group comparisons. The final analyses included only the participants who had completed all relevant questionnaires and items. All analyses were performed using SPSS (IBM, US). The demographics and study results were presented using means and/or percentages, medians, and standard deviations. The data distributions were examined using the Shapiro–Wilk test. T-tests were applied to normally distributed data, and non-parametric tests (Mann–Whitney) were applied when skewness was detected. The data were analyzed separately for both organizations due to differences in sample size ($n_1 = 50$; $n_2 = 26$) and learner profiles, which may have influenced the learning outcome measures. The non-parametric Wilcoxon test was applied to scrutinize those safety learning outcomes that involved a repeated-measure test.

Qualitative data analyses. The transcripts were checked against the original recordings and corrected before importing them to NVivo (1.4, Lumivero, US) for both theory- and content-driven analyses. The transcripts were all read in full several times. They were then autocoded into sections corresponding to the interview structure to help recognize recurring themes and code them accordingly during the analyses. A coherent thought or idea, expressed by one or more sentences, was used as a unit of analysis. Analysis frameworks were prepared in advance for theory-driven content analysis of the data to address the research questions. The concepts determined by the framework were identified in the data during the initial round of coding. Next, the coded material was subjected to content-driven analysis in which the units of analysis were categorized according to any negative or positive sentiments expressed. Occasionally, it was possible for both sentiments to be present in a single coded excerpt. As the coding progressed, the codes were arranged into thematic subcategories, and occasionally re-named, combined, and re-arranged. Code frequencies and overlaps between codes were examined in matrix analyses.

The learners' explicated notions of agency and germane cognitive load during their IVR experiences, as defined in the analysis framework, were the focus of Substudy II. During the theory-driven analysis that pursued the findings for RQ1, repeated themes concerning the learners' experiences of the differing levels of interactivity in the IVR training scenarios were discovered in the data. These were grouped together and submitted to further analysis, which contributed to the qualitative findings for RQ2. Coding matrices were used to study code frequencies in terms of overlapping codes or categories and background variables (experimental group and organization). The codes and categories were discussed in the research team before the analyses were finalized.

5.4 Substudy III: Further Exploration of the Empirical Data

5.4.1 Hypotheses and Measures

Three hypotheses were set for Substudy III. High learner-IVR interactivity was hypothesized to increase their sense of spatial presence (H1), ECL (H2), and sense of embodiment (H3) (Dalgarno & Lee, 2010; Johnson-Glenberg, 2019; Kilteni et al., 2012; Sweller, 2020). Learners' background characteristics of gender and previous VR experience were collected with other demographics at baseline (T1), and studied using an exploratory approach. All measures utilized seven-point Likert scales, ranging from "very little" (1) to "very much" (7). The sense of spatial presence measure was based on the Igroup Presence Questionnaire created by Schubert et al. (2001), who referenced Witmer and Singer (1998). It had four items (e.g., "I felt present in the virtual space," $\alpha = 0.75$). The cognitive load scale, adapted from Klepsch et al. (2017), measured ECL using two items ("The design of this task was very inconvenient for learning" and "During this task, it was exhausting to find the important information"; $r_{sb} = 0.59$). The reliability score for ECL was considered low.

The sense of embodiment measure, adapted from Gonzalez-Franco and Peck (2018), had two items for body ownership and three items for motor agency ($\alpha = 0.73$). The body ownership items were modified to suit the IVR environment design, where the learner had no visible avatar; simplified abstract shapes were displayed in place of the hand controllers to indicate their locations and movements to the learners (e.g., "I felt as if the virtual controller was a natural part of me"; "It felt as if the virtual controller was somebody else's"). The motor agency items were similarly adapted for the hand controllers (e.g., "The movements of the virtual controllers were caused by my movements"). All questionnaire items were translated into each participant's native language.

5.4.2 Data Analyses

Quantitative data analyses. Only between-group comparisons were made in Substudy III. The quantitative data from both organizations were pooled and examined against the background characteristics of experimental group, gender, and previous VR experience. Distributions were examined using the Shapiro–Wilk test. Nonparametric Mann–Whitney tests were applied. Confidence intervals and effect sizes (Hedges' *g*; Lakens, 2013) were reported. Linear regressions were performed, and Pearson correlations were computed. The Hayes PROCESS macro (see Igartua & Hayes, 2021) was employed in SPSS to perform mediational analyses between the key constructs.

Qualitative data analyses. An analysis framework was prepared in advance to provide theory-based definitions of the learners' sense of embodiment, sense of spatial presence, and extraneous cognitive load. The content analysis process in

NVivo was identical to the one used in Substudy II, starting with a theory-based approach with the aid of a thematic framework and continuing with a content-based approach within the themes. Matrix analyses were also performed to examine the code frequencies in terms of the learners' background characteristics, including their gender and previous VR experience, and to discover overlaps between categories. The coding and categories were validated by a senior researcher in the team.

5.5 Research Ethics

All substudies were submitted to the Ethical Committee of the Finnish Institute of Occupational Health (FIOH) as part of the Safety Learning for Immersive Virtual Reality (SLIVeR) project.[2] The review took place at the start of the research process (The Finnish National Board on Research Integrity TENK, 2019). The review covered formal research information materials directed at the participants and their work organizations, the study participant recruitment plan, consent forms, the data administration plan (including identity protection and data storage), data collection practices, such as questionnaires and interview protocols, and the ethical declaration signed by the scientific director of the joint research project. All participants were adults employed by the companies participating in the study, and recruited on the basis of informed consent. Participants' rights to confidentiality and data protection were exercised at all stages of the research (e.g., Twining et al., 2017). They were advised that they could withdraw from the study at any point if they wished. None of them exercised this option.

The IVR scenarios were instructionally designed to provide positive learning experiences that offered the learners constructive feedback on their performance in the high-interaction condition. The scripted events were designed not to inflict physical or emotional stress on the learners. The IVR environment used in the study, developed at FIOH, prioritized user comfort to reduce the possibility of simulator sickness. For example, the graphics were simplified to ensure frame rate consistency on the wireless platform and to reduce unnecessary visual elements that could distract the learner or add to their extraneous cognitive load (Mayer, 2014; Sweller, 2020). Tutorials were used to help the learners become accustomed to the IVR environment and controls prior to entering the IVR scenarios during the training sessions. The learners were advised to alert the research team if they felt any discomfort or needed help advancing in the scenario during the IVR practice phase. It is important to acknowledge that commercial HMD technology is often

2 SLIVeR was a two-year (2021–2023) joint research project between University of Lapland and Finnish Institute of Occupational Health, funded by the Finnish Work Environment Fund.

inaccessible by design for individuals with vision- or mobility-related issues (see Scavarelli et al., 2021). The research team was not equipped to provide accessibility support, such as HMD accessories designed to accommodate wearing eyeglasses under the device.

6 Substudy Results and Evaluations

6.1 Conceptualizing a Pedagogical Model for Immersive Virtual Reality Safety Training: Pedagogical Practices in Trainer Interviews

The first substudy combined a literature review on simulation learning, IVR learning, and occupational safety training with the qualitative findings from trainer interviews to conceptualize a pedagogical model for IVR safety training. It explored the safety trainers' pedagogical practices to gain an understanding of the sociocultural contexts for occupational safety and workplace learning that informed the model design.

Results

For RQ1, "What kinds of pedagogical practices do trainers apply in safety training?", three main categories of pedagogical practices were identified: (1) match the pedagogy to training goals, (2) guide social interaction in training situations, and (3) utilize organizational resources for training development.

Category 1 included examples of pedagogical practices used by safety trainers to ensure a good fit encompassing the training, the organizational goals, and the learners' work. These practices included, for instance, ensuring training relevance by targeting specific learner groups in the planning phase or taking extra measures to train for teamwork; selecting the most suitable teaching methods, such as hands-on training, lectures, or simulations; and assessing the training outcomes appropriately.

Category 2 contained practices used by trainers to guide social interaction during the training situations, such as facilitating group interaction by promoting discussion and creating and maintaining a positive learning atmosphere; modeling positive safety behaviors; and upholding the temporal structure of the training by using pre- and post-briefings.

Category 3 included practices related to the utilization of organizational social or material resources in training development, such as collegial collaboration on training coordination, material preparation and delivery, and using organizational data and feedback to develop safety training programs.

For RQ2, "How do the trainers' pedagogical practices inform the sociocultural contextualization of the pedagogical model for IVR safety training?", the findings illustrated the trainers' awareness of situational and individual factors (Tynjälä, 2013), and highlighted the role of their pedagogical content knowledge (PCK; Berry et al., 2008; Shulman, 1986). The importance of including the social learning

phases in the pedagogical model for IVR safety training was confirmed. The findings contributed to the trainer's explicit actions pre- and post-training, as well as during the introduction and debriefing discussions in the conceptualized and contextualized pedagogical model presented in Substudy I. See Figure 8.

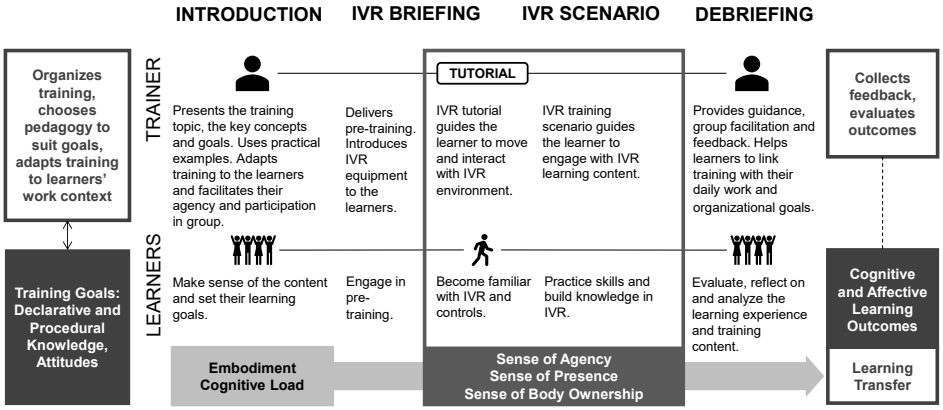

Figure 8. *Conceptualized Pedagogical Model for IVR Safety Training (Lehikko et al., 2025a)*

Trainers develop occupational safety training programs and organize the training sessions in collaboration with their colleagues and utilize material resources and artifacts, such as databases and feedback systems. Training is designed and coordinated within the organizational sociomaterial environment (Holdsworth et al., 2022; Vuojärvi & Korva, 2020). Trainers choose suitable pedagogical methods to match the training goals and adapt the training content to the learners' work contexts. Afterwards, they collect feedback and evaluate the training outcomes, and use the collected information to develop the training. To support the achievement of the training objectives, trainers help learners to connect the safety training content with their daily work duties and the organizational safety goals both during the introduction and debriefing phases, using, for example, practical examples and adapting their delivery and facilitation to the learner group.

The trainers' role is pivotal in connecting the training content and delivery to the organizational safety culture (Casey et al., 2021; Tynjälä, 2013) as well as in supporting the learners to gain membership of the shared practices and discourses in the occupational safety domain of their work while maintaining sensitivity to the contextual and individual facets of the learning experience (Billett, 1996; Tynjälä, 2013; Vygotsky, 1978): A feat that requires not only pedagogical and subject matter expertise, but sufficient intra- and interpersonal skills (e.g., Chai et al., 2013; Ling Koh et al., 2014). Organizations may support trainers in their role by ensuring their access to organizational resources and professional development opportunities.

Interviewing the trainers at the beginning of the DBR process was essential to gain valuable contextual information about the intended end users of the model and the sociocultural context of safety training in the target organizations and to uphold the DBR principles by involving the safety training personnel in the organizations participating in the study. The findings revealed the pedagogical practices considered most functional by the safety trainers, and contributed to the design by providing valuable insight into the conceptualization process of the pedagogical model. The pedagogical practices were operationalized in the discussion script prepared for the training interventions.

Evaluation

Several methodological limitations were present in this study. The number of the safety trainers recruited to participate in the interviews depended on their availability in each work organization. Both organizations were large, but recruiting trainers from O2 appeared to be more difficult for their contact person. However, 18 interviewees were sufficient to saturate the interview data. To achieve a larger number of informants and to relieve the pressure of recruitment on the contact persons, the interviews could have been extended to other work organizations. Some participants considered Microsoft Teams an inconvenient means of interviewing, mainly due either to previous unfamiliarity with it, or to technical issues, such as the sound quality problems occasionally experienced during the interviews. Alternative conference tools and arrangements should be explored in future implementations. Only one researcher performed the content analyses of the interview data, which can be considered a methodological weakness—triangulation during the qualitative analysis process is strongly advocated (Creswell, 2009). However, the coding and categories were discussed with another researcher with training and occupational safety expertise before finalizing the findings.

The aim of the interviews was to provide contextual information on the practical and pedagogical aspects of safety training in the target organizations, especially the pedagogical practices. It can be argued that the mapping and analysis of the training plans, evaluation frameworks, and other artifacts used in training design and delivery in these organizations could have provided another dimension to the analysis of the qualitative interview data. It should also be noted that none of the views of the learners, occupational health and safety professionals, or organizational management were sought to confirm or challenge the trainers' perceptions of the most functional occupational safety training practices in this study. The trainers' professional networks were left outside the study scope (cf. Tiippana et al., 2024).

The pedagogical model applies sociocultural and social constructive approaches to learning (e.g., Keskitalo, 2015; Sutherland et al., 2009; Vygotsky, 1978). They can be perceived as epistemologically conflicting with the cognitivist approach evident in Makransky and Petersen's (2021) cognitive affective model of immersive learning,

which informed the initial model's design. A situational view of workplace learning (Billett, 1996, 2013, 2021) was therefore applied in this study to present a cohesive epistemological framework for the conceptualization (Twining et al., 2017). The importance of understanding and aligning the contexts of the training situation and everyday work practices, suggested in the model, is supported by the literature on both workplace learning and safety training (e.g., Casey et al., 2021; Burke et al., 2006a). The epistemological rifts—and overlaps—may have offered interesting possibilities for further theoretical development had the study focus been allowed to shift from the pragmatic context.

6.2 Exploring Interactivity Effects on Learners' Sense of Agency, Cognitive Load, and Learning Outcomes: A Mixed Methods Study

In Substudy II, interactivity was studied in the context of the learners' sense of agency, their cognitive load, and two selected learning outcomes—safety knowledge and proactive safety behavior self-efficacy—using both quantitative and qualitative methods.

Results

The demographic data revealed significant differences between the samples in the two organizations. Their quantitative data were therefore analyzed separately. See Table 3.

Table 3. *Demographics of Study Participants at Baseline (Lehikko et al., 2024)*

Variable		O1 (n=50) % or mean*	O2 (n=26) % or mean*	Total (n=76) % or mean*
Gender	Female	50.0	19.2	39.5
	Male	50.0	80.8	60.5
Age (years)		40.1*	44.1*	41.5*
Job tenure (years)		8.09*	12.48*	9.7*
Personal VR devices usage	Never used	56.0	26.9	46.1
	Tried	36.0	65.4	46.1
	Once a month	8.0	3.8	6.6
	Once a week or more often	0.0	3.8	1.3
Has had a work-related accident within 3 years (yes)		31.8	9.5	24.7
Previously participated in VR training (yes)		0.0	42.3	15.5
Prevalence of IVR scenario task in current job	Never	8.0	42.0	23.7
	Once a year or less	12.0	11.5	10.5
	Monthly	22.0	3.8	19.7
	Weekly	32.0	38.0	28.9
	Daily	26.0	3.8	17.2

For RQ1, "How does interactivity influence learners' sense of agency?", the learners in O1 ($n = 44$) reported a higher sense of agency ($p < 0.01$) in the high interactivity treatment compared to the limited interactivity treatment. This phenomenon was not found in O2; thus, H1 was only partially supported. The qualitative findings revealed that the learners' sense of agency could be supported by involving them in the scenario activities. The responsiveness of the IVR environment appeared to strengthen their feelings of being in control. On the other hand, unmet agency expectations and script-induced restrictions appeared to hinder the learners' perception of agency: This applied in both high and limited interactivity scenarios. Some interviewees, who considered themselves subject matter experts in the topics covered in the IVR learning contents, expressed that their actions were restricted by the scenario script, and that they could not demonstrate their expertise in the scenario. Several interviewees made references to their lack of control. They referred to, for instance, being in a passenger or observer role, not being "allowed" to perform actions, or scenario events unfolding "automatically." The learners in O2 expressed a diminished sense of agency more frequently, possibly due to having greater previous experience with different IVR training environments.

For RQ2, "How does interactivity influence learners' cognitive load and learning outcomes?", higher GCL was reported in both O1 ($n = 46$, $p < 0.01$) and O2 ($n = 22$, $p < 0.05$) in the high interactivity treatment. Self-reported ECL was low, and no significant difference was found between the treatment groups. Thus, H2 was not supported, while H3 was supported. A significant pre-post-test increase in proactive safety behavior self-efficacy ($p < 0.01$) and safety knowledge ($p < 0.01$) was discovered in the high interactivity treatment in O1. A significant increase in safety knowledge ($p < 0.05$) was also discovered in the limited interactivity condition in O1. No statistically significant training effects were found in O2. Thus, H4 and H5 were partially supported.

The qualitative findings on GCL indicated that learners' ability to focus on the learning content and to reflect on real work procedures relevant to their duties during the IVR scenario allowed them to process the learning content in the training situation; however, focusing on performance speed had an adverse effect (see also Lawson & Mayer, 2024). Based on the results, some recommendations were made for IVR safety training. Learners' embodied involvement and participation in the scenario may influence the achievement of affective learning goals. Supporting the learners in managing their cognitive load was suggested. The learners' background, expertise, and previous IVR experience should be considered when prebriefing learners before the IVR scenario. The findings also implied that including familiar safety checks and procedures from the learners' work supported their generative cognitive processing, which may have been due to motivational effects (Albus et al., 2021; Mayer, 2014).

The qualitative findings of the inductive content analysis revealed that the main interactivity learning benefits from the learners' point of view were similar to those

attributed to embodied learning in the literature: increased interest and challenge, the possibility to learn by doing, better learning retention, learning from errors, and the opportunity to practice real work tasks (e.g., Korte & Körkkö, 2024). The interviewees from O1, where IVR was a new learning medium, particularly emphasized the interest and challenge aspects, whereas the more experienced O2 interviewees mentioned their preference for learning by doing more frequently when discussing their perceptions of interactivity. The findings illustrated the differences in learner attributions between the two organizations, hinted at the possibility of some novelty effect in the O1 results (Clark, 1983), and confirmed that awareness and acknowledgment of the sociocultural and situational contexts is essential in IVR training interventions (Billett, 2021; Casey et al., 2021; Evans et al., 2006; Parchoma, 2014; Vygotsky, 1978). To conclude, interactivity may enable embodied learning that many learners perceived as superior to less activating pedagogical approaches but is not uniformly considered essential for IVR learning outcomes in the literature (e.g., Khorasani et al., 2023).

Evaluation

Challenges in participant recruitment in O2 had serious consequences for this study. First, the small sample size resulted in little statistical power for the results. Second, the samples from the two organizations were uneven, with O1 providing nearly twice as many participants as O2. Third, to make up for the lack of study participants from O2's factory floor level at whom the training was targeted, several persons from administrative roles were recruited for the study. These factors led to unexpectedly heterogeneous learner profiles: the safety training was of little relevance for a number of O2 learners, and this was likely reflected in their self-report data on the learning outcome measures. Some miscommunication was also indicated by one STRI interviewee, who told the researcher that they had expected to receive crane operation training during the intervention due to an email received from a colleague. The root causes for the recruitment issues in O2 remain unknown, but it is likely that the differences in the sociocultural environment for safety training in the organizations influenced both the research and the achieved results. Pyysiäinen (2021) proposed a transactional view on sociocultural affordances and agency in which the affordances, which are constructed and embedded in the sociocultural environment, may not just afford but actively constrain the possibilities to enact agency. Agents are always subject to the normative scrutiny of their coparticipants.

Other factors may also have contributed to the differences evident in the results between the organizations. Other VR training developments were already in progress in O2, whereas the training media was introduced for the first time in O1 in the interventions. The qualitative analysis of the STRIs on the learners' perceived interactivity learning benefits revealed that the O1 participants emphasized the interest and challenge provided by the high interactivity scenarios, whereas in O2,

the learning-by-doing aspect was mentioned more often. Against the background of the O1 learners' diminutive VR experience prior to the study, it is likely that some novelty effect (Clark, 1983) influenced their self-report data.

The hypotheses on the increased sense of agency and positive short-term learning outcomes in the high interactivity condition were confirmed only in O1. Learning outcomes were measured by self-report measures, a method that is common for affective outcomes such as self-efficacy (Kraiger et al., 1993). However, the accuracy of self-report measures has been questioned in some recent IVR learning studies (e.g., Fokides & Antonopoulos, 2024; Khorasani et al., 2023; Lawson & Mayer, 2024). It may have been possible to apply other methods of evaluation, such as performance and recall tests, to assess the safety knowledge outcomes (see Kraiger et al., 1993). Multiple data sources could have been used to triangulate the self-report data.

The STRI data were collected from selected participants 2–5 weeks after their respective training sessions. The STRI technique was efficient in eliciting the participants' recollections even after 4 weeks' delay: based on the data, the average interview duration was diminished by no more than 3 min in the fifth week. The timing was suitable for collecting data on learners' experiences of the training situation, but it did not support the assessment of learning transfer. Furthermore, the interviewed learners were participants in a convenience sample of training groups that participated in video data collection. The heterogenicity of the learner profiles was not known when the video recording dates were set, and the interviews were not targeted at those whose learner profiles were compatible with the agreed preconditions for study participation. Addressing this issue would have required more active communication between the research institutions and the organizations participating in the research.

The experimental design assumed a within-group comparison between the two experimental groups. The learners in both groups underwent safety training in which they first performed one scenario that was decidedly removed from the contexts of their daily work, and later another scenario specifically tailored to their organization and work role. For experimental group A, the first scenario employed high interactivity, and the second one employed limited interactivity. For group B, the interactivity versions of these scenarios were reversed. However, a decision was made to limit the length of the questionnaires presented during the training interventions. Therefore, the T2A questionnaire completed after the first scenario only included measures relevant to the learners' IVR experience, and training outcomes were measured only after the organization-specific scenario in T2B. This arrangement limited the data analysis options within the study. For instance, using quantitative data to assess relationships between the IVR experience measures and the learning outcomes was not possible. As a solution, the overall number of included measures could have been reduced to accommodate combining both IVR experience and safety learning outcome measures into one questionnaire that would

have been repeated after each scenario, making it easier to isolate any possible order effects in the study.

Additionally, it may have been beneficial to collect survey data from the learners after each training phase, not only after the IVR scenarios (e.g., Garcia Estrada et al., 2024). However, this would have disrupted the safety training process even further. The main purpose of the training interventions was to test the pedagogical model in the field conditions and collect data in authentic training settings at the participating workplaces. Qualitative data were collected by video recording selected training groups. If more time and multiple researchers had been available for qualitative data collection and analyses, video data could have been collected from each training phase for all training groups and analyzed in greater depth. Multiple coders would have improved the qualitative analysis processes by enabling inter-rater reliability assessments and triangulation.

6.3 Previous VR Experience Increases Embodiment in Immersive VR Safety Training: An Exploratory Mixed-Methods Study

In Substudy III, the empirical data collected in the training interventions were examined further. The study objectives were threefold: (1) to examine, using statistical methods, whether interactivity or learner characteristics influence learners' perceptions of embodiment, spatial presence, and ECL; (2) to explore the factors contributing to the learners' training experiences by applying qualitative methods; and (3) to provide recommendations for addressing these factors in IVR training design, based on the empirical findings.

Results

The demographics were presented only for the participants who attended the training interventions in the target organizations. In the between-organization comparison, differences were observed in sample size, gender balance, previous VR experience, and previous participation in VR-based training. There were 46 participants from O1 and 22 participants from O2. The O1 sample comprised 52.2% females, in contrast to the 18.2% in the O2 sample. In O1, the percentage of VR novices in the sample was 54.3; in O2, it was 31.8. None of the O1 participants had attended VR-based training before, in contrast to 36.4% in O2. No significant baseline differences were discovered in the comparison between the experimental groups. For the exploratory study of learner characteristics, the sample was divided by gender and VR experience for between-group comparisons.

RQ1, "Do learner–IVR interactivity or learner characteristics influence the learners' perceptions of spatial presence, ECL, and embodiment in IVR safety training?" was addressed by performing statistical analyses on the questionnaire

data. The nonsignificant statistical results were discussed with the aid of qualitative findings. RQ2, "What kinds of factors influenced the learners' training experiences, and how can they be addressed in IVR safety training design?", was addressed by performing content analyses on the qualitative interview data. Both positive and negative factors affecting the studied constructs were identified. Next, a summary of the findings for RQ1 and RQ2 will be presented for each construct.

Extraneous Cognitive Load. No significant differences were found for self-reported ECL between the experimental groups; H1 was not supported. Based on the learners' responses, they had experienced little ECL, as the results were skewed toward the lower end of the scale. No significant differences were discovered in gender- or VR experience-based comparisons. However, the qualitative data indicated that learners' cognitive effort may not have been reliably reflected in the quantitative data. Fourteen interviewees discussed getting stuck or slowed down in the scenario. Twelve interviewees mentioned the lack of instructions; for instance, some scenario features in the high interactivity versions had not been explained in the tutorial. Some interviewees also had difficulties understanding the instructions and carrying out the actions in the limited interactivity versions of the scenarios. Some interviewees expressed satisfaction with the instructional features, such as the combination of audio and text instruction (Baceviciute et al., 2020), but negative comments on ECL-related issues dominated the code frequencies. In conclusion, the qualitative findings cast some doubt on the reliability of the self-report measures on ECL (Khorasani et al., 2023; Lawson & Mayer, 2024).

Sense of Spatial Presence. The participants' responses indicated strong spatial presence across the experimental groups; no significant differences were discovered in the group comparison. Thus, H2 was not supported. Comparisons based on gender and VR experience had similar outcomes. In the qualitative analyses, several factors that enhanced the learners' sense of spatial presence were identified. The learners discussed a state of deep immersion; a feeling of familiarity with the virtual surroundings; moving around physically, which appeared to add credibility to the IVR experience; movement and presence of animated objects; and strong buy-in. Factors that diminished spatial presence were also discussed: hearing sounds and voiceovers from outside the IVR scenario; low buy-in; and perceptual discrepancies between the IVR and the real world. Overall, spatial presence was influenced by the IVR design choices but was also subject to external distractions stemming from the training arrangements (see Parong et al., 2020). The presence illusion was possibly supported by the participants' perceptions of movement in the 3D space (see Johnson-Glenberg, 2019; Pritchard et al., 2016). External distractions were also a source of ECL (e.g., Petersen et al., 2022) and likely disrupted the learners' ability to select and process the relevant learning content (see Lawson & Mayer, 2024).

Sense of Embodiment. The results of the analysis of the sense of embodiment were skewed toward the upper end of the scale. The comparisons between the

experimental groups and genders did not reveal statistically significant differences, leaving H3 unsupported. In the VR experience-based comparison, however, those with some previous experience rated their sense of embodiment significantly higher than the VR novices did (Mann–Whitney p = 0.03; g = 0.56). The measurement components were scrutinized. There was no statistical significance for the motor agency component, but there was a significant difference for the body ownership component (Mann–Whitney p = 0.02; g = 0.59) of the embodiment measure between the VR experience groups. The linear relationships between the variables were examined using the Pearson correlation coefficient. Negative correlations existed between ECL and body ownership—$r(64) = -.471$, $p < 0.01$—and between ECL and spatial presence—$r(64) = -.326$, $p < 0.01$. Positive correlations were discovered between spatial presence and body ownership—$r(64) = .404$, $p < 0.01$—and between previous VR experience and body ownership—$r(64) = .277$, $p < 0.05$. There were no additional linear relationships between the participants' VR experience and other study variables.

Multiple linear regressions were performed, first with body ownership as the dependent variable and VR experience, ECL, and spatial presence as predictors ($R^2 = .336$, $F(3, 63) = 10.61$, $p < .001$). Next, spatial presence was placed as the dependent variable and the other key variables as predictors ($R^2 = .179$, $F(3, 63) = 4.59$, $p = .006$). Here, only body ownership was found to significantly predict spatial presence ($\beta = .332$, $p = .016$). Mediational analyses were performed. See Figure 9.

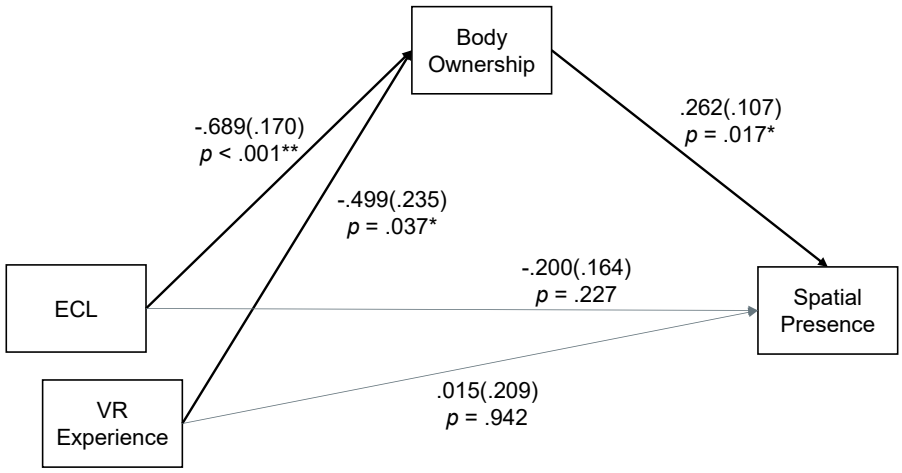

Figure 9. *The Mediational Model for VR Experience, ECL, Body Ownership, and Spatial Presence (Lehikko et al., 2025b)*

ECL as the independent variable (β = -.689, p = .000) and VR experience as a covariant (β = .499, p = .037) were discovered to have significant effects on body ownership. Body ownership had a significant effect on spatial presence (β = .262, p = .017). ECL had a nonsignificant direct effect (β = -.200, p = .227) on spatial presence in the mediated model. The Sobel test was performed to see if body ownership significantly mediated the relationship between ECL and spatial presence; the significance of the mediation was confirmed (z = -2.09, p = 0.03).

In the qualitative analyses, a strong overlap was found between the coded references for the participants' remarks on their spatial presence and their embodied actions in the IVR (see Kilteni et al., 2012). The learners made references to their perceptions of available physical space in the virtual environment, and the presence of large, moving virtual objects appeared to evoke a sense of physical threat in some participants (e.g., Schöne et al., 2021). However, some participants also expressed that they had broken the embodiment illusion on purpose by, for instance, walking through a virtual object. Matrix analyses were performed to explain the differences revealed by the quantitative analysis. The VR novices were overrepresented in the coded references to spatial presence. They discussed poor buy-in and IVR–real-world discrepancies more often than those with previous VR experience. The VR novices had struggled with adjusting to the controls and movement in the IVR. They had experienced pressure from the scripted instruction, and they expressed that their focus had been directed to the instructional text boxes more frequently.

To summarize, interactivity and the learners' gender did not impact the results of the studied constructs of ECL, spatial presence, and embodiment. However, previous VR experience was discovered to have a medium-sized effect on the learners' sense of embodiment. Those with previous VR experience appeared to adapt to the IVR environment more easily, and possibly to use their cognitive resources more efficiently in the virtual learning environment. The recommendations for IVR training included (1) reducing the ECL inflicted by the instructional and design features, focusing on enhancing instructional clarity and scaffolding in the scenario (e.g., Mulders et al., 2020), and (2) supporting especially the VR novices' attention and motivation by giving them a comprehensive tutorial and repeated practice sessions (see Chauvergne et al., 2023; Laine et al., 2024). Familiar elements from the learners' work environment could add motivational (Mayer, 2014) and situational interest benefits (Makransky & Petersen, 2021; Wirth et al., 2007) and support the learners' attention and affordance perception by increasing salience (Skulmowski & Rey, 2020; Gibson, 2014; Norman, 2013; Schöne et al., 2021). Selectively applied motion and flicker cues to call attention to specific virtual locations may be used to support the spatial presence illusion (see Holcombe, 2023; Theeuwes, 2010; Wirth et al., 2007).

Evaluation

Substudy III provided valuable insights into the results of Substudy II. The presence of some novelty effect in the self-reported learning outcome results could not be ruled out based on the findings of Substudy III. The findings also provided a fresh angle into the experiences of VR novices, especially on the attentional and motivational issues that should be considered in IVR safety training. The study provided additional insight into the researchers' and collaborators' success in isolating and studying the interactivity design component of the IVR experience. The IVR scenarios used in the study were sufficiently alike for the participants to provide fairly similar ratings for their spatial presence, ECL, and embodiment across the conditions; in this sense, the statistically nonsignificant results also yielded valuable information. Perhaps this study will set an example in developing carefully planned and executed experimental value-added designs (e.g., Buchner & Kerres, 2023) for the study of learner characteristics, learning objectives, and learning outcomes.

Several aspects could have been improved upon in the methodological execution of this study. Substudy III focused on the perceptual side of the learners' IVR experiences, so it was not as vulnerable as Substudy II to sociocultural influences and shortcomings in participant recruitment. Nevertheless, the sample size was quite small for applying statistical methods, and the effect sizes for the statistically significant findings were mediocre. The mixed-methods design likely did not fully mitigate the weaknesses of the quantitative part of the study. Translations to the participants' native language from the original English instruments may have introduced some confusion in the interpretation of the questions. The reliability of the ECL measure was quite low. In the multidisciplinary study setting, it was necessary to limit the number of questionnaire items to avoid creating questionnaire fatigue in the participants and to keep the questionnaire length acceptable during the interventions. It should be noted that Tran et al. (2024) advised against the use of single items or subscales, such as spatial presence, instead of the full Igroup Presence Questionnaire.

More robust measures for the key constructs would have enabled factorial analyses and improved the reliability of the results. Furthermore, the proposed mediational model was very simple; structural equation modeling could have offered a more comprehensive picture of the relationships between the measured constructs. For these reasons, the relationships and interactions between the constructs proposed by the mediational model should be subjected to further testing in studies with larger samples and extended measurements. In the current study, coding collaboration between several researchers during the qualitative analyses would have enhanced the validity and reliability—or credibility and dependability (Bengtsson, 2016)—of the findings by triangulation in circumstances in which the available time for performing the analyses was very limited. As it was, another research group member provided triangulation by validating the codes and categories.

7 Discussion

7.1 Summary of the Results and Implications for IVR Safety Training Design

The aim of this dissertation study was to investigate how pre- and post-briefings and individual IVR training scenarios should be designed and implemented in a simulation training model to support the achievement of safety training objectives in the sociocultural setting of the workplace. Substudy I validated the simulation pedagogical approach, evident in the training phases, by examining the pedagogical practices that safety trainers in the target organizations considered the most functional in terms of training effectiveness and transfer. The findings from the trainer interviews were incorporated into the contextualized pedagogical model for IVR safety training. The thematic categories "Match the pedagogy to training goals" and "Utilize organizational resources for training development" illustrated those of the trainers' pre- and post-training activities that helped trainers maintain the relevance of the training to both the learners and the safety culture.

The inclusion of these trainer activities is in accordance with earlier models for professional development contexts, such as Casey et al.'s (2021) model of safety training engagement and transfer, Holdworth et al.'s (2022) professional learning design framework, Keskitalo's (2015) pedagogical model for simulation-based healthcare education, and Tynjälä's (2013) 3-P model of workplace learning. The third category, "Guide the social interaction in training situations," contained pedagogical practices that the trainers relied on to create a learning-conducive atmosphere, promote social interaction between learners, and accommodate the needs of individual learners. The findings indicated that trainers' pedagogical content knowledge (e.g., Shulman, 1986) is essential in all training phases. The themes identified in the inductive content analysis provide an interesting snapshot of the sociomaterial aspects of safety training in the organizational setting, created and recreated in the daily interactions of the work community (e.g., Orlikowski, 2007).

In Substudies II and III, learner–IVR interactivity—a key design feature for IVR—was studied empirically. The empirical results from Substudy II revealed that the learners in both organizations experienced a higher germane cognitive load in the high interactivity condition, indicative of generative processing of the learning content that is essential for learning according to the CLT (Mayer, 2014). A significant increase in the learners' sense of agency measured for the shared Scenario

1, and self-reported proactive safety behavior self-efficacy and safety knowledge after the organization-specific training Scenario 2 were detected only in O1 in connection with the high interactivity scenario versions—and only in the short-term delayed test.

The focus of Substudy III was on the exploratory study of individual learner factors that may affect their IVR learning experiences, but it also provided grounds for reflecting on certain methodological issues in the intervention study. All quantitative data were collected after the first scenario, which allowed for simple between-group comparisons. Learners were compared by experiment group, gender, and previous VR experience (none vs. some experience). A significant statistical difference, with a medium-sized effect, was discovered only for the self-reported embodiment in the experience-based comparison—previous VR experience appeared to be linked to higher embodiment ratings. The difference originated from the body ownership component of the embodiment measure. Mediational analysis performed on the key variables indicated that body ownership mediated the impact of ECL on spatial presence.

The qualitative findings suggested that the self-report measures did not entirely succeed in reflecting the cognitive load experienced by the learners in Substudy III (see Lawson & Mayer, 2024). Their self-rated ECL appeared to be low across organizations and experimental conditions. However, the findings indicated that many learners experienced difficulties, for instance, in advancing the scenario and understanding the instructions. On further scrutiny, the learners, especially those without any previous VR experience (the "VR novices"), frequently discussed challenges related to both IVR operation and instruction, regardless of the scenarios' interactivity level. External distractions should be minimized during the training event to reduce the learners' working memory load, enabling them to use their cognitive processing more efficiently.

The findings suggest that body ownership mediates the effects of ECL and VR experience on the learners' sense of spatial presence. Issues related to attention and motivation also appeared to have influenced the learners' perceptions. Allowing the learners to move around in the virtual training area and selectively applying animations and spatial cues may support the spatial illusion. On the other hand, creating an atmosphere of psychological safety in the training situation may be essential for learners' motivation and suspension of disbelief (e.g., Dieckmann et al., 2007). Substudy III highlighted the importance of considering the previous VR experience of the learners and adjusting the tutorials and practice sessions accordingly to accommodate the VR novices.

These findings have some interesting implications. First, they confirm that learners' agency, autonomy, and involvement should be considered focal aspects of IVR safety training. Based on the results from Substudy II, the inclusion of interactive features and mastery-building experiential learning opportunities in the IVR is

recommended when promoting the participants' proactive safety behavior self-efficacy is a key objective. The qualitative findings provide additional insight into the design features that may create premises for the learners' sense of agency. Learning tasks that involve the learner directly in the scenario events and let them apply their expertise are recommended. An inflexible scenario script may diminish the learners' autonomy and hinder their perception of agency. Furthermore, practitioners and IVR researchers are strongly encouraged to factor in the influence of the situated and sociocultural dimensions of safety training implementations, which may vary between organizations and teams. The attitudes and values embedded and co-constructed in the embodied safety training practices, related artifacts, and discourses may have profound impacts on the learners' interpretation of the events, and on the manifestation of the training outcomes (e.g., Nicolini, 2012; Schilhab & Groth, 2024).

Second, supporting learners' motivation and attention are focal training design considerations. Creating a safe container for the training situation by clarifying expectations, paying attention to detail, and respecting the learners and their psychological safety is recommended (Dieckmann et al., 2007; Lehikko et al., 2025a; Muckler, 2017; Rudolph et al., 2014). The individual learners' expertise in the training topic, as well as prior VR experience, have implications for the training design. Based on the findings of Substudy III, tutorials and practice arrangements are recommended to help VR novices develop the necessary embodied fluency for maneuvering in the IVR environment. Furthermore, the findings from both Substudies II and III indicate that evoking feelings of familiarity with the IVR design may have several benefits in the safety training context. According to the previous literature, familiarity may increase learner motivation (Albus et al., 2021; Mayer, 2014), improving learning retention and training transfer. Evoking the emotions and beliefs connected to real-world tasks may support emotional buy-in (e.g., Muckler, 2017).

Including familiar safety-related tasks and procedures from the learners' daily work provides them with opportunities to reflect on the learning content against the background of their previous experiences, supporting their generative processing and the embedded and situated aspects of cognition (e.g., Schilhab & Groth, 2024). Familiar surroundings may also influence a learner's illusion of spatial presence by evoking recollections of existing work locations and environments, increasing situational interest (see Wirth et al., 2007). The training scenario may elicit a strong sense of embodiment in the learners, depending on individual attributes and IVR features. For example, animated movement may help direct learners' involuntary attention to the learning content. However, carefully considering the spatial placement of the learners' virtual body in the 3D space is advised, especially in the presence of moving virtual objects, to avoid unintentionally evoking the feeling of physical threat and possibly inflicting discomfort on the learners.

7.2 Simulation-Based Model for IVR Safety Training

The conceptualization of the pedagogical model in Substudy I was completed by integrating the findings from trainer interviews with the research literature. In Substudies II and III, findings from the data collected before, during, and after training interventions were applied to the formulation of recommendations for IVR safety training design. All the substudy results informed the design revisions made to the model: Substudies I and II contributed to all training phases, and Substudy III contributed to the IVR briefing and scenario phases. See Table 4.

Table 4. *Design Revisions Based on Substudy Results*

Substudy	Training Phase				Design Revisions Based on Study Findings
	I	II	III	IV	
Substudy I: Conceptualizing a pedagogical model for IVR safety training with trainer interviews.	X	X	X	X	• Maintain contextual validity and relevance for the learners throughout the training.
					• Trainers' pre-training actions: Organize training, choose pedagogy to suit goals, adapt training to learners' work context. • Trainers' post-training actions: Collect feedback, evaluate outcomes.
	X				• Use practical examples, adapt training to the group of learners.
				X	• Help learners link the training with their daily work and organizational goals.
Substudy II: Interactivity effects on sense of agency, cognitive load, and learning outcomes.			X		• Design for high interactivity and learner autonomy to support the learners' sense of agency and affective learning outcomes in particular, and to enable generative processing in the training situation. • Support generative processing by including the learners' familiar work tasks and procedures in the scenario. • Support the learners' focus and IVR affordance perception through IVR design.
	X	X	X	X	• Consider individual differences in cognitive processing and support the learners in managing their cognitive loads. • Consider the influence of organizational and team-level sociocultural factors in the training design, implementation, and evaluation.
Substudy III: Previous VR experience increases embodiment in immersive VR safety training.		X	X		• Minimize external distractions to support the learners' focus, spatial presence and embodiment in IVR.
		X			• Give VR novices a comprehensive tutorial and repeated practice sessions before they engage with the learning content.
			X		• Selectively apply motion and flicker cues to call attention to specific locations. • Apply familiar features to support spatial presence, motivation, and situational interest.
	X	X	X	X	• Uphold psychological safety to support buy-in and training effectiveness.

The qualitative findings from Substudy II confirmed that both the high and limited interactivity IVR scenario versions had elements that supported, but also suppressed, the learners' sense of agency. Directing learners' attention was found to

be important for enabling their generative processing of the learning content. The STRI findings revealed that the learners in O1 and O2 perceived different learning benefits for IVR, which points to differences in the sociocultural aspects of IVR safety training, such as expectations and predispositions toward the learning technology, between the participating organizations. In Substudy III, the quantitative results exposed the weaker sense of embodiment experienced by VR novices. The qualitative findings illustrated the factors that contributed to the phenomenon, either directly or indirectly, by affecting the learners' experiences of embodiment, spatial presence, and ECL. Considering the former research literature, the findings indicated that IVR safety training would benefit from the inclusion of various attention-guiding and motivational elements.

The following paragraphs present the iterated and re-named model incorporating the results of the substudies. See Figure 10.

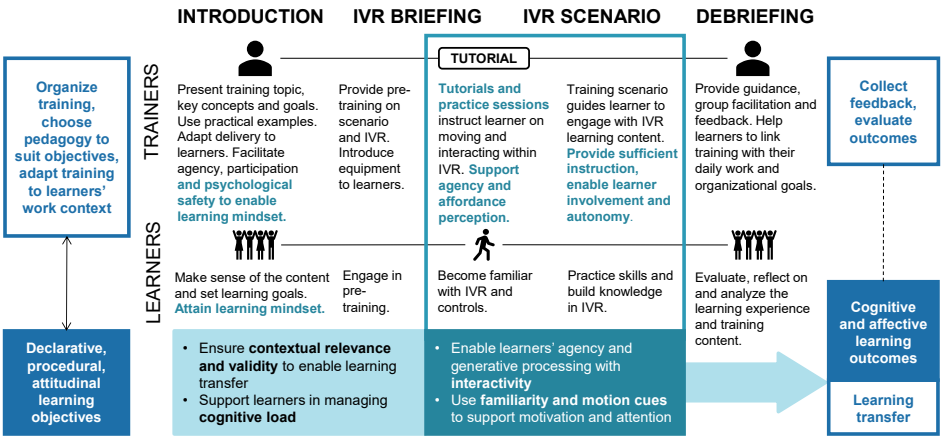

Figure 10. *The Simulation-Based Model for Immersive Virtual Reality Safety Training.*

Pairing the IVR scenarios with group discussions creates premises for a dynamic learning space in which individual experiences, learning needs, and emergent topics can be addressed (see Damşa et al., 2019). In the introduction, the trainer provides an outline of the training session, and introduces the topic, the objectives, and the key concepts. The trainer may use examples or anecdotes of their own experiences to clarify focal points and build rapport (Billett, 2021). The learners' prior knowledge, assumptions, and beliefs on the safety-related values and practices at their workplace are explored; relevance to their current work duties and work environments is essential for training transfer. They are asked to discuss their previous experiences of VR learning, and to review the training topics and key concepts in the contexts of their prior knowledge and current work role (e.g., Billett, 2013; Evans et al.,

2006; Lehikko et al., 2024; Tynjälä, 2013). The learners are also asked to voice their expectations and set their personal goals for the training. The trainer upholds the psychological safety of the training situation, supporting the learners in attaining a learning mindset and managing cognitive load (Dieckmann et al., 2007, 2009; Lehikko et al., 2025a, 2025b; Muckler, 2017).

In the IVR briefing, the learners are shown how to operate and comfortably wear the IVR equipment. Before the scenario commences, a tutorial instructs the learners on how to interact with the IVR environment, how to move around in it, and how to interact with virtual targets. The principle of high learner–IVR interactivity is applied in the tutorial and scenario design to support the learners' agency, involvement, and generative processing (see Korte & Körkkö, 2024). The tutorial components are comprehensive and can be repeated until the learner feels adjusted to the IVR experience and comfortable with the controls, instructional logic, and semiotics of the learning scenario (Lehikko et al., 2025b). The training situation and the IVR experience are designed to minimize distractions and support the learners' cognitive processing. Familiarity is introduced by means of tailored scenario contents, environment design, and signaling. Motion and flicker cues are used to enhance learners' affordance perception.

After scenario completion, the learners return to the group for debriefing, which provides further opportunities for dialogue and action-oriented reflection. The debriefing starts with a reflection on the IVR experience; the trainer facilitates the discussion, and both provides and asks for feedback. The learners' expectations and goals are revisited. The scenario contents are discussed in relation to the learners' prior experiences and their daily work (Lehikko et al., 2025a). Throughout the debriefing, the trainers use their expertise to model proactive safety behaviors (Burke et al., 2006b) and provide proximal guidance (Evans et al., 2006; Vygotsky, 1978) on agentic safety practices, embodying and affirming the inherent values and assumptions on agency and personal control that underlie a positive safety culture in the professional community (see Damşa et al., 2019; Nicolini, 2012; Schein, 2004; Somerville & Lloyd, 2006). In the facilitated group discussions, the learners have an opportunity to share and generate knowledge in dialogue with each other, and to enter critical action-focused reflection on the safety practices and discourse within the current safety culture at their workplace (Burke et al., 2006b; Evans et al., 2006; Hedlund et al., 2016; Mezirow, 2009).

Overall, the simulation-based model for IVR safety training has some key implications. A novel approach toward IVR safety training delivery is introduced in the model—not only by combining individual practice scenarios with pre- and post-briefings in a group setting but also by considering the sociocultural and situational aspects of educational IVR use. Safety training may have several goals in the workplace, but its ultimate purpose is to keep individuals and communities out of harm's way (see Lehikko & Ruokamo, 2025; Somerville & Lloyd, 2006).

From this perspective, the simulation-based training model provides guidance for linking safety training to the sociomaterial organizational context, illustrating the individual actions, knowledge, and relationships embedded in the social practices and artifacts; safety trainers' actions and pedagogical expertise are given a leading role. The multilevel presentation provides theoretical grounding for the next design cycles when the model's systemic and ecological dimensions can be further researched and extended. The current model can also be viewed as a practical tool to guide IVR implementation as part of a safety training curriculum in workplaces and educational settings.

7.3 Implementing the Training Model in the Sociomaterial Organizational Context

Investing in the occupational safety of their employees is mandatory for work organizations operating in Finland; their adherence to rules and regulations is not only expected by customers and consumers but also promoted by businesses as a virtue to boost investor and financier confidence. The value of upholding the safety of the work community manifests itself at a more concrete level for its members. In the initial trainer interviews, one interviewee expressed their perception of safety as not just a training topic but also an underlying principle for planning and implementing the training to prioritize the participants' safety (see Lehikko & Ruokamo, 2025). The trainer's twofold understanding of occupational safety training echoed the underlying beliefs, values, and assumptions of their organizational safety culture (e.g., Schein, 2004). In the work organizations that participated in this study, consideration for safety was ingrained very deeply in the operational guidelines and work procedures. However, deviations in individual assumptions and interpretations may still occur, even in the most safety-aware work communities, due to the nature of human cognition and interaction.

The simulation-based model for IVR safety training was developed for the benefit of the learners and practitioners at workplaces and various education providers, but it may also interest the administrative functions tasked with developing training programs that align with strategic goals. Successful model deployment relies on the active roles of trainers and learners, as well as on the trainers' pedagogical content knowledge (see Lehikko et al., 2025a). In this model, the trainer acts as a facilitator and knowledgeable expert who can guide learners in the safety-related sociomaterial practices of the work community (Billett, 1996, 2021; Gherardi, 2012). Their facilitative actions support the learners' agency and proactive involvement in these practices (e.g., Damşa et al., 2019); they may also smooth out obstacles for desired action (Lewin, 1947). For instance, upon discovering that learners are unfamiliar with incident-logging systems or procedures, the trainer may provide them with

information and guidance, nudging the learners toward taking a proactive stance by emphasizing their personal agency and responsibility for their own safety and that of their coworkers.

To meet the demands of this challenging role in the sociomaterial setting of the workplace, safety trainers must have the support of their superiors, access to organizational resources, and opportunities for personal growth and professional development. The trainer is expected to guide the employees in reflecting and enacting on the basic ethical assumptions, values, and norms regarding collective safety during training (Gherardi, 2012; Jarvis, 1997; Lewin, 1947). Actively promoting these values and norms in one's daily work requires sufficient commitment. Moral agency requires courage (Jarvis, 1997) to engage in interaction with the environment as well as awareness of the sociocultural affordances that enable interaction in the community (Pyysiäinen, 2021). The trainer must be aware of the relevant value-grounded principles and safety practices to be able to guide the discussion if divergent interpretations arise (see Schein, 2004; Jarvis, 1997). Engaging with value-laden learning content during experiential and embodied IVR practice scenarios, followed by facilitated critical reflection on one's safety-related assumptions and beliefs, may support the participants' motivation to transfer (see Pham et al., 2023). Intellectual stimulation and inspirational motivation are characteristics of transformational learning that can be evoked in co-constructive and activity-focused IVR safety training (see Damşa et al., 2019; Mezirow, 2009). See Figure 11.

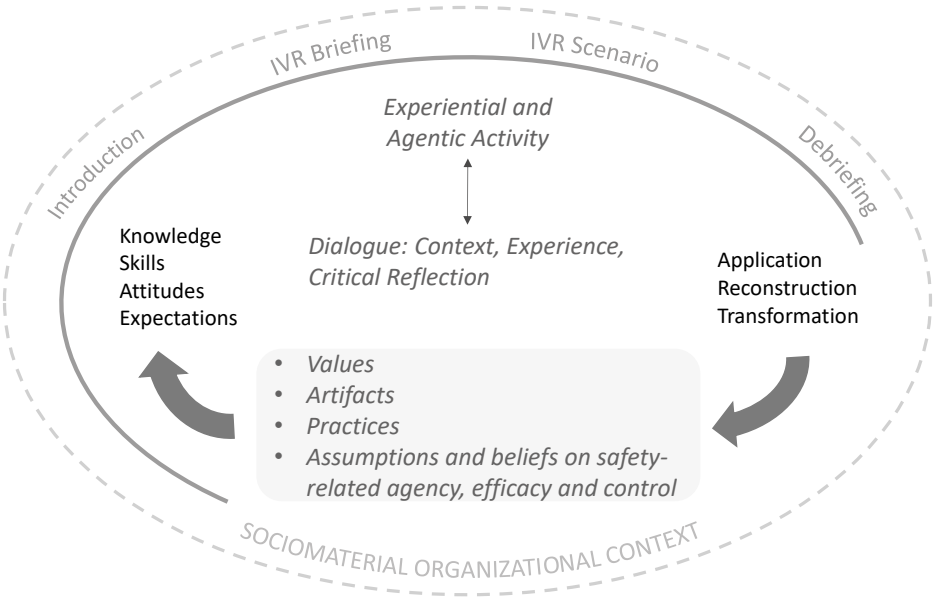

Figure 11. *The Sociomaterial Context of the Simulation-Based Model for IVR Safety Training*

Set against the sociomaterial background, the simulation-based model for IVR safety training illustrates the multiple facets and complexity of safety trainers' pedagogical role between the individual learners' needs and capabilities and the organizational demands, all encompassed in the sociomaterial setting of the workplace. It underlines the essentiality of clear and unambiguous definitions of the organizational values, practices, and norms that form the core of the positive safety culture, influence the design, implementation, and evaluation of safety training, and guide the trainers' facilitative interactions (e.g., Evans et al., 2006; Gherardi, 2012). If the guiding principles are unclear or in conflict with the management practices reflected in the daily operations, the trainer may not have sufficient sociocultural leverage (see Lewin, 1947) to deliver impactful training regardless of their professional expertise. Ultimately, successful training implementation depends on the enablement and enactment of the professional and personal agency not only of the learners but also of the trainers.

Traditional simulation environments may be expensive to build, but offer plentiful flexibility and variability for educators in terms of tailoring the learning scenarios to suit the learners and the learning objectives (Dieckmann et al., 2007; Gaba, 2004). From the practitioners' point of view, virtual learning environments have different benefits and drawbacks. Currently, the available IVR equipment may be relatively more affordable, but it only provides the technology to access the virtual environment—the environment itself and the training scenarios must be created separately by other means, such as 360° video recording or programming. Fully outsourcing the training development may not be possible or even desirable. Developing pedagogically viable IVR training scenarios that adhere to the applicable rules and regulations—such as the General Data Protection Regulation (GDPR) in the European Union—and the work organizations' internal policies and practices may be a resource-intensive and time-consuming process that also requires the collaboration of several subject matter experts in the training design. Nevertheless, just as increasing patient safety is a key driver for simulation training in the medical discipline, the goal of improving employee safety should drive the development and adaptation of educational IVR for occupational safety training.

7.4 Study Strengths and Limitations

The training model developed in this dissertation study aims to improve the pedagogical viability of IVR use in occupational safety training curricula. Training interventions were implemented in two work organizations. A mixed-methods approach was adopted and applied to collect and analyze empirical data that would inform the design process; quantitative data was chosen as the primary data source. Measures were carefully selected on the basis of previously validated instruments

where possible (see Tutwiler et al., 2023); nevertheless, low reliability was detected for the ECL measure. The field notes collected during the interventions revealed that 13 learners (19%) asked for assistance during the training interventions, and assistance was needed in 11 training sessions (50%). Ten persons got stuck during Scenario 1, and three during Scenario 2. The findings from the STRI data in Substudy III confirmed that the ECL measurements were unlikely to accurately reflect the learners' cognitive effort.

The small number of participants acquired due to the time and resource constraints in the study—68 learners in the 22 training interventions—may undermine the reliability of the statistical analyses, and the quantitative results must be treated as indicative. A replication study with larger samples could add credibility to the statistical conclusions presented here. However, the number of participants (18 trainers in Substudy I; 23 learners in Substudies II and III) was sufficient for qualitative content analysis. The qualitative findings were applied in triangulating the quantitative results in both Substudies II and III. A degree of investigator triangulation was achieved by arranging for a senior researcher to perform validation of the codes and thematic categories. Multicoder arrangements were not possible for the qualitative content analyses—the author was the only researcher in the team allocated to the task and in possession of the necessary competence. For the quantitative analyses, triangulation by several researchers was fully performed only in Substudy II (Twining et al., 2017).

The samples from O1 and O2 differed in several aspects. The O2 sample did not meet the criteria for the target learner group in its entirety, as several members of the administrative staff were invited by the company contact persons to join the study. This weakened the sample quality, with possible implications for the transferability of the DBR study results (see Tutwiler et al., 2023). The O2 participants reported having more prior experience with IVR and its use in professional development. It is possible that some of the self-reported safety learning outcomes, particularly in O1, were influenced by the novelty effect (Clark, 1983). All the learners who participated in the interventions were debriefed according to the training model, but only those who participated in the STRIs were guided to reflect on their training experience later, which may have given them some advantage in the long-term delayed test. This possibility was not explored in the statistical analysis.

Lawson and Martella (2023) recommended careful examination and assessment of the comparison conditions used in experimental IVR research. They advocated choosing a single component or feature of the IVR environment for study, such as interactivity, and constructing the conditions to retain the same learning content while applying the modifications to the studied component only. Clark (1983) expressed similar methodological concerns in the field of learning media research. These prerequisites were met to a high extent in this study, as the scenario events and learning objectives remained identical across the scenario versions. However,

enabling more interactivity enabled the learners to have more experiential training events due to more varied interactions between the learner and the IVR. To acknowledge this aspect and not to lead the reader astray on the experimental design, the differences in the scenario versions and their instructional features have been reported in detail.

According to Zheng (2015), the lack of more than one reported iteration of the design is a common DBR shortcoming. Due to limitations on time and resources during the SLIVeR project, and because the study was conducted amid the continuing operations of the work organizations, only one iteration could be completed during the study. The number of study participants from each organization was too small to perform two iterations based on their separated quantitative data. The qualitative datasets provided the researchers with interesting insights into the sociocultural nuances of the work communities during the research process, but they were not used independently as a basis for iteration. Unfortunately, the sole completed development cycle, combined with the limited methodological range of the outcome evaluation, makes the longitudinal aspects of the study appear minuscule (Tutwiler et al., 2023).

Collaboration was established initially with the organizational contact persons, who demonstrated a high personal commitment to the research project. On the administrative side, some differences in adhering to the agreed-upon research process were observed. These possibly impacted the authenticity of the training intervention in one organization and therefore also affected the results of this study. Some practitioners responsible for organizing and providing safety training in their respective organizations were involved in the study as collaborators. The learners, however, were not involved until the commencement of the training interventions because the target worker groups for the training were not selected before the scenario development phase. Initially, safety trainers were interviewed to fully contextualize the conceptual model applied in the interventions. In addition to the contact persons, three trainers were involved in the training design, the development of the discussion scripts for training facilitation, and the training implementation. During the intervention, the trainers were debriefed after each session—not only to collect feedback but also to provide them with space for reflection to support their professional and personal growth (e.g., McKenney & Reeves, 2021).

In one participating work organization, the training intervention led to concrete occupational safety improvements. During the group discussions, the trainers noticed that the purpose and correct practices concerning the organizational safety observations logging system were not clear for most of the learners. The trainers decided to systematically cover the topic in the debriefings, and—as proposed in the model—emphasized the learners' agency and ability to improve their own, and their coworkers', occupational safety. As a result, certain observations about the safety of the learners' daily work environment that were generally recognized in the work

community but had previously gone unreported were logged into the system by the participants, picked up by the management, and put into action. The pedagogical model was also adapted and modified locally to suit other training objectives in the organization after the project. Sharing the developed resources with the practitioners is one of the aims of DBR (Hjalmarson et al., 2021).

7.5 Future Study Directions

The iterative cycles of development and empirical testing should be continued to improve the simulation-based model for IVR safety training and to discover the most suitable instructional strategies and training design features for different training objectives and contexts. The theoretical development would benefit from more in-depth explorations of ecological learning theories, the 4E theory, and theories of distributed and embodied cognition. A single-user IVR environment was used in the current study. Whereas individual practice may be appropriate for certain training objectives associated with safety-related procedures, multi-user IVR (see Laine & Lee, 2024; Makransky & Petersen, 2023; Scavarelli et al., 2021) could potentially allow socially distributed training arrangements between operational locations. This approach should be studied in the future to enable the model's suitability for different work settings.

Substudy II confirmed learner–IVR interactivity as an essential design consideration and highlighted the significance of the sociocultural setting in intervention studies. The findings warranted further research on the learners' senses of embodiment and spatial presence alongside their cognitive load; these were the focus of the exploratory Substudy III. This substudy revealed the pivotal role of the learners' previous VR experience, which will require special attention in training design (see also Laine et al., 2024). The study findings have several implications for field research. Including tests or measurements for individual differences in executive function (Lawson & Mayer, 2024) and trait absorption (Wild et al., 1995; Wirth et al., 2007) in future study designs could advance research on body ownership and spatial presence in relation to learning outcomes.

Low ECL was reported across the experimental conditions. However, the instrument reliability was low, and the qualitative findings indicated that the measure did not accurately capture the learners' ECL. Methodological improvement should be undertaken in the future to measure cognitive load originating from different sources more accurately (Lawson & Mayer, 2024): For instance, physiological measurements and interviews could be used to triangulate self-report data (e.g., Garcia Estrada et al., 2024). Previous studies suggest that learners' assessment of their learning may not match their actual learning gains (Fokides & Antonopoulos, 2024; Khorasani et al., 2023).

Several steps could be taken to enhance the reliability of the results on outcomes and training transfer (e.g., Albus et al., 2021; Khorasani et al., 2023; Luo et al., 2021). National and international collaborations to develop robust instruments for IVR experience-related measurements in non-English speaking populations could improve the comparability of empirical results and increase study reproducibility. Similarly, establishing industry-standard methods of assessing learning outcomes and learning transfer for different types of learning objectives would benefit educational IVR research. Investing time and effort in developing suitable and practical frameworks for evaluating long-term safety training effectiveness by, for instance, using Dr Donald L. Kirkpatrick's four-level evaluation model as a starting point could contribute to further validation of the pedagogical viability of IVR applications as a part of safety training curricula (see Holdsworth et al., 2022; Stefan et al., 2023). Large sample sizes are preferable for employing robust statistical designs, although these may be difficult to achieve while continuing workplace collaborations. Nevertheless, DBR and other inclusive and collaborative approaches to educational IVR development are recommended to ensure the contextual and situational validity that enables large-scale societal benefits, such as increased workplace safety, in the long run.

Conclusion

The promises of increased learner safety and engagement associated with IVR learning technologies should be concretized into more meaningful and effective training experiences for the innovation to have any practical significance in the field of professional education. This study introduced a novel, simulation-based training model and sought to advance the study of the educational use of IVR environments in a workplace learning context and for mature learners by adapting the DBR approach. Adhering to DBR principles, the study documents the design revisions and changes justified with evidence (Hjalmarson et al., 2021; Zheng, 2015). The design principles incorporated in the simulation-based model for IVR safety training (see Section 7.2) were formulated by synthesizing a body of literature from multiple research disciplines with the findings from Substudies I, II, and III. The revisions based on the findings and the evolved model were systematically presented, and recommendations on IVR scenario design were provided for practitioners. The challenges of deploying the training model in the sociomaterial organizational contexts of real-life application (Section 7.3) were reflected upon with the support of previous literature.

In Substudy I, the thematic interviews on the safety trainers' favored pedagogical practices provided new information concerning the safety trainers' pedagogical content knowledge (e.g., Shulman, 1986) that is essential for implementing safety training. Substudy II provided empirical evidence on the role of learner–IVR interactivity in cognitive and affective training outcomes. In addition, the qualitative findings highlighted the importance of considering the sociocultural context when designing and performing field research. Substudy III revealed the significance of the learners' previous VR experience for their sense of embodiment and spatial presence and offered multiple insights into the learners' experiences during the IVR scenario, which may open up new research questions and research avenues. In the course of this study, the findings were integrated with existing theories of learning for the benefit of the research field and practitioners alike.

Hjalmarson and colleagues (2021) noted that DBR may produce decision-making or design principles that can be applied in different situations: it is grounded in theory and expected to contribute to it. Anderson and Shattuck (2012) emphasized the importance of making a theoretical contribution through DBR. The training design principles incorporated in the model represent the main theoretical contribution of the current study (see McKenney & Reeves, 2021): they are related

to the educational fields of occupational safety training and IVR training—both concerned with adult learners—and they also carry methodological implications for educational IVR research. Ultimately, the introduced simulation-based model can be applied by practitioners to guide their IVR safety training development and implementation within a training curriculum, or as a theoretical framework and a starting point for the research community to guide their aspirations for developing effective practice- and theory-grounded educational XR.

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Appendices

APPENDIX A

Discussion Scripts for Introduction and Debriefing (Substudies II-III)

Translated to English by the author. Passages concerning the organization-specific VR training scenario themes and learning goals have been omitted for conciseness.

Introduction

In the introduction, everyone is involved in the discussion. The goal is to create premises for the learners to understand the content of the VR exercises and to set learning goals.

The aim of the training is to develop the learners' occupational safety skills. The aim is not to assess their skills or learning. During the training, [Research Organization] collects information on participation, but information on the individuals is not shared with [Employer].

Give the learners an outline of the training situation.

Introduce the topics and objectives of the VR exercises. Introduce key concepts.

The topic of the VR exercise is traffic safety. The learners will practice making safety observations in an environment that is not directly related to their occupation. However, the risk factors observed may also be important for their work.

Training objectives: The learners gain knowledge on traffic safety and develop the capacity to assess the risks of working in traffic. The learners build knowledge of accident prevention and learn to make safety observations.

Key concepts:

> **Traffic safety**. Being mindful of traffic at work and in transport during the working day, including traffic on commutes.
>
> **Safety observations**. Observing possible physical or psychological hazards in the work environment.

Discuss the learners' goals for the training.

- *What are your expectations for this training?*
- *What would you like to learn?*

Discuss past experiences.

- *Are you already familiar with virtual reality?*
- *How much do you think about occupational safety daily? Examples from recent times?*

Discuss scenario topics in relation to the learners' work

- *In your opinion, how are traffic and transportation safety connected to your work?*
- *In what kind of situations should you pay attention to traffic safety?*
- *Why is it important to wear personal protective equipment at work?*
- *Examples of accident prevention in your work?*

Debriefing

In the debriefing, the learners' experiences of the VR exercises are discussed. The learners are guided to evaluate and review what they have learned. They can analyze and reflect on their experiences, learning goals, and work tasks.

Provide space for interaction between the learners.

Review experiences.

Use the observations you made during the learners' VR exercises in advancing the dialogue.

- *What did VR training feel like?*
- *Did any part feel difficult? What do you think is the reason for this?*
- *What went well?*
- *What stood out in particular in the VR scenario?*
- *What aspects related to occupational safety do you remember?*

Discuss the learners' expectations and goals for the training.

- *Were your expectations met? If not, why?*
- *Were the goals of the training achieved?*
- *Did you achieve your own learning goals?*

Discuss the VR scenarios in relation to the learners' work.

- *Did the training evoke any thoughts about your own work? What kinds of thoughts?*
- *Can the tasks practiced in the training be applied in your own work? What are you going to do differently in the future?*
- *Why are these things important?*

(Supporting questions:)

- *Keeping track of the traffic: When and why is it especially important in your work?*
- *What aspects of transportation and road safety require special attention in your work?*
- *Does the placement of [a work vehicle] matter? What are the benefits of correct vehicle placement?*
- *In what situations is the use of personal protective equipment particularly relevant?*

Give feedback and ask for feedback.

Create a positive atmosphere for learning. Engage, encourage, and support the learners' activity and self-efficacy.

APPENDIX B

Stimulated Recall Interview Protocol (Substudies II-III)

Translated to English by the author.

1 Warm-up

What did you learn during the safety training arranged as a part of the study?

Do you feel that the training has been or will be useful to you in your work? How?

2 Stimulated Recall Interview

Introduction

Description: In the introduction, the objectives of the training and the learners' previous experiences were discussed.

What kind of goals did you have when you came to the training?

What kind of goals do you think that the training had?

How would you describe the introduction? Supporting questions:

- Did you think the discussion was successful?
- Was it easy to concentrate?
- Did the discussion feel motivating?
- Did it give you confidence to participate in the training?

What could have improved the introduction as a learning situation?

IVR Briefing

Description: The IVR Briefing began with a presentation of the VR headset and controllers. The learners were equipped, and they familiarized with IVR in a brief tutorial.

How would you describe the IVR Briefing in relation to the training goals? Supporting questions:

- Did you think the briefing/tutorial was successful?
- Was it easy to concentrate during it?
- Did briefing/tutorial feel easy or difficult?
- Was it easy to operate and to move around in it the IVR?
- Did you feel in control of the situation?

Was the briefing/tutorial sufficient for performing the VR exercise?

What could have improved the briefing/the tutorial as a learning situation?

IVR Scenarios

Description: After the tutorial, IVR scenarios 1 and 2 were performed independently. After each scenario, the learners filled out a questionnaire.

Scenarios 1 and 2 are discussed in that order.

How would you describe the IVR scenario (1) (2) in relation to the training goals?

How did it feel to be in the IVR environment during the scenario (1) (2)? Supporting questions:

- Did you think the scenario was successful?
- Was it easy to concentrate during it?
- Did the scenario feel easy or difficult?
- Was it easy to operate and move around in the IVR?
- Was the IVR environment realistic?
- Did you feel in control of the situation?
- Did you find the exercise interesting?
- Did you feel that performing the scenario required perseverance?

What goals do you think scenario (1) (2) had? Did you achieve these goals?

How did two scenarios differ from each other in your opinion?

What could have improved the scenarios as a learning situation?

Debriefing

Description: After completing the scenarios and questionnaires, the learners returned to the group for debriefing. The IVR experiences and safety training topics were discussed.

How would you describe the debriefing, what kind of impression did you get? Supporting questions:

- Did you think the debriefing was successful?
- Did the discussion feel motivating?
- Was it easy to concentrate during it?
- Did you gain new perspectives or insights related to the training or your own work during the discussion? Did you share your insights with others in the group?

Did the debriefing help you achieve the goals you set for the training?

What could have improved the debriefing as a learning situation?

3 Video Clips

A total of one to three video clips of the interviewee's actions during the training are shown in the appropriate phase(s). Supporting questions:

- What were you doing in this situation?
- What did you think in this situation and why?
- Do you remember how you felt?
- What kind of feelings did you have?
- How did you advance from here?
- Why did you choose to do what you did here?

4 Summary

- What was the best or most successful part of the training in your opinion?
- How would you like to the training to be developed?
- Is there anything else you would like to share about this training experience? Do you have feedback for the research group?
- Can we contact you later if necessary?

Original Publications

I

Lehikko, A., Nykänen, M., & Ruokamo, H. (2025). Conceptualizing a Pedagogical Model for Immersive Virtual Reality Safety Training: Pedagogical Practices in Trainer Interviews. *Educational Technology Research and Development, 73,* 2543–2565. https://doi.org/10.1007/s11423-025-10490-1

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Education Tech Research Dev (2025) 73:2543–2565
https://doi.org/10.1007/s11423-025-10490-1

DEVELOPMENT ARTICLE

Conceptualizing a pedagogical model for immersive virtual reality safety training: pedagogical practices in trainer interviews

Anu Lehikko[1] · **Mikko Nykänen**[2] · **Heli Ruokamo**[1]

Accepted: 2 March 2025 / Published online: 17 March 2025
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Abstract

The potential of immersive virtual reality (IVR) to deliver engaging occupational safety training has been established by previous research; however, to date, there have not been any pedagogical models to guide its implementation. This study's objective was to conceptualize a pedagogical model for IVR safety training by combining a multidisciplinary theoretical framework with safety trainers' contextual and pedagogical expertise. The research questions were (1) what kind of pedagogical practices do trainers apply in safety training, and (2) how do the trainers' pedagogical practices inform the sociocultural contextualization of the pedagogical model for IVR safety training? Eighteen safety trainers were interviewed across two work organizations. An inductive approach was used in the interview data analysis. Three main categories of pedagogical practices were identified: (1) matching pedagogy to training goals, (2) guiding social interaction in training situations, and (3) utilizing organizational resources for training development. The findings extended our understanding of the sociocultural training context and provided insight into the pedagogical practices used in safety training. Based on the findings, pre- and post-training activities were added to the pedagogical model, and the descriptions of trainers' actions during the facilitated introduction and debriefing phases were modified to support the training's relevance to the learners, trainers, and organizations. This study illustrates a pragmatic approach to developing safety training in the context of advanced learning technology in design-based research. The pedagogical model will be applicable by training and education providers in IVR safety training across industries and in practice-based learning.

Keywords Immersive virtual reality · Safety training · Pedagogical model · Pedagogical practices · Qualitative methods

✉ Anu Lehikko
alehikko@ulapland.fi

1 University of Lapland, P.O. Box 122, 96101 Rovaniemi, Finland

2 Finnish Institute of Occupational Health, Työterveyslaitos, P.O. Box 40, 00032 Helsinki, Finland

Introduction

Immersive virtual reality (IVR) learning environments offer opportunities to provide engaging occupational safety training in which employees can rehearse hazardous work situations and develop their hazard identification and prevention abilities (Li et al., 2018). Safety training is integral not only in workplaces but also to learning many skills and trades in vocational and higher education. Previous research has highlighted the importance of safety training in increasing safety knowledge, modifying safety attitudes, increasing motivation to prevent accidents, and improving safety behaviors (Ricci et al., 2016; Robson et al., 2012). Casey et al.'s (2021) review study on safety training effectiveness and Babalola et al.'s (2023) systematic review on IVR applications in occupational health and safety training and education have indicated the potential of IVR as a safety training medium. Empirical studies performed by Nykänen et al. (2020) and Rey-Becerra et al. (2023) have provided evidence for small to medium effect sizes in favor of IVR compared to lecture-based safety training implementations. However, IVR research has remained detached from theories of learning (Radhakrishnan et al., 2021; Radianti et al., 2020), and pedagogical models fully capable of guiding its implementation in safety training have not yet been proposed.

Our pragmatically oriented research aims to support IVR safety training implementation by proposing a pedagogical model that combines existing research on simulation learning, safety training, and IVR learning. The current study belongs to the initial phase of a design-based research (DBR), but it does not report a full DBR cycle. Both sociocultural and cognitivist views on learning are applied in the model: Whereas educational research often sits comfortably within the sociocultural framework (e.g., Billett, 2021; Sutherland et al., 2009; Vygotsky, 1978), a cognitivist approach is more often applied in the research disciplines of IVR learning (e.g., Makransky & Petersen, 2021; Mulders et al., 2020) and occupational safety training (e.g., Burke et al., 2006; Nykänen et al., 2020). Current conceptual models (see Tondeur et al., 2021) relevant to workplace learning design (e.g., Holdsworth et al., 2022; Tynjälä, 2013) advocate for the recognition of situational and contextual factors in professional learning.

Our theory-based pedagogical model for IVR teaching and learning (Lehikko et al., 2022) combined a simulation learning framework with IVR scenarios. In the model, simulation training's inherent social learning processes enrich the IVR learning experience in the form of facilitated introduction and debriefing discussions (Dieckmann, 2009; Keskitalo, 2015), which precede and follow the safety training scenarios performed in IVR. To fully acknowledge the multimodal nature of learning with IVR technology (Billett, 2021), elements of the Cognitive Affective Model for Immersive Learning (CAMIL; Makransky & Petersen, 2021) were incorporated into the pedagogical model. Our model thus considers the learners' sense of agency (Braun et al., 2018), sense of presence (Lee, 2004), sense of body ownership (Shin et al., 2021), embodiment (Johnson-Glenberg, 2019), and cognitive load (Sweller, 2020). The purpose of this qualitative study was to anchor the pedagogical model in the sociocultural framework of workplace learning with the aid of qualitative findings from safety trainer interviews.

This paper reports on a qualitative study that advanced the pedagogical model's conceptual development prior to its empirical testing, reported elsewhere (Lehikko et al., 2024). Occupational safety training goals are discussed in the literature section alongside the former theoretical background. We performed semi-structured thematic interviews with trainers who plan and deliver safety training and orientation at the two participating

organizations to further understand the training context in this study (Bengtsson, 2016; Creswell, 2009). The interviews provided us with insight into the pedagogical practices that are essential for safety training delivery, and they also served as a means for channeling the trainers' pedagogical content knowledge (PCK; Berry et al., 2008; Shulman, 1986) into the model development process within the practical constraints (Amiel & Reeves, 2008; Creswell & Plano Clark, 2017). Understanding the trainers' pedagogical practices and their views on the training goals and expectations in their work organizations was also important for training design and trainer preparation in the subsequent stages of the DBR cycle (Billett, 2021; Creswell & Plano Clark, 2017; Moore et al., 2023). In this study, pedagogical practices are understood as social practices intended to shape learners' educational development (Higgs, 2012).

Literature review

Occupational safety training goals

The training goals should be well defined (Anderson & Krathwohl, 2001; Dieckmann, 2009; Kraiger et al., 1993; Krathwohl et al., 1973). In occupational safety training, declarative knowledge goals refer to knowledge of safety-related facts (e.g., occupational hazards and personal protective equipment). Procedural knowledge goals refer, for example, to knowledge related to performing safety-promoting procedures, using personal protective equipment, and engaging in safety behaviors to reduce risk. Safety attitudes are individual beliefs, commitment, and a sense of personal responsibility regarding safety policies, procedures, and practices (Henning et al., 2009). Psychomotor skills refer to the ability to execute physical work-related tasks safely and with a degree of precision (Burke et al., 2006). Learning psychomotor skills in a simulation demands high physical realism (Dieckmann, 2009), which should be noted when considering hand-controller-operated IVR as a training media for tasks that include detailed hand and finger movements (e.g. Harris et al., 2020). The systematic review on computer-aided health and safety training technologies in the construction sector by Gao et al. (2019) provided evidence on VR effectiveness for knowledge acquisition.

Safety knowledge and safety attitudes play an important role in promoting occupational safety and preventing accidents (e.g., Christian et al., 2009). We consider motivation and self-efficacy to be examples of attitude-related training goals (Kraiger et al., 1993; Krathwohl et al., 1973). Motivation to promote safety plays a key role in accident prevention (Neal & Griffin, 2006). Previous studies have indicated that safety training methods through which learners significantly participate in learning activities have a stronger impact on this motivation (Hedlund et al., 2016). Intrinsic safety motivation is particularly important for preventive safety behavior, as it involves a feeling of fulfillment related to enacting such behavior (Mariani et al., 2015); it encourages people to perform safety-related activities because they perceive them as interesting and satisfying. There is evidence that as a learning medium, IVR induces greater motivation in learners—possibly due to the learners' heightened sense of presence—than do less immersive media (Makransky & Lilleholt, 2018).

Self-efficacy (SE) is a key determinant of preventive safety behaviors in the workplace (Brown et al., 2000; DeJoy, 1996). Enhancing the learner's safety-related SE is a common goal in safety training, as it increases the learner's likelihood of using the learned safety

knowledge and skills at work (e.g., Burke et al., 2006). Achievement is closely linked to SE; a person with higher SE in a certain domain of action will set more demanding goals for themselves and persist longer with these challenges. Having first-hand experience of success with a certain task or in a certain domain provides a firm basis for SE development and links it to personal feelings of agency (Bandura, 1977, 1997, 2012). There is empirical evidence that IVR learning environments may support SE development (e.g. Meyer et al., 2019), but the contributing factors are not yet clear (Lehikko, 2021). However, IVR's emotion-inducing capability is considered especially advantageous to safety learning (Casey et al., 2021).

Simulation learning for IVR safety training outcomes and transfer

Simulations can play a vital role in inducing and consolidating an increasingly safety-oriented organizational culture (Gaba, 2004). Previous research indicates that occupational safety training based on learners' active participation is more effective in terms of knowledge acquisition and motivational outcomes than passive safety training approaches such as lectures; in the former, dialogue and action-focused reflection are strongly encouraged (Burke et al., 2006, 2011; Hedlund et al., 2016). Debriefing the learners may have a beneficial effect, especially on behavioral outcomes in IVR safety learning (Feng et al., 2021). Thus, the simulation training principles and practices appear to be well suited for IVR safety training. A single-user IVR scenario can be compared to individual simulation-based training, which is common in, for instance, basic clinical skills training in medical education.

Simulator practice is often preceded by introductory and pre-training activities that support learners' metacognitive processes. The trainer may apply strategies, such as the use of analogies and artifacts, direct explanations, and representations of new concepts or procedures, to assist the learners in understanding and processing the training content (Billett, 2021). The learners' individual expectations, attitudes, knowledge, and skills (Billett, 2013; Gaba, 2004; Holdsworth et al., 2022; Sutherland et al., 2009) may also be addressed or influenced in the pre-briefing (Dieckmann, 2009). A debriefing follows the simulation: The trainer should maintain a positive learning atmosphere and deliver necessary and helpful feedback to the learners (Decker et al., 2013; Gaba, 2004; Rudolph et al., 2014). After attending the training, the participants return to their daily work, ideally reconstructing and transforming what they learned in the simulation and assimilating it into their work practices (Billett, 2013; Dieckmann, 2009; Sutherland et al., 2009).

Any IVR safety training requires close consideration of the situated nature of learning and training transfer in the workplace context (Billett, 2013; Harris et al., 2020; Tynjälä, 2013). It has been suggested that the situational nature of learning makes transfer difficult to achieve (Mason, 2007). Billett (2013) proposed that the circumstances of thinking, acting, and learning influence its adaptability. Depending on the learners' backgrounds and previous experiences, as well as on the many possible interchanges and occurrences during the training session, the exact same learning scenarios may have different learning outcomes for individuals and training groups (Billett, 2013; Rystedt et al., 2019; Säljö, 2004). Learning conceptual and procedural knowledge is most effective when the representations of these forms of knowledge are coherent with work practice (Billett, 2021). Based on Harris et al.'s (2020) framework for testing and validation of simulated environments, a close resemblance between the IVR scenario and authentic work activities and interactions may

support learning transfer directly by increasing the psychological, affective and ergonomic fidelity of the scenario, and indirectly by supporting learner buy-in.

Immersive virtual reality in safety training

The term *virtual* refers to computer-generated environments wherein the experienced objects do not actually exist but are artificially created or simulated (Lee, 2004). This study considers immersive virtual reality (IVR), a simulated environment that is accessed by a head-mounted display and hand controllers that fulfil the technical prerequisites for immersion (Concannon et al., 2019; Elbamby et al., 2018; Pelargos et al., 2017; Rebelo et al., 2012), presenting "a vivid virtual environment while shutting out physical reality" (Cummings & Bailenson, 2016, p. 3). Immersion is thought to increase learner engagement, but it may also have adverse effects on learning due to its demands on the learner's cognitive resources (Makransky et al., 2019; Skulmowski & Xu, 2022).

Sense of agency describes the learner's feeling of generating and controlling actions in the IVR (Braun et al., 2018). The agency experienced by the learner is considered to enable embodied learning and increases learning retention (Johnson-Glenberg, 2019; Kilteni et al., 2012), and it helps the learners to assume responsibility and experience more motivation and self-efficacy in the learning process (Dieckmann, 2009; Ryan & Deci, 2000). *Sense of presence* is defined as "a psychological state in which the virtuality of experience is unnoticed" (Lee, 2004, p. 32): It has been associated with stronger spatial learning outcomes. Empirical research indicates that presence may be affected by distraction factors, such as isolation and interference awareness (Parong et al., 2020).

The learners' *sense of body ownership* should be considered when the IVR training objectives extend beyond declarative knowledge acquisition. Body ownership, i.e., the feeling of possessing a body, has been found to negatively influence IVR task performance in high-risk conditions such as the teleoperation of high-risk machinery (Shin et al., 2021), which has relevance for occupational safety training. A sense of body ownership influences *embodiment*, which may be pivotal for training effectiveness (Johnson-Glenberg, 2019; Kilteni et al., 2012). Embodiment means the feeling of "being inside, having, and controlling a body" (Kilteni et al., 2012, pp. 374–375). In the IVR safety training context, embodiment may play an important role in increasing attention to the learning task and increasing training engagement, which may lead to better learning outcomes (Casey et al., 2021; Johnson-Glenberg, 2019). Embodiment may be especially important for attaining procedural learning goals. However, previous empirical results suggest that the learner's physical and virtual movements should be carefully mapped for congruency to avoid detrimental effects on their motor performance (Odermatt et al., 2021; Pritchard et al., 2016).

Cognitive load describes the amount of information that the learner must process during the learning situation; if it exceeds the limits of their working memory, overload may occur (Skulmowski & Xu, 2022; Sweller, 2020). In simulations, higher realism may free up some cognitive capacity by reducing the need for simulation orientation; however, the training scenario's relevance to the learning goals outweighs maximizing simulation fidelity. According to previous studies on IVR learning, high fidelity and excessive detail may hinder learning by overtaxing the learner's cognitive ability; the appealing details that foster learner engagement may also work against the training goals (Makransky & Petersen, 2021; Makransky et al., 2019; Skulmowski & Xu, 2022). Previous experience impacts the learners' cognitive load: Based on their integrative review on nursing simulations, Rogers and Franklin (2021) recommend scaffolding simulation fidelity. Progressing from

simplified to more realistically detailed environments by modifying the available cues and the noise to signal ratio may better facilitate training transfer. The learner's technological self-efficacy may contribute to their perceived ease of use of IVR (Holden & Rada, 2011). Introducing the key concepts in pre-training may ease the learner's cognitive load during the training scenario while also supporting their self-efficacy development (Dieckmann & Ringsted, 2013); empirical evidence indicates that pre-training may support the achievement of IVR learning outcomes (Delgado & Mayer, 2025; Meyer et al., 2019).

Combining experiential IVR learning with reflective group activities

We propose that utilizing a phased simulation training framework in an IVR scenario-based safety training design allows the blending of experiential and reflective components (Kolb, 1984) within the social learning and training processes that enhance the effectiveness of the individually performed IVR safety training scenarios. Facilitated discussions provide the sociocultural setting needed to ensure the relevance and contextual validity of the training, and they may also yield cognitive benefits to the learners. We suggest four essential training phases: introduction, IVR briefing, IVR scenario, and debriefing (Dieckmann, 2009; Keskitalo, 2015).

Introduction

In the introduction phase, the trainer presents the training topic, the key concepts, and an overview of the course content. The learners are provided with the background knowledge needed to fully understand the concepts and are prompted to reflect on the training topic's context and relevance to their previous life and work experiences (Billett, 2013; Dieckmann, 2009; Sutherland et al., 2009). This will foster situational interest and motivation (e.g., Ryan & Deci, 2000; Schraw et al., 2001) and help the learners to engage their former knowledge and competences in the training setting (Billett, 2021; Tynjälä, 2013). According to earlier studies, establishing a positive and psychologically safe atmosphere in the learning group (Rudolph et al., 2014), encouraging the learners to take active roles in the learning process, and helping them determine personal training goals support the learners' SE, motivation, and agency (Bandura, 1997; Casey et al., 2021; Dieckmann, 2009). IVR learning environments may be designed to foster active learning, but it is nonetheless important to encourage and enable learners to actively participate in all phases of the training situation (Billett, 2021; Sutherland et al., 2009; Vygotsky, 1978).

IVR Briefing

Once the introduction phase is complete, the learners attend a guided briefing on the IVR equipment and environment operation. This may help them use their cognitive resources more effectively during the training session (Dieckmann & Ringsted, 2013; Meyer et al., 2019; Sweller, 2020). If the trainees are unfamiliar with IVR technology, the trainer can reduce uncertainty by personally demonstrating use of the equipment and sharing their previous experiences of IVR use (Bandura, 1977, 1997; Billett, 2021). The learners also complete an interactive tutorial in the IVR environment before entering the training scenario. The tutorial supports learner self-efficacy by reducing cognitive load (Meyer et al., 2019;

Sweller, 2020) and creating opportunities for IVR-related mastery experiences (Bandura, 1977, 1997; Holden & Rada, 2011).

IVR scenario

After completing the tutorial, the learners may advance in the training scenario at their own pace and without the trainer's assistance. Learners' motivation and self-efficacy are supported by designing the IVR-guided scenario to allow the learner to feel autonomous and in control (Dieckmann, 2009; Makransky & Petersen, 2021; Ryan & Deci, 2000). The scenario script should guide learners to identify the positive outcomes of their actions. This contributes to SE throughout learning activities (Bandura, 1997; Stajkovic & Sommer, 2000). Giving learners an opportunity to make choices and influence the course of events in the IVR scenario will also accommodate embodied learning (Johnson-Glenberg, 2019; Kilteni et al., 2012).

Debriefing

Once the scenario is over, the learners return to their groups for debriefing. The trainer supports learner SE and agency by offering feedback and creating opportunities for positive affect, as well as by maintaining an active and positive group atmosphere (Bandura, 1997; Dieckmann, 2009; Rudolph et al., 2014). The learners discuss the scenario and analyze it together, constructing and co-creating an understanding of the learning experience in relation to their goals (Decker et al., 2013; Keskitalo, 2015; Säljö, 2004; Sutherland et al., 2009; Vygotsky, 1978). They are guided to share their personal experiences of work hazards as they relate to the simulated activities (Bhandari et al., 2019). The generative learning strategies of summarization and reflection after the IVR training scenario improve factual and conceptual knowledge building, which are connected to cognitive learning outcomes (Burke et al., 2006; Kraiger et al., 1993; Parong & Mayer, 2018). Through their facilitative actions, the trainer supports the learners' proactive stance and active participation in safety practices and a positive safety culture (Billett, 2021; Tynjälä, 2013).

The research aim was to design and conceptualize a pedagogical model for IVR safety training by integrating these theoretical viewpoints with the pedagogical practices applied in the design and delivery of safety training by 18 experienced trainers in two work organizations. We set two exploratory research questions, (1) what kind of pedagogical practices do trainers apply in safety training, and (2) how do the trainers' pedagogical practices inform the sociocultural contextualization of the pedagogical model for IVR safety training?

Method

This current qualitative study was carried out in the conceptual design phase of pedagogical model development as the first step in a pragmatically motivated design-based research (DBR). The DBR method has long been associated with technological interventions: It seeks to connect educational research with practice and is well-suited to research on learning environments and to the development of related learning theories in innovative collaboration between researchers and practitioners (Anderson & Shattuck, 2012; Moore et al.,

2023; Wang & Hannafin, 2005; Zheng, 2015). The cyclical DBR process typically has four stages: design, implementation, analysis, and redesign (Fig. 1).

Semi-structured thematic interviews (Creswell, 2009) were selected as the qualitative data collection method in order to gain an in-depth understanding of the relevant pedagogical practices in the sociocultural contexts surrounding occupational safety training in trainers' daily work and the various skills demanded from the trainers. The interviews allowed us to engage with more trainers in the collaborator organizations than was otherwise possible during the research, and informed training development in the next stage of the DBR process prior to the model's implementation and empirical data collection. Pedagogical content knowledge built by experience is often tacit, making it difficult to articulate and share (see Nind & Lewthwaite, 2018). The interview protocol (see Appendix A) was designed to support knowledge elicitation by emphasizing the interviewees' first-hand knowledge and professional experience. The protocol included instructions, warm-up questions, two interview themes and the corresponding questions and prompts, wrap-up questions and a thank you statement (Creswell, 2009). The current study focuses on Theme 2—pedagogical practices.

Eighteen persons involved in designing and implementing safety training for two work organizations in Finland were interviewed for this study. These individuals were selected due to their practical experience in safety promotion and first-hand knowledge of the factors that contribute to successful safety training. They were recruited by contact persons within the organizations—one training expert and one digitalization expert—and they joined the study on the basis of informed consent. The semi-structured thematic interviews were carried out by one researcher in December 2021 and January 2022. The interviewer and the interviewees made the interview arrangements via email, and the interviews lasted between 25 and 40 min, averaging 34 min and totaling 10 h and 9 min. They were conducted by means of a video conferencing tool and recorded on two external audio recording devices. Cameras were kept on during the video conference if preferred by the interviewee, but no video was recorded. An external service provider transcribed the audio recordings. The transcribed material totaled 55,920 words. Before being subjected to content analysis using

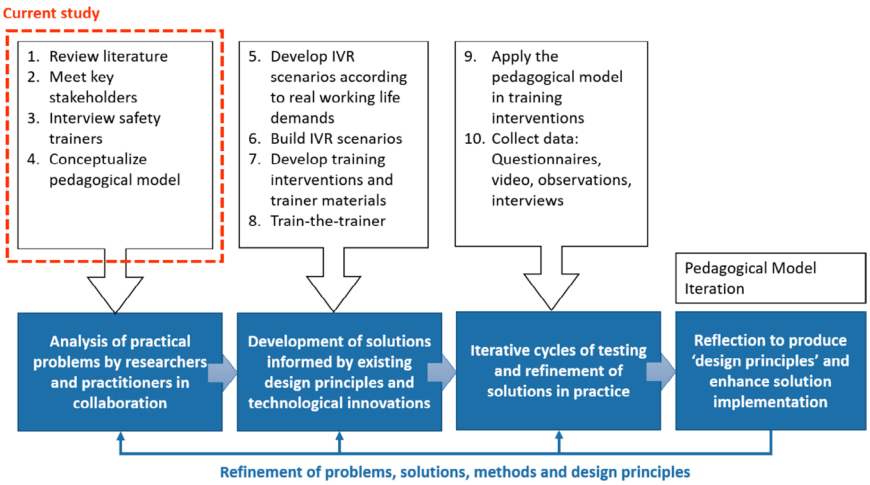

Fig. 1 DBR Process in Pedagogical Model Development (adapted from Amiel & Reeves, 2008, p. 34)

NVivo software, the transcripts were checked against the audio recordings for accuracy and were corrected as necessary.

For RQ 1 (what kind of pedagogical practices do trainers apply in safety training?), a content-driven approach was applied in the analysis (see Bengtsson, 2016; Hsieh & Shannon, 2005). In the thematic interviews, we asked the trainers about their experiences with functional pedagogical practices and asked them to describe effective safety training implementations. The transcripts were read several times while an initial round of codes was created using topical sentences as units of analysis. To ensure conceptual clarity, the codes were edited, occasionally renamed, combined, and grouped as the coding progressed. The codes were grouped into subcategories and, finally, into main categories. Coding was initially performed by the first author, and coding consistency was checked by another member of the research team (see Creswell, 2009). The findings were quantified and reported as frequencies. The second research question (how do the trainers' pedagogical practices inform the sociocultural contextualization of the pedagogical model for IVR safety training?) was then addressed by synthesizing the findings for RQ 1 with research literature and producing a conceptualization of the pedagogical model for IVR safety training based on the synthesis.

Findings

Pedagogical practices identified in the trainer interviews

To answer RQ 1, we sought to explore the pedagogical practices that trainers use in safety training. Three main categories were discovered: (1) matching the pedagogy to training goals, (2) guiding social interaction in training situations, and (3) utilizing organizational resources for training development.

Category 1: match the pedagogy to training goals

Three subcategories were discovered, the first of which was *ensure relevance.* This was the most frequently mentioned code within the subcategory (Table 1).

Fifteen trainers mentioned selecting topics from the learners' direct work contexts. Twelve referred to the use of practical examples, and five talked about providing training that focused on teamwork. The second subcategory was *select delivery method*; depending on the type of training goals, the trainers selected the most appropriate methods. Seventeen trainers mentioned providing hands-on training, which was the most frequently coded item in this subcategory. Twelve trainers mentioned giving lectures. Eight talked about using simulations for challenging situations, and seven talked about utilizing learning technology. The third and final subcategory was *evaluate outcomes.* Eleven trainers talked about evaluating the learning outcomes via, for example, written tests, interviews, and learner observation in work situations. The trainers had practical views on training relevance and sought to incorporate examples of the learners' everyday work situations in the training process. They made decisions about the delivery method on the basis of the learning context and goals and considering learner engagement (Burke et al., 2006). Ensuring that the learners attained the training goals was a priority, and the learning outcomes were subjected to evaluation.

Table 1 Pedagogical Practices in Category 1: Match the Pedagogy to Training Goals

Subcategory	Code	*f*	*n*	Example Interview Quote
Ensure relevance	Fit training to the learners' work context	22	15	*Practicality... that they are just those normal, everyday things that students do every day at work and at the site [Trainer #17]*
	Use examples to increase relevance	18	12	*I always think of an example, or someone else comes up with one and then goes through it [Trainer #18]*
	Train for teamwork	7	5	*And I usually tell, before we go [to train in practice], what it's like to work with a pair and how to communicate. And how to agree on what everyone will do in that... inspection [Trainer #16]*
Select delivery method	Provide hands-on training	24	17	*The applied exercises, that is, when the topic is applied to working life and the exercise is done there. They are the best in terms of learning [Trainer #17]*
	Give lectures	18	12	*Of course, there are some basics that you have to teach in the classroom [Trainer #10]*
	Use simulations for challenging situations	14	8	*... to train for safety–critical events for which you would not otherwise be able to practice [Trainer #13]*
	Utilize learning technology	18	7	*... we have noticed, now, that these new technologies have been introduced and used, that people would rather be involved with them than sit, for example, in a classroom, looking at slides [Trainer #2]*
Evaluate outcomes	Evaluate learning outcomes (e.g., tests, interviews, observation)	28	11	*And then we help the students to prepare for the demonstration of [their] knowledge at the end of the course [Trainer #3]*

f number of coded units, *n* number of interviews with coded units

Category 2: guide the social interaction in training situations

Two subcategories were identified. The first was *facilitate social interaction*. The trainers facilitated learners' interactions by, for example, actively promoting discussion (14 trainers), which was the most frequent code in this subcategory (Table 2).

Other actions mentioned by the participants were applying professional experience and setting an example (12 trainers), adapting the training to the target group (11 trainers), observing and modulating the emotional atmosphere (10 trainers), and promoting learner activity and agency by engaging the learners in tasks and exercises (10 trainers). The second subcategory was *maintain temporal structure*. The trainers provided the learners with a temporal structure by discussing the training plan and the training goals early in the process (8 trainers), as well as by debriefing the learners afterwards (7 trainers).

In the learning situations, the trainers used a wide range of pedagogical practices to promote a learning-conducive mindset and atmosphere for the learners. Peer discussions were seen as opportunities to create a shared understanding of the importance of safety training and as helpful in terms of connecting the topic to one's work (Billett, 2013; Burke et al., 2006). The trainers recognized their positions as role models for the learners and used them to lend credibility to the subject at hand. The trainers aimed to adapt the training to the group in the planning phase; however, the trainers also observed the group during the learning situations and adjusted their actions according to individual needs, such as encouraging quieter individuals to contribute to the discussion. They aimed to promote an open and relaxed atmosphere to lower the threshold for participation, and many preferred to challenge the learners instead of simply handing out information. Training was structured to support the learning process.

Category 3: utilize organizational resources for training development

Two subcategories of pedagogical practices were discovered. *Social resources* was the first—the trainers utilized the organization's social resources, i.e., they cooperated with other trainers in training design and delivery (10 trainers) and collected feedback from the learners (9 trainers; Table 3).

The second subcategory was *material resources.* The trainers planned training materials and methods (8 trainers), organized training programs (6 trainers), and monitored statistics and training data (5 trainers) with the help of their organization's material systems and frameworks. Conceptual and physical artifacts that support training development, such as systems for safety incident management or training feedback delivery, were mentioned in both subcategories (Sutherland et al., 2009). The trainers were able to draw on both social and material resources to plan, prepare, and carry out safety training (Casey et al., 2021; Vuojärvi & Korva, 2020). When describing cooperation with other trainers during training, the interviewees' focus was on their collective action; when discussing feedback collection, they described the ways in which the feedback was requested or received in their interactions with the learners. In their comments on preparing training materials and methods, the trainers' focus shifted to the learning content, and they discussed training programs in terms of the importance of training frequency. The trainers who described utilizing statistics and data did so by referring to safety-related processes and systems.

Table 2 Pedagogical Practices in Category 2: Guide the Social Interaction in Training Situations

Subcategory	Code	*f*	*n*	Example Interview Quote
Facilitate social interaction	Promote discussion and interaction	30	14	*Preferably talking to other learners. So that one would understand why that topic is important and why it should be considered in one's own work [Trainer #13]*
	Apply professional experience and set an example	17	12	*Especially in safety matters, it must show that I'm talking about something I really believe in and this is how things have to be done to be safe at work there [Trainer #11]*
	Adapt training to the learner group	16	11	*... tailored it a little for the target group, if there were people working in the controlled area or if they never really visit it... [Trainer #14]*
	Promote learner activity	23	10	*So that you really have to think about it; I won't give an answer straight up, but you have to work for it a bit yourself [Trainer #2]*
	Observe individual differences	21	10	*... there are perhaps some people who... shy away from the situation [Trainer #16]*
	Modulate emotional atmosphere	19	9	*... the learning environment needs to be relaxed enough for learning to take place [Trainer #15]*
Maintain temporal structure	Give an outline of training and goals first	14	8	*Usually we start with going through the basic principles of the training, what are we aiming for, why we have this training [Trainer #11]*
	Debrief learners afterwards	12	7	*And then afterwards a joint discussion, what we got out of this, what kind of observations we made [Trainer #3]*

f number of coded units, *n* number of interviews with coded units

Table 3 Pedagogical Practices in Category 3: Utilize Organizational Resources for Training Development

Subcategory	Code	*f*	*n*	Example Interview Quote
Social resources	Cooperate with other trainers in training design and delivery	11	10	*... when they were divided into two groups, there were both of us there too; I was in one group and another trainer was in the other group, watching all the time... [Trainer #14]*
	Collect feedback from learners	13	9	*Well, of course, we have a feedback system where the trainees are allowed to give feedback on their training and, of course, also the trainers [Trainer #11]*
Material resources	Plan training materials and methods	11	8	*... we'll break those themes down into smaller ones in basic training and then combine them with others so that they can be taken in more easily [Trainer #17]*
	Organize training programs	11	6	*... radiation protection training packages... are repeated x times a year. Everyone who needs it can enroll... [Trainer #14]*
	Use statistics and training data for development	8	5	*I think it is worthwhile to use the information that is extracted from the organization where people work so that training can be developed from its point of view [Trainer #12]*

f number of coded units, *n* number of interviews with coded units

The pedagogical model for IVR safety training

With RQ 2, we sought to determine how the trainers' pedagogical practices informed the sociocultural contextualization of the pedagogical model. Our findings support the sociocultural framing in several aspects. The trainers' pedagogical practices demonstrated their awareness of the learning context and learner factors while displaying pedagogical and procedural skill (Tynjälä, 2013). The trainers introduced the learners to the organizational safety culture by drawing on their own experiences of work safety matters and acting as examples or role models for the learners (Billett, 2013, 2021; Burke et al., 2006; Casey et al., 2021). The trainers facilitated the discussions along both the social and the temporal axes of the training and used the organizations' material and social resources to arrange, deliver, and develop safety training (Casey et al., 2021; Tynjälä, 2013). The trainers acted as mediators as they connected the training to the learners' current work and previous experiences, ensured that clearly defined training goals guided the process, and afterwards evaluated the training outcomes (Anderson & Krathwohl, 2001; Casey et al., 2021; Dieckmann, 2009; Kraiger et al., 1993). The trainer's role is pivotal, both in communicating the practices and discourses of the organization's safety culture and in guiding the learners to become active participants in that culture.

The IVR environment used to deliver the safety training scenarios in the training interventions only accommodates individual learning (i.e., the learner advances through the IVR tutorial and the training scenario independently of the other learners)—a feature that is observed in the conceptualized model (Fig. 2).

Our findings confirm the importance of including the social setting in the pedagogical model for IVR safety training. The introduction and debriefing phases enact social learning; the learners are engaged in small-group discussions and interactions (Burke et al., 2006; Dieckmann, 2009; Säljö, 2004; Vygotsky, 1978). The trainer links the training goals and contents to the organization's safety culture and safety practices by applying select pedagogical practices, such as adapting the training to the learner group and connecting the subject and examples to the actual work situations (Billett, 2013; Burke et al, 2006; Casey et al., 2021; Holdsworth et al., 2022). In the interviews, the trainers also described guiding the group interaction, modulating the emotional atmosphere, and activating the learners. These pedagogical practices are essential in supporting learner agency and motivation

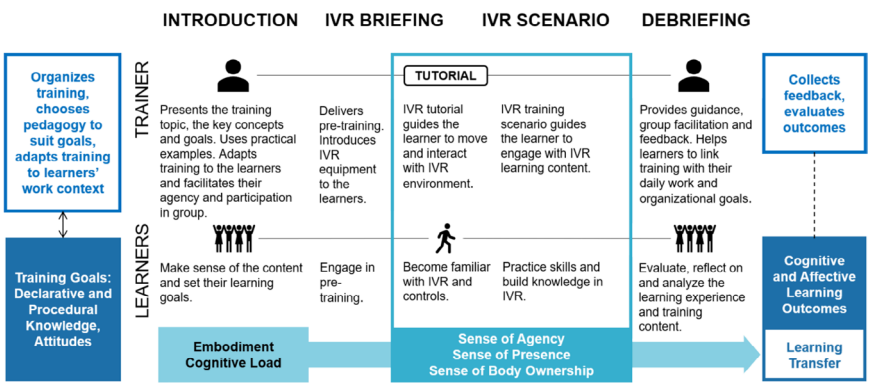

Fig. 2 The Pedagogical Model for IVR Safety Training

(Bandura, 1997; Ryan & Deci, 2000). The introduction provides the trainer with an opportunity to adjust the training to the group of learners while providing them with context and background information that will benefit their learning (Tynjälä, 2013). The debriefing allows the learners to discuss and reflect on the IVR experience together. Based on our findings, we place an emphasis on trainer-facilitated reflection on the training experience in relation to the organization's safety practices and the learners' work context in the debriefing phase of the pedagogical model. This approach will help learners apply the learning content to their daily work, allowing for training transfer (Billett, 2013, 2021; Kolb, 1984).

Occupational safety training is designed, coordinated, and implemented within the sociomaterial environment of the work organization (Holdsworth et al., 2022; Vuojärvi & Korva, 2020). The findings have encouraged us to include the trainers' pre- and post-activities in the pedagogical model to encourage the practitioners to strive for a good fit between the training goals, the learners' work tasks, and the organizational safety culture (Casey et al., 2021; Tynjälä, 2013). Pre-training activities include organizing training programs, choosing pedagogies, and adapting the training to the learners' work context. The trainers frequently talked about collecting learner feedback and mentioned several ways of evaluating the training outcomes. However, evaluating training viability or impact was not a prominent theme. Post-training activities therefore encompassed feedback collection and outcome evaluation, which should also include an appraisal of the technological tools used in the process (e.g., Harris et al., 2020; Holden & Rada, 2011).

Discussion

The qualitative findings contributed to the design of the trainer-facilitated discussions in the pedagogical model (i.e., introduction and debriefing) and broadened our understanding of the contextual possibilities and limitations of safety training in the trainers' organizational settings (Tynjälä, 2013). The proposed model's underlying assumptions about learners and trainers, such as the expected level of competence upon entering the training situation, should be noted. Our study highlights the role of the trainers' pedagogical content knowledge (e.g. Berry et al., 2008). The trainers choose appropriate pedagogical methods to suit the objectives, adapt training content to the learners' work context, collect feedback, and evaluate outcomes. To do this, they need to understand the occupational safety hazards, issues, and procedures that are relevant to the learners. Some tech-savviness is required to support the learners' interactions with the IVR and to solve any possible technical problems. In their facilitator role, the trainer guides the learners to become participants and members of the expert community, whose actions, discourses, practices, and artifacts contribute to a positive safety culture. Intra- and interpersonal skills help trainers create positive and effective learning experiences (Chai et al., 2013; Ling Koh et al., 2014).

For the pedagogical model for IVR safety training to be applied successfully, trainers must be provided with sufficient training and facilitation materials beforehand. Some may need coaching and support to create the positive learner–facilitator interaction that is a key element of the pedagogical model. In this study, the trainers reported using a range of means to evaluate whether the desired learning outcomes had been achieved. In their organizational roles, trainers must be adequately supported, not only in exploring the possibilities of learning evaluation in IVR but also in assessing the overall viability of various IVR training applications as part of a learning curriculum (Harris et al., 2020).

IVR learning environments may enable more engaging training experiences in the occupational safety context, but training design should not rely on immersive technology alone. Establishing clear, well-formulated goals is fundamental. We propose that identifying the organization's training needs and the learners' immediate work context should be prioritized, followed by carefully formulating the training objectives and selecting the best methods for attaining them. It is advisable to consider possible technological limitations when designing IVR scenarios and setting goals. Overall, the learning tasks for the IVR scenarios should be designed to feel relevant to the learners. Our interviews with trainers highlighted the importance of selecting the scenario topic from the learners' direct work context and using practical examples. Aligning the concepts from the training session with safety practices and operating procedures in the learners' work tasks supports both declarative and procedural training goals (Billett, 2021). Applying this principle to IVR safety training creates better premises for training transfer.

Limitations and future considerations

The research community has identified certain possible weaknesses in DBR. The first of these is researcher bias, which may be induced by the researcher's close involvement with the design, development, and application of a pedagogical approach. Scientific objectivity and detachment must be maintained, despite the commitment and persistence required throughout DBR's iterative processes. We have striven for this by ensuring cross-disciplinary researcher collaboration during all stages of the research. Additionally, while DBR is often used to develop educational theory, its results may have little impact on educational practices, and its iteration frequency may remain low (Anderson & Shattuck, 2012; Zheng, 2015). In this study, data were collected from 18 semi-structured thematic interviews in two work organizations, and the results were used in the conceptual design of a pedagogical model for IVR safety training. The model will be applied in empirical research to continue the iteration, but this study has not reported empirical results. Learners were not interviewed at this stage, as the target groups for the safety training interventions had not yet been identified. The challenges for training facilitation that can be brought on by the learners' varied backgrounds, previous experiences and attitudes towards IVR safety training must be further explored in empirical research to increase the model's practical relevance.

This study focused on the sociocultural aspects of safety training design. As the causal pathways between the IVR learning-critical cognitive and affective factors proposed in the pedagogical model, on one hand, and the learning outcomes, on the other, are not yet clear, they should be studied further (see Makransky & Klingenberg, 2022). Quantitative and mixed-methods research would add robustness to the study design. Questions about IVR training evaluation should also be directly addressed in future research, as they were not included in this study (Harris et al., 2020; Lai et al., 2022). Other future research directions include a follow-up study on the affective learning objectives that are central to occupational safety learning (Christian et al., 2009). Finding the best ways of moving toward these goals with engaging training methods such as IVR could have a major impact on safety training effectiveness.

Conclusion

This study presented a multi-disciplinarily informed pedagogical model for IVR safety training that has been conceptually designed with the aid of safety trainer interviews. Our findings reveal the importance of tailoring safety training to both the learners' and the organization's context. They illustrate the pedagogical practices employed by the trainers and further clarify how the trainers sought to fulfil the training goals set by themselves and others. The study illustrated in multiple ways how carefully planned and facilitated social learning complements individual IVR training scenarios. Establishing clear, explicit learning goals and tasks with high relevance to the learners' work context is pivotal in designing effective occupational safety education and training scenarios. IVR safety training should be aligned with the organization's safety culture. Moreover, the trainers play a major role in learner engagement: Using their experiences and views as a starting point for discussion, they invite the learners to become active participants in the positive safety culture. Finally, rather than relying solely on IVR's engaging features, it would be beneficial to consider including social learning opportunities in the IVR safety training design.

Appendix A

Interview protocol

Introductions and welcome.

The informant's agreement to participate in the study, including their acceptance of the privacy and data processing declarations supplied in advance, is confirmed before the interview begins.

Warm-up questions

1. Tell us how you are involved with safety training at your workplace.

   a. Describe your specific area of responsibility in safety training
   b. What kind of work duties are connected with this area of responsibility?

Theme 1: Training Goals

2. Please tell us what kinds of goals your organization has for safety training.
3. What kinds of goals do you have for safety training?
4. What kinds of goals do the learners have for safety training?

   a. Give 1−2 examples of the goals.

Theme 2: Pedagogical Practices.

5. Describe what kinds of instructional practices are most functional, in your experience, in

a. Training in general, and
b. Safety training carried out within your organization.

Supporting prompts:

- In your experience, what are the best ways to achieve the learning goals in the training sessions, so that learning can be transferred to work practice?
- Please describe some safety training implementations that you have observed to be effective and influential on the learners' work practice.

6. Describe how you would like to develop the instructional practices applied in your organization's safety training.

Wrap-up.

7. Is there anything else you would like to tell us? Would you like to revisit any of the previous questions and add something to your comments?

Thank you. Interview ends.

Acknowledgements This work was supported in part by the Finnish Work Environment Fund (grant numbers 210177 and 210182), Fortum Power and Heat, and Stereoscape Ltd. We also wish to express our gratitude to the occupational safety and training personnel at the participating work organizations.

Author contributions Anu Lehikko: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Visualization, Writing—original draft, Writing—review and editing. Mikko Nykänen: Conceptualization, Funding Acquisition, Methodology, Validation, Writing—original draft. Heli Ruokamo: Conceptualization, Funding Acquisition, Methodology, Supervision, Writing—review and editing.

Funding Open Access funding provided by University of Lapland. This study was funded by the Finnish Work Environment Fund (Työsuojelurahasto), grant numbers 210177, 210182.

Data availability The research data is not publicly available due to the data privacy agreement.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval This study has been reviewed and approved by the Finnish Institute of Occupational Health's Ethical Committee.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Anu Lehikko (M.Ed.) is a Doctoral Candidate and a Researcher in the Faculty of Education at University of Lapland. Her research interests include workplace learning and immersive virtual learning environments.

Mikko Nykänen (Ph.D.) is actively involved in projects aimed at promoting occupational wellbeing and work ability in the workplaces. The common themes running through his work include evaluation of organizational development activities and occupational wellbeing interventions.

Heli Ruokamo (Ph.D.) is a Professor in the Faculty of Education and the Director of the Media Education Hub at University of Lapland.

II

Lehikko, A., Nykänen, M., Lukander, K., Uusitalo, J., & Ruokamo, H. (2024). Exploring Interactivity Effects on Learners' Sense of Agency, Cognitive Load and Learning Outcomes: A Mixed Methods Study. *Computers & Education: X Reality, 4,* 100066. https://doi.org/10.1016/j.cexr.2024.100066

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Computers & Education: X Reality 4 (2024) 100066

Contents lists available at ScienceDirect

Computers & Education: X Reality

journal homepage: www.journals.elsevier.com/computers-and-education-x-reality

Exploring interactivity effects on learners' sense of agency, cognitive load, and learning outcomes in immersive virtual reality: A mixed methods study

Anu Lehikko [a,*], Mikko Nykänen [b], Kristian Lukander [b], Jose Uusitalo [b], Heli Ruokamo [a]

[a] University of Lapland, P.O. Box 122, FI-96101, Rovaniemi, Finland
[b] Finnish Institute of Occupational Health, P.O. Box 40, FI-00032, Työterveyslaitos, Helsinki, Finland

ARTICLE INFO

Keywords:
Immersive virtual reality
Interactivity
Sense of agency
Cognitive load
Learning Outcomes

ABSTRACT

This study explored the effects of IVR interactivity on learners' sense of agency, cognitive load, and learning outcomes. The research questions were: 1. "How does interactivity influence the learners' sense of agency?" and 2. "How does interactivity influence the learners' cognitive load and learning outcomes?" A mixed-methods experimental design was applied. Safety training interventions, including individually performed IVR scenarios, were held for 68 participants in groups of two to four persons in two work organizations. Single- and repeated-measure questionnaires were the main source of the quantitative data. Qualitative data collection by video recordings and stimulated recall interviews was carried out on 23 persons in total. The results indicate that high interactivity enables a stronger sense of agency for the learners and yields learning benefits by supporting generative cognitive processing. Based on the results, interactivity and learner involvement may be particularly important for achieving affective training goals. Considering the sociocultural and individual factors in training design and pre-briefing the learners are also recommended.

1. Introduction

Immersive virtual reality (IVR) refers to an artificial, computer-generated 3D environment (Lee, 2004) that is usually operated by a head-mounted display (HMD) and hand controllers (Concannon et al., 2019; McGowin et al., 2021) presenting the user with a vivid artificial environment while shutting out their actual physical surroundings (Cummings & Bailenson, 2016). IVR has proved an effective training medium for several disciplines, demonstrating special promise in the area of safety training (Buttussi and Chittaro, 2018; Casey et al., 2021; Gao et al., 2019; Nykänen et al., 2020). However, the frequent absence of learning theory in educational IVR research and the scarcity of research on the appropriate instructional strategies for IVR training have been recognized by several authors (Lawson & Martella, 2023; McGowin et al., 2021; Radhakrishnan et al., 2021; Radianti et al., 2020). These issues must be addressed by empirical study to ensure the pedagogical validity, ethicality and efficiency of IVR training (Harris et al., 2020; Oje et al., 2023; Skulmowski, 2023).

Interactivity is considered a key design element of the IVR learning environments (Checa & Bustillo, 2020; Heeter, 2000; Khorasani et al., 2023; Makransky & Petersen, 2021). Interactivity can be described as the objective degree of control given to the user over the actions and changes in the IVR environment, enabling their active participation in the learning event (Roussou, 2004; Steuer, 1992). Makransky and Petersen (2021) propose that the effect of IVR interactivity on the learner's sense of agency – their individual perception of initiating and controlling their actions (Braun et al., 2018) – and cognitive load is essential for the learning outcomes. In empirical studies, interactivity has been found to improve declarative learning outcomes in particular (Fokides & Antonopoulos, 2024; Petersen et al., 2022). Affective learning outcomes, such as increased motivation and self-efficacy, are essential to the generation of the positive effects of the safety training (Burke et al., 2006), but they have received considerably less attention in the IVR training field compared to cognitive outcomes, despite their relatedness (McGowin et al., 2021). Considering the learners' cognitive load is relevant for designing IVR safety training scenarios and training modules that can be implemented as a part of a workplace learning curriculum (Dieckmann & Ringsted, 2013; Sewell et al., 2019; Sweller, 2020).

Intervention studies, design-based research (DBR) and mixed-methods approaches using standardized training outcome measures have been advised to further the study of the best practices for

* Corresponding author.
E-mail addresses: alehikko@ulapland.fi (A. Lehikko), miknyka00@gmail.com (M. Nykänen), kristian.lukander@ttl.fi (K. Lukander), jose.uusitalo@ttl.fi (J. Uusitalo), heli.ruokamo@ulapland.fi (H. Ruokamo).

https://doi.org/10.1016/j.cexr.2024.100066
Received 13 November 2023; Received in revised form 26 February 2024; Accepted 19 April 2024
Available online 14 May 2024
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educational IVR (e.g. Checa & Bustillo, 2020; Conrad et al., 2024; Luo et al., 2021; Makransky & Klingenberg, 2022; Radianti et al., 2020). Our empirical mixed-methods study contributes to the prior IVR learning research by investigating the effects of interactivity on the learners' sense of agency, cognitive load, and affective and cognitive learning outcomes. We prepared two different versions of each IVR safety training scenarios used in the training interventions in two work organizations and collected both quantitative and qualitative data. The qualitative data provided insight on the participants' experiences and the training context. The study utilized a pedagogical model for IVR safety training (Lehikko et al., 2023) in the design and implementation of the safety training sessions. The results of this study will be used to provide recommendations for IVR safety training design and will contribute to the iteration of the pedagogical model in DBR (Amiel & Reeves, 2008; Wang & Hannafin, 2005).

2. Literature review

2.1. Interactivity and sense of agency

Interactivity describes the degree of control that the user has over the environment and its objects and the immediacy with which their actions and modifications take effect (Steuer, 1992); it is understood as a reciprocal and engaging activity (Roussou, 2004). Within embodied interaction, directly observable bodily actions—such as gaze, body position, motion, and speech—represent the interface between the cognitive system and the IVR environment. An increased level of interaction between the user and the environment is considered undesirable if it stems from weak design (Heeter, 2000; Norman, 2013; Sweller, 2020). Interactivity defines whether the IVR learning experience can be described as experiential: learning by doing or simply observing (Slater, 2017). Engaging the learners in relevant physical activity may yield significant learning benefits (Johnson-Glenberg, 2017, 2019); however, some empirical studies have challenged this view (Khorasani et al., 2023; Petersen et al., 2022). Enabling interactivity is essential for the learners' perceptions of the IVR affordances: the opportunities for action fostered by the environment—often described as the relations and dynamic interactions between the environment and user (Dalgarno & Lee, 2010; Gibson, 2014; Petersen et al., 2022; Shin, 2017). Different individuals may perceive different affordances in the same environment – and so may the same individual at a different time; in essence, the affordance perception and actualization depend on the subjective states of the observer (Gibson, 2014; Norman, 2013; Withagen et al., 2012).

In IVR research, *sense of agency* refers to a user's perception of generating and controlling actions and their effects within the virtual environment (Braun et al., 2018; Farrer et al., 2013). It reflects their conscious judgement of agency based on their beliefs and contextual cues, whereas the implicit aspect of agency does not involve conscious reflection and is informed by sensory feedback (see Moore et al., 2012). Learners experiencing agency are more likely to assume responsibility for their learning: the autonomy and control experienced by the learner support their motivation and self-efficacy (Dieckmann, 2009; Ryan & Deci, 2000). Agency accommodates the embodied learning that is considered to enhance learning retention (Johnson-Glenberg, 2019; Kilteni et al., 2012). The mastery experiences enacted during training are expected to foster self-efficacy development (Bandura, 1997; Stajkovic & Sommer, 2000). Allowing the learners to make errors and providing them with engaging corrective feedback may also improve learning retention (Metcalfe, 2017). The negative affective outcomes of one's actions may diminish one's perceived sense of agency compared to positive or neutral outcomes (Yoshie & Haggard, 2013). In this study, we measured the learners' sense of agency in IVR training scenarios designed for either high or limited interactivity (see Ch. 3.2).

2.2. Cognitive load in IVR

Cognitive load refers to the amount of mental effort and memory resources used during learning (Lawson & Mayer, 2024; Mayer, 2014). The IVR features that support affordance perception, such as visual cueing, also affect the learners' cognitive load (Albus & Seufert, 2023; Baceviciute et al., 2020; Sweller, 2020). Cognitive load also depends on the learner's level of expertise; novices and experts are expected to benefit from a different instructional design (Sweller, 2020). Other factors related to cognitive load include, for example, task complexity and time pressure (Mutlu-Bayraktar et al., 2019; Rogers & Franklin, 2021). The cognitive load theory (Sweller, 2020) delineates three specific types of cognitive load: intrinsic, extraneous, and germane. We measured all of them in this study.

Intrinsic cognitive load (ICL) refers to the complexity of the learning content and is influenced both by content presentation and the learner's previous domain knowledge. *Extraneous cognitive load* (ECL) is generated by the IVR design features that rely on the capacity of the learners' working memory, such as the complexity of the interface and the instructional procedures. The instructional content delivery method, such as text overlay or audio, contributes to the learner's cognitive load and thus has an effect on learning outcomes and learning transfer (Albus & Seufert, 2023; Baceviciute et al., 2020; Parong & Mayer, 2021; Sweller, 2020). The ECL caused by the IVR technology-induced novelty effect can be countered by pre-training the learners to interact with the IVR environment in a tutorial (Miguel-Alonso et al., 2023). *Germane cognitive load* (GCL) describes the cognitive resources used to process the learning content and involves the effort of reorganization, extraction during task completion, and incorporating a learning content into memory (Li et al., 2023; Rogers & Franklin, 2021). GCL has been defined as the mental effort to generate schema of the knowledge to be learned; this process has been suggested to facilitate learning (Kirschner et al., 2011; Mayer, 2014).

ICL and ECL may act as motivational costs in learning processes, but GCL is considered to benefit learning through cognitive engagement (Skulmowski & Xu, 2022). Albus et al., 2021 suggested that IVR environments should be designed to enable germane cognitive processing. Frederiksen et al. (2020) found that immersive VR with a higher level of element interactivity was associated with higher ICL and ECL. However, using attentional guidance to signal the interaction possibilities in IVR fosters germane processing in working memory and may actually help learners to engage in deeper learning processes (Albus et al., 2021). In other sources, the link between the cognitive investment in germane cognitive processing and learning outcomes has not been confirmed (Klepsch et al., 2017).

2.3. Learning outcomes in IVR safety training

Proactive safety behavior self-efficacy was chosen as an affective learning outcome measure in this study. *Self-efficacy* refers to "beliefs in one's capabilities to organize and execute the course of action required to produce given attainments" (Bandura, 1997, p. 3); it is considered an activity domain-specific construct. Self-efficacy measurements do not focus on the comparative aspects of evaluating competence or ability in the learning situation, but on the learner's self-assessment of their ability (Bandura, 2006, 2012; Wigfield & Cambria, 2010). Self-efficacy is a key determinant in human behavior: it is an important target for behavior change interventions (Sheeran et al., 2016) and educational interventions where higher self-efficiency is considered to increase the learner's persistence, effort, and achievement (Klassen and Usher, 2010; Kraiger et al., 1993). Occupational safety-related self-efficacies are associated with the safety performance and positive safety behaviors (Katz-Navon et al., 2007; Kim et al., 2014); hence, safety related self-efficacies are important learning objectives in safety training. In this study, the self-efficacy measure reflected the learners' judgement of their ability to engage in a variety of proactive safety behaviors, such as

making safety-related observations and demonstrating a personal initiative to promote safety.

Furthermore, we measured study participant safety knowledge as a cognitive learning outcome. Earlier studies (see Christian et al., 2009) have shown that safety knowledge is a key determinant of preventive safety behaviors. In this study, *safety knowledge* refers to the extent to which employees have a clear idea of the safety processes and correct procedures and behaviors (see Braunger et al., 2013). It should be noted that affective and cognitive learning goals are often intertwined, and it is difficult to draw a clear distinction between the two (Krathwohl et al., 1973; McGowin et al., 2021). Hence, self-efficacy on proactive safety behaviors, as described above, can be interpreted as the learner's innate disposition and belief that they possess the required declarative and procedural knowledge to act accordingly and to successfully identify the potential hazards in their work situations (see Bandura, 1997).

2.4. Pedagogical model for IVR safety training

Pre- and post-practice briefings are commonly used in simulation training (Dieckmann, 2009; Dieckmann et al., 2007; Feng et al., 2021; Rudolph et al., 2014). Situated before and after IVR activities, they offer a means to reduce the overall cognitive load experienced by the learners and to consolidate the learning process with facilitated reflection (Bandura, 1997; Casey et al., 2021; Dieckmann, 2009; Rudolph et al., 2014). In the pedagogical model for IVR safety training, the trainer guides the learners to become participants and members of the expert community whose actions, discourses, practices, and artefacts contribute to a positive safety culture (Billett, 2021; Lehikko, Nykänen, & Ruokamo, 2023; Sutherland et al., 2009; Vygotsky, 1978) (Fig. 1).

The model establishes four training phases. In the introduction, the topic, key concepts, and goals are introduced and discussed. The trainer facilitates the learner agency, motivation, and participation (Billett, 2021; Ryan & Deci, 2000; Schraw et al., 2001). The learners make sense of the learning content and set their own goals for the training. In the IVR briefing, the trainer introduces the IVR equipment to the learners and helps them to wear it comfortably. A pre-programmed tutorial guides the learners to interact with and to move around the IVR environment before the IVR scenario starts (Meyer et al., 2019; Miguel-Alonso et al., 2023; Sweller, 2020). The IVR scenario instructs the learners to engage with the learning content. After the scenario, the learners return to a group setting for a debriefing in which the trainer facilitates reflection and exchange on the IVR experience. The trainer guides the learners to discuss and evaluate their learning from the perspectives of their daily work and the organizational safety goals and supports their agency by role modeling and proximal guidance (Billett, 2021; Dieckmann, 2009; Vygotsky, 1978).

The aim of this study was to explore the role of interactivity in relation to the sense of agency, cognitive load, and learning outcomes in IVR safety training by using both quantitative and qualitative methods and by drawing on the theoretical viewpoints mentioned above. Combining the qualitative findings with the quantitative results will provide additional insight on the learners' experiences and perceptions of interactivity in the IVR safety training context. The results will also inform the iteration of our pedagogical model in DBR, reported elsewhere. The study addressed the following research questions: 1. "How does interactivity influence the learners' sense of agency?" and 2. "How does interactivity influence the learners' cognitive load and learning outcomes?"

3. Methods

We applied a mixed-methods experimental design to address the research questions, using quantitative data as the primary form of data and qualitative data as the secondary form of data (Creswell, 2009; Creswell & Plano Clark, 2017). A mixed-methods approach is well-suited for pragmatist research objectives and is often employed in design-based research (DBR) (Wang & Hannafin, 2005). In DBR, the emphasis lies in discovering the best solutions for educational practice in a particular context (Campanella & Penuel, 2021). For us, this meant collecting the data in authentic safety training situations and in close collaboration with the key stakeholders, such as the safety trainers who participated in the study (Amiel & Reeves, 2008; Campanella & Penuel, 2021; McKenney & Reeves, 2018).

Five hypotheses were set (see hypotheses generation table in Appendix A). The level of interactivity in an IVR scenario affects the learner's ability to control their IVR experience and act according to their own volition within the IVR environment (Steuer, 1992). Furthermore, interactivity supports the embodied affordance perception in the IVR environment (Braun et al., 2018; Heeter, 2000; Kilteni et al., 2012; Norman, 2013). Thus, it was hypothesized that a high degree of interactivity in the IVR scenario is connected to stronger self-reported agency (H1). Higher interactivity was also hypothesized to increase the learners' ECL (H2) and GCL (H3) (Albus et al., 2021; Frederiksen et al., 2020; Gibson, 2014; Sweller, 2020). High interactivity provides opportunities for experiential learning (Slater, 2017), learning from errors (Metcalfe, 2017), and providing proximal support via scenario scripting (Bandura, 1997; Johnson-Glenberg, 2017; Vygotsky, 1978). Thus, we hypothesized that a high degree of interactivity has a beneficial

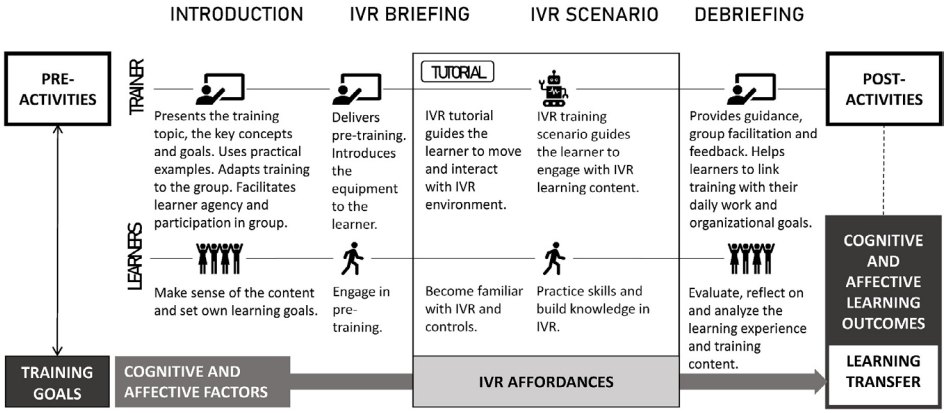

Fig. 1. The pedagogical model for IVR safety training (Lehikko et al., 2023).

effect on the learning outcomes of self-efficacy (H4) and safety knowledge (H5).

3.1. Equipment and IVR environment

Wireless VR headsets with two wireless motion controllers and built-in cameras for inside-out tracking, allowing for six degrees of freedom in movement, were used. The IVR scenarios were developed using the Unity game engine and a custom-built framework for interacting with IVR environments and learning content. The IVR hardware enabled the learners to freely move within a designated four-by-four meter training area and provided high motion tracking fidelity for the headset and motion controllers. The learners' physical movement was mapped 1:1 to the virtual environment. No virtual movement such as teleporting or joystick-driven movement was enabled to increase the sense of physical presence and to reduce the possible simulator sickness effects. Fade-out and fade-in were applied in the transitions between the virtual settings that were not feasible to cover by walking, such as transitioning from the tutorial to the training scenario.

The virtual environment and objects were 3D-modeled to match the scale of their real-world counterparts. A consistent art style was applied to the IVR learning platform: the shapes of objects were simplified by removing small details while keeping the objects clearly recognizable, all high-frequency detail and variation in the surface texture and color were removed, and a coherent color scheme was maintained across all the objects. The learners did not have a virtual body or avatar, and the controllers were presented as simple blue shapes. The presence of extraneous objects was minimized to encourage the learner to focus on the learning content. These design choices also ensured a consistent frame rate that contributes to the smoothness of the view changes on the selected platform. The IVR learning environment was designed for ease of use: the motion controllers were used to point and click at targets and allowed for simple gesturing, such as waving the controller above one's head to complete a signaling task in the scenario.

3.2. IVR training scenarios

The scenarios were single-user experiences designed to guide the learners without the need for a human instructor. The interactions with the IVR scenarios consisted of activating scenario-relevant objects and virtual people for a conversation, clicking through instructional text boxes, making simple gestures by waving the controller, and walking to designated areas within the scenario when instructed to do so. This simplified action set was developed to make interacting with the environment consistent and to keep the learners' focus on the learning content. All the text displayed within a scenario was also narrated in audio. Clicking a text box to advance the storyline also caused the voiceover to skip to the next content.

Three occupational safety training scenarios with different themes were used in the study: 1. valve works on a city street, 2. luggage inspection, and 3. bridge crane lifting (see Appendix B for scenario content description and illustrations). For the experiment, two versions of each of the three IVR scenarios were prepared. The difference between the versions was in the level of interactivity; the learning objectives and the storyline were identical in both versions. In the high interactivity setting, the learner was addressed in the 2nd person singular when instructed to look for safety defects, to perform safety-related procedures, and to proceed in the scenario. Each safety observation had to be discovered before the scenario could proceed. The learners could interact with the IVR environment directly by pointing at and clicking on virtual objects as the scenario script unfolded. Multiple-choice events allowed the learner to make mistakes and to correct them.

In the limited interactivity version, the learner tasks were replaced with a sequence of information spots corresponding to the correct observation or procedure. Personal pronouns were changed to the passive voice in the instructional script. The learners could only interact with the environment by clicking on the instructional text boxes, which advanced the script and presented the content for the correct choice in place of the multiple-choice events. The safety defects and procedure steps were indicated to the learner instead of prompting them to perform actions. As a consequence, in the limited interactivity version, the learner could not make mistakes in the multiple-choice selections or receive feedback for their actions. However, the learner could advance the scenario at their own pace and they were able to move around freely in both scenario versions.

3.3. Experiment design, participants, and training procedure

A randomized-controlled experiment design was used, with the participants randomly allocated to either condition A or B after signing up for the experiment and filling out the baseline questionnaire. In the training session, the participants completed the IVR scenarios according to their experiment group. The A participants performed the high interactivity valve work scenario first, and the B participants started with the limited interactivity version of the same scenario. Next, the A participants continued with a limited interactivity version of the organization-specific IVR scenario, whereas the B participants performed the high interactivity version of it (Fig. 2).

In total, 76 study participants were recruited on the basis of informed consent by the contact persons—one trainer and one digitalization expert—out of the staff of the two organizations. The participants were expected to work within the roles that correlated with the organization-specific IVR training scenario topic and not to have been involved in scenario planning. Fifty persons from organization 1 (O1) in government services and 26 persons from organization 2 (O2) in the energy sector completed the T1 questionnaire that was administered before the training sessions.

The safety training was initially targeted at groups of four workers, but groups of two and three were also accepted in both organizations due to issues with participant recruitment, shift arrangements, and no-show on training day. The training group size did not influence the training procedure. Due to attrition, only 68 persons attended the training sessions. Twenty-two training sessions were held: 14 sessions for 46 participants in O1 and 8 sessions for 22 participants in O2. A total of five trainers from the participant organizations were trained to facilitate the training according to the pedagogical model. They facilitated the training sessions either alone or as a pair, depending on their availability. Three members of the research group were present in all the sessions for data collection and technical support purposes. During the IVR briefing, the fit of the HMD was adjusted individually to all the learners to improve the image clarity and to ensure that the device was comfortable to wear. We advised the learners to ask for assistance if they encountered problems; in total, 13 learners were either helped to re-adjust their HMDs or guided with questions to find the necessary safety observations during either scenario 1 or 2.

3.4. Data collection and analysis

3.4.1. Quantitative data and analysis

Four questionnaires were administered to the participants in both study organizations: baseline (T1) from two to four weeks before the intervention, short-term delayed (T2A) after the first scenario, short-term delayed (T2B) after the second scenario and long-term follow-up (T3) approximately three months after the intervention. Sense of agency and cognitive load were measured at T2A. Proactive safety behavior self-efficacy and safety knowledge were measured at T1, T2B, and T3. Two units of observation were removed from the T2B questionnaire data for O1 due to a data collection error.

The sense of agency was measured using three 7-point (strongly disagree–strongly agree) items (e.g., "My experiences and actions felt self-generated," $\alpha = 0.79$) adapted from the measure developed by Polito et al. (2013) and further modified to the VR context by Pritchard

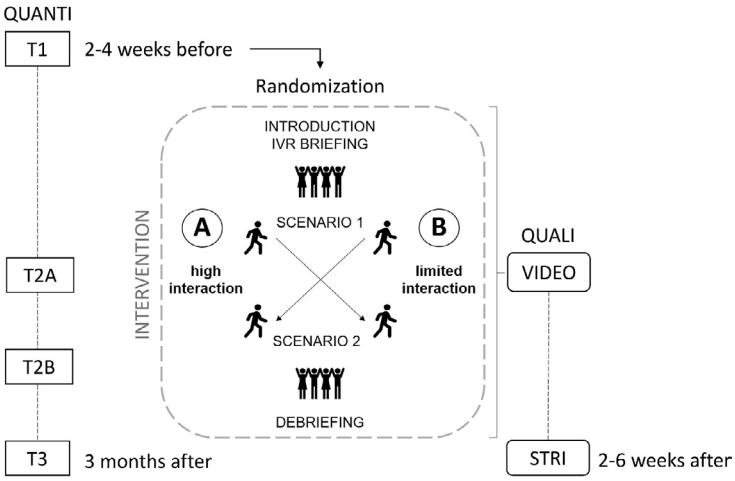

Fig. 2. Experiment design.

et al. (2016).

To assess the perceived cognitive load, we adapted a measure developed by Klepsch et al. (2017). The responses were made on a two-item seven-point scale (1 = "strongly disagree" to 7 = "strongly agree"; e.g., germane cognitive load: "For this task, I had to think intensively what things meant," $r_{sb} = 0.84$., extraneous cognitive load: "The design of this task was very inconvenient for learning," $r_{sb} = 0.59$, and intrinsic cognitive load: "For this task, many things needed to be kept in mind simultaneously," $r_{sb} = 51$).

The proactive safety behavior self-efficacy was measured at baseline (T1), immediately after the second IVR scenario (T2B) and at the long-term follow-up (T3). The study participants were asked about their confidence in safety-related activities. Four items of the 7-point scale (1 = very poorly; 7 = very well) were determined on basis of the content of the organization-specific IVR scenarios. The contents of the scale were also connected to the concepts of safety participation (Neal et al., 2000) and safety citizenship (Hofmann et al., 2003), which are characterized by change-oriented safety behaviors and demonstrate the personal initiative to promote safety. Four items were related to: 1) observing problems or deficiencies in the work environment, 2) identifying hazards, such as tripping or slipping hazards in the work environment, 3) inventing ways to improve occupational safety, and 4) reporting safety observations at the workplace. The reliability (α) for self-efficacy measure was 0.85 at T1, 0.76 at T2B, and 0.75 at T3.

The safety knowledge was measured at baseline (T1), immediately after the second IVR scenario (T2B) and at long-term follow-up (T3). We used three 7-point (strongly disagree–strongly agree) items (e.g., "I know how to improve safety at my work," $\alpha = 0.81$ at T1, $\alpha = 0.83$ at T2B, and 0.80 at T3) adapted from Neal et al. (2000) (see Appendix D for the English translation of the questionnaire items).

The background characteristics of the study participants and the outcome variables were described using means and/or proportions and medians and standard deviations. We screened the skewness and kurtosis of the study variables and investigated the baseline-differences between the training conditions. The Mann-Whitney *U* test was used to explore the differences between the training conditions in terms of the IVR environment design impact on the perceived sense of agency and germane cognitive load. The Wilcoxon paired signed-rank test was used for the pre- and post-comparison in terms of the learning outcomes (self-efficacies, safety knowledge). Since the study was carried out as an iterative and explorative design-based study with the training interventions taking place in two organizations, we analyzed the organization-specific data separately.

3.4.2. Qualitative data and analysis

Eight training groups were video recorded and observed throughout their training sessions. Videos were recorded by external cameras and VR headsets. We selected the video clips of what appeared to be the significant moments of learning based on learner behavior and vocalization and used them in STRIs with the 23 participants (see interview protocol in Appendix C). Nine persons from three training groups in O1 and fourteen persons from five training groups in O2 were interviewed two to six weeks after the training sessions, depending on participant availability. The STRIs were held using a video conferencing tool and recorded on an external audio recording device. The interviews were arranged and carried out by one researcher who had been observing the training sessions but had no personal connection to the interviewees. The recordings were between 36 and 70 min in length, averaged 49 min, and totaled 18 h 39 min. They were transcribed by a service provider. The transcriptions totaled 112,413 words and 285 pages (A4 standard page, 12 pts Times New Roman, interviewer and interviewee lines in single space). We checked the transcriptions against the recordings and corrected them manually before importing them to NVivo (1.4, Lumivero, US) for analysis.

We addressed research questions 1 and 2 by submitting the transcriptions to a systematic content analysis that applied both theory-driven and content-driven approaches (Creswell, 2009; Hsieh & Shannon, 2005). Before the analysis procedure, we prepared a coding framework (Table 1).

The STRI transcriptions were read several times, one by one. They were auto-coded and clustered by the interview phases. The predetermined coding framework was applied. One or more sentences expressing one coherent thought or idea were used as a unit of analysis (Creswell, 2009). After the theory-driven analysis was completed, a

Table 1
Theory-driven coding framework for qualitative content analysis.

Theme	Coding Reference
Sense of agency	Learner comments on their ability to initiate and perform actions in IVR environment (Braun et al., 2018)
Germane cognitive load	Learner talks about concentrating on and processing the IVR learning content (Klepsch et al., 2017)

content-driven analysis was performed to reveal categories within the themes. During this step, the inductive approach also led to the formation of the categories that did not fit within the pre-determined themes; they were unified under a new theme, which contributed to the qualitative findings for research question 2. Matrix analyses were performed in NVivo to examine the relationships and overlaps between the coding categories, coding by the interview phase and learner attributes such as experimental condition and organization and coding consistency. The categories were re-adjusted and renamed when needed. The first author performed the initial analyses; the coding and categories were then discussed in the research group, and STRI excerpts were selected to illustrate the findings.

4. Results

The recruitment principles were maintained successfully in O1 but challenged in O2, which led to unexpectedly heterogenous learner profiles; the training was targeted at the factory-floor-level operators, but the administrative staff made up a large portion of the O2 sample. The sample size was also considerably lower than expected (Fig. 3).

The study participants varied in age from 25 to 65; the mean age was 41.5 years (SD 10.33). Of the total sample, 39.5 % were female and 60.5% male. In the between-organizations comparison, the participants differed in their gender balance and the participants' previous VR experience. Separate analyses were run for each organization (Table 2).

The chi-square and t-tests showed that the study participants in the two different training conditions did not differ significantly in terms of the background variables at the baseline. The Shapiro-Wilk tests revealed that all the study outcomes departed significantly ($p < .05$) from normal distribution at the follow-up (T2 and T3); hence, we used non-parametric tests in the further analyses. The reliability of the intrinsic cognitive load measure was very low (0.51) and it was removed from the analyses. The simulator sickness symptoms were low intensity (mean 2.25, SD 2.57; observed range from 0 to 12). We found no significant differences in the simulator sickness between the training conditions (high vs. limited interactivity).

Table 2
Background characteristics of study participants.

Variable	O1 (n = 50) % or mean*	O2 (n = 26) % or mean*	Total (n = 76) % or mean*
Gender			
Female	50.0	19.2	39.5
Male	50.0	80.8	60.5
Age (years)	40.1*	44.1*	41.5*
Job tenure (years)	8.09*	12.48*	9.7*
Personal VR devices usage			
Never used	56.0	26.9	46.1
Tried	36.0	65.4	46.1
Once a month	8.0	3.8	6.6
Once a week or more frequently	0.0	3.8	1.3
Has had a work-related accident within 3 years (yes)	31.8	9.5	24.7
Has previously participated in VR training (yes)	0.0	42.3	15.5
Prevalence of IVR scenario task in current job			
Never	8.0	42.0	23.7
Once a year or less	12.0	11.5	10.5
Monthly	22.0	3.8	19.7
Weekly	32.0	38.0	28.9
Daily	26.0	3.8	17.2

4.1. Interactivity effects on learner's sense of agency

Our analyses showed that in O1, the study participants in the high interactivity condition had significantly higher scores on sense of agency (mean difference 5.34 vs 4.46; median difference 5.66 vs. 4.66; $p. <0.05$). The effect could not be detected in O2. Hence, the results partly supported hypothesis 1. Table 3 presents the results in terms of the interactivity impact on the perceived sense of agency and cognitive load.

4.1.1. Qualitative findings: learners' perceptions of agency

Comments related to the learners' sense of agency were made in 19 out of the 23 STRIs. Fourteen interviewees talked about agency in the positive terms of performing and controlling actions. Ten learners described the activity during the scenario as fun, enjoyable, good, nice, and interesting. Four learners expressed enjoyment, especially in being "involved" in the scenario events (Table 4).

Seven learners commented positively about feeling in control; these comments mostly concerned the limited interactivity scenario versions and often referred to the responsiveness of the technology.

In total, 16 interviewees had negative perceptions of agency: 44% of the O1 interviewees and 86% of the O2 interviewees. Eleven learners mentioned wanting or anticipating to perform certain actions themselves, such as moving traffic cones, pressing buttons, or discovering safety observations, indicating that they would have preferred more involvement. Some learners, those who had started with the high interactivity scenario, expressed disappointment at the limited interactivity in the second scenario; they could not apply their expertise in the tasks. However, similar frustration was expressed by some experienced learners in the high interactivity scenarios; they knew the safety checks and procedures thoroughly but had to abide by the scenario script. A total of 11 interviewees made references to a diminished sense of control in both the high and limited interactivity scenario versions. They described being placed in an observer or passenger role, not being "allowed" to advance in the scenario, being "moved" to another spot, being "refused" object interaction, "having to" click text boxes or "following the instructions blindly" to advance, and events unfolding "automatically."

Based on the qualitative findings, the learners' direct involvement in the learning events accommodated by high interactivity was essential for their perception of agency (Gibson, 2014; Johnson-Glenberg, 2019). However, in the limited interactivity versions of the scenarios, the causal relationship between the user actions and the IVR responses was possibly easier to perceive (Farrer et al., 2013). Several learners also discussed their unmet expectations of agency. Many interviewees criticized the restrictions placed upon their actions by the script, regardless of the level of interactivity provided. The majority of the criticism was received from O2, where the participants had more previous experience with VR; they may have already formed certain expectations based on their prior experiences, which affected the perception and interpretation

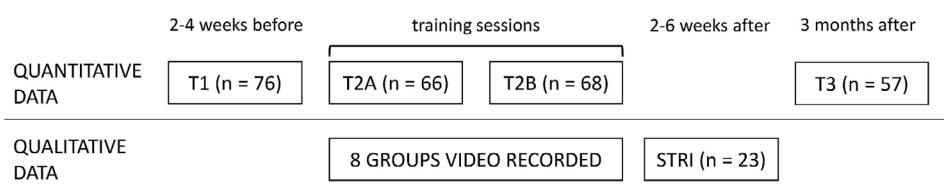

Fig. 3. Quantitative and qualitative data.

Table 3
Sense of agency (SoA) stratified by study organization and training condition.

	O1 (n = 46)			O2 (n = 22)		
	High Int. (n = 21)	Limited Int. (n = 25)		High Int. (n = 12)	Limited Int. (n = 10)	
	Mean (SD) [median]	Mean (SD) [median]	Mann-Whitney U (p.)	Mean (SD) [median]	Mean (SD) [median]	Mann-Whitney U (p.)
SoA	5.34 (1.10) [5.66]	4.46 (1.18) [4.66]	153.500 (0.01)	4.75 (0.84) [5.00]	5.00 (1.36) [5.00]	67.000 (0.67)

Table 4
Categories of factors influencing sense of agency in learner STRIs.

SoA	Category	n	f	Excerpts
Supported by	Involvement	10	14	*… you could carry it out yourself, check the tools that you had, and the van and the traffic. That made it really interesting, because it involved me a lot. (Learner #19)*
	Responsivity	7	8	*I thought it was consistent and it reacted to what I did. That helped me feel like I was in control of it. (Learner #5)*
Diminished by	Unmet expectations	11	20	*I expected [that] … we'd discuss some topics briefly, and then get down to business; we'd act and make choices. That's what I hoped for. (Learner #23)*
	Script-imposed restrictions	11	18	*I tried to place the traffic cones and … the road signs, but [the scenario] didn't allow them to be used. Only later, it said, "do this and that" [with the objects]. (Learner #16)*

Note. n = number of STRI interviews with coded units of analysis; f = number of coded units of analysis.

of agency enabled by the training scenarios (Gibson, 2014; Moore et al., 2012; Withagen et al., 2012). The IVR related expectations, assumptions, discourses, and practices evidently differed between the two work communities (Parchoma, 2014).

4.2. Interactivity effects on cognitive load and learning outcomes

The self-reported ECL was low in both organizations and no significant difference was detected between the conditions. Hypothesis 2 was not supported. The increased interactivity in the IVR-environment resulted in a significant effect for the GCL in both organizations. Thus, the results provided support for hypothesis 3 (Table 5).

Table 6 presents the results of the pre-post self-efficacy and safety knowledge measures, stratified by organization. The Wilcoxon paired-samples tests showed that the study participants in O1 had significantly higher safety knowledge scores and self-efficacy scores at the short-term follow-up. However, these pre-post changes did not reach a significance level with the data from O2. In the long-term follow-up, the pre-post changes in terms of self-efficacy and safety knowledge scores were not statistically significant for either organization.

Finally, we examined the role of the level of interactivity in the IVR-environment in terms of the training in the short-term outcomes on self-efficacy and safety knowledge. Since no statistically significant training effects were detected for O2, only the participants from O1 were included in these final analyses. The Wilcoxon tests showed that a significant increase in self-efficacy ($mean_{T1} = 5.06$ $median_{T1} = 5.12$, $SD_{T1} = 0.88$ vs. $mean_{T2} = 5.42$, $median_{T2} = 5.55$, $SD_{T2} = 0.55$, $Z = 2.24$, $p < 0.05$) and safety knowledge ($mean_{T1} = 4.97$, $median_{T1} = 5.00$, $SD_{T1} = 0.87$ vs. $mean_{T2} = 5.52$, $median_{T2} = 5.66$, $SD_{T2} = 0.66$, $Z = 2.62$, $p < 0.01$) was found among the study participants in the high interactivity training condition (n = 24). In the training condition of less interactivity (n = 20), a statistically significant difference was detected in the increase of safety knowledge ($mean_{T1} = 5.21$ $median_{T1} = 5.00$, $SD_{T1} = 0.89$ vs. $mean_{T2} = 5.75$, $median_{T2} = 5.66$, $SD_{T2} = 0.82$, $Z = 2.25$, $p < 0.05$) but not in enhancing self-efficacy ($mean_{T1} = 5.47$ $median_{T1} = 5.50$, $SD_{T1} = 0.87$ vs. $mean_{T2} = 5.82$, $median_{T2} = 6.00$, $SD_{T2} = 0.71$, $Z = 1.90$, $p = 0.05$). Hypotheses 4 and 5 were thus partially supported.

4.2.1. Qualitative findings on germane cognitive load: the importance of directing learner focus

Fifteen interviewees talked about GCL-related topics in both the high and limited interactivity context. Ten learners remarked on concentration and thinking during the scenario; six of them discussed the level of challenge offered by the scenario and indicated that it required concentration. Two learners described physically moving around to gather information before deciding on the correct course of action, and one of them emphasized that, by doing so, they had aimed to memorize the important learning content. Two learners referred to forgetting about the real world when describing their deep concentration, which may refer to the evocation of spatial presence in the IVR (Table 7).

Seven interviewees mentioned reflecting on their current safety procedures while performing the IVR scenario. Five of them did so in the high interactivity context. Seven interviewees spoke about wanting to advance the scenario at the expense of concentration; these comments were made in both the high and limited interactivity context. Most of the remarks concerned trying to find the safety observations required by the script. Three learners referred to "just clicking on" without much thought to the scenario. For instance, one learner explained that they would, under no circumstances, go below the lifted heavy object in real life, but that they made that error in the scenario, as they didn't pause to think and just tried to advance quickly. One learner expressed that seeing how many observations were left created a feeling of pressure to find the remaining ones.

The quantitative results indicated that the high interactivity in the IVR scenarios appears to foster germane processing—considered beneficial for learning. Based on our qualitative findings we propose that the learners' deep engagement and reflective action help them to connect the IVR learning content to their prior knowledge and experiences of occupational safety in a similar context (Billett, 2013; Norman, 2013). Evoking the familiar work surroundings and procedures in the IVR interaction may support germane processing due to motivational benefits (Mayer, 2014). Concentrating on the IVR learning content may also

Table 5
Germane cognitive load (GCL) and extraneous cognitive load (ECL) stratified by study organization and training condition.

	O1 (n = 46)			O2 (n = 22)		
	High Int. (n = 21)	Limited Int. (n = 25)		High Int. (n = 12)	Limited Int. (n = 10)	
	Mean (SD) [median]	Mean (SD) [median]	Mann-Whitney U (p.)	Mean (SD) [median]	Mean (SD) [median]	Mann-Whitney U (p.)
GCL	3.97 (1.86) [4.00]	2.54 (1.15) [2.00]	143.500 (<0.01)	2.58 (0.76) [2.50]	1.75 (0.67) [1.75]	24.000 (<0.05)
ECL	1.78 (0.64) [2.00]	1.52 (0.58) [1.50]	199.000 (0.14)	1.95 (1.01) [1.50]	1.50 (0.47) [1.50]	47.000 (0.41)

Table 6
Proactive safety behavior self-efficacy (SE) and safety knowledge measures at baseline and short-term follow-up stratified by study organization.

	Proactive safety behavior SE			Safety knowledge		
	Baseline	Short-term follow-up		Baseline	Short-term follow-up	
	Mean (sd) [median]	Mean (sd) [median]	Wilcoxon test, Z (p)	Mean (sd) [median]	Mean (sd) [median]	Wilcoxon test, Z (p)
O1 (n = 44)	5.25 (0.89) [5.37]	5.60 (0.65) [5.70]	2.92 (<0.01)	5.08 (0.87) [5.00]	5.62 (0.74) [5.66]	3.48 (<0.01)
O2 (n = 22)	5.74 (0.94) [6.00]	5.85 (0.81) [6.00]	0.63 (0.52)	5.93 (0.84) [6.00]	5.59 (1.01) [5.66]	−1.13 (0.25)

Table 7
Categories of learner focus supporting or hindering germane processing in learner STRIs.

Germane Processing	Category of Learner Focus	n	f	Excerpts
Supported by	Deep engagement with learning content	10	16	*… you completely forgot the rest of the environment and just focused on that task. (Learner #9)*
Supported by	Reflecting on work safety procedures	7	7	*I kept thinking throughout this task [in STRI video clip] … So, if [the lifted object] had fallen, I would have been far enough from it, but the crane operator would've been still able to see me. Because I was the signaler. (Learner #19)*
Hindered by	Attempting speedy performance	7	10	*I started to hurry, like where's this and this and that … That took my focus. (Learner #4)*

Note. n = number of STRI interviews with coded units of analysis; f = number of coded units of analysis.

Table 8
Interactivity learning benefits identified in learner STRIs.

Category	n	f	Excerpts
Interest and challenge	11	33	*And then again, the second task was kind of challenging; you had to point at things and participate in the change in the environment. (Learner #2)*
Learning by doing	11	16	*You got to participate in that training, it was pretty central … That first [scenario] felt like you learned something from it. (Learner #18)*
Better learning retention	9	9	*It feels real and physical. It's easier to remember than if you just listened to a presentation and watched [a slideshow]. (Learner #3)*
Learning from errors	7	13	*There could be an option of letting the trainee also make mistakes and … learn from it. Now you just click on the boxes and [the scenario] tells you which ones are the right and wrong [cargo straps] and so on. (Learner #16)*
Practicing real work tasks	6	7	*Maybe the first one was, how shall I put it … "better designed." So that you don't spend [time] … clicking on text boxes … It focused more on the so-called real work. (Learner #7)*

Note. n = number of STRI interviews with coded units of analysis; f = number of coded units of analysis.

require sufficient buy-in or suspension of disbelief (Dede et al., 2017); learners should be supported in assuming a learning-conducive mindset before performing the training scenarios, for instance by ensuring an emotionally safe training environment (Dieckmann et al., 2007; Rudolph et al., 2014).

4.2.2. Qualitative findings on interactivity learning benefits as perceived by learners

Twenty-one interviewees discussed the various advantages that they thought high interactivity had for learning. They compared the scenario versions and expressed a preference for the high interactivity, often by pointing out what they felt was lacking in the limited interactivity scenario. Eleven learners described how the interactivity adds challenge, interest, engagement, and meaning to the learning experience: seven interviewees (78%) from O1 and four (26%) from O2 (Table 8).

Eleven learners expressed a preference for learning by actively participating and being physically involved in the learning task: two interviewees (22%) from O1 and nine (64%) from O2. Eight learners emphasized that involvement makes the learning content easier to recall. Seven learners discussed making errors and learning through them. Six learners also talked about being able to practice their real work tasks in a safe environment and envisioned more complex tasks that could be trained for in IVR. On the whole, the interactivity learning benefit themes recurring across the STRIs were consistent with the benefits of embodied learning identified in earlier studies.

The interviewees emphasized different learning advantages depending on their organization. In O1, where IVR appeared to be a less familiar training media, the increased challenge and interest received more mentions – possibly revealing a novelty effect (Clark, 1983). In O2, references to learning by doing were more frequent, as were the interviewees' perceptions of a diminished sense of agency. Our findings support the view that social and contextual factors influence the perception of agency (see Moore et al., 2012). Learning by doing, mastery experiences, learning from errors, and feedback were enabled for all the learners, but the statistically significant learning outcome effects on self-efficacy and safety knowledge were only detected in O1. Our findings highlight the importance of understanding and the acknowledgement of the local values and expectations in the organizational context throughout the processes of training design, implementation, and outcome analyses.

5. Discussion

This study provides evidence on the significance of interactivity for the learners' sense of agency, germane cognitive load, and learning outcomes in IVR safety training, especially considering the self-efficacy related training goals. Whereas a significant increase in safety knowledge was detected across both experimental conditions in O1, the positive effect on proactive safety behavior self-efficacy was only found in the high interactivity condition, along with a stronger perceived sense of agency. Our findings suggest that learner involvement and IVR responsivity support their sense of agency, whereas the learners' unmet agency expectations and strict scenario scripting may diminish it. In addition to enabling direct object interaction, the high interactivity scenarios used in this study allowed the learners a more agentic experience by, for instance, providing the possibility to learn from errors and to receive feedback on their actions (Casey et al., 2021; Metcalfe, 2017). However, several interviewees expressed their disappointment on the limitations imposed by the scenario script.

The learners' extraneous cognitive load did not increase in the high interactivity condition, but their germane cognitive load increased significantly in both O1 and O2. However, generative processing appears to be dependent on the learner's ability to focus on the learning content. Lawson and Mayer (2024) suggest considering the role of executive function: Some learners are more adept at directing their attention than others. Based on our qualitative findings we propose that the opportunity to practice the actual work tasks related to one's own work adds challenge and relevance to the scenario and may facilitate

safety learning by adding a motivational component (Albus et al., 2021; Mayer, 2014). However, attitudinal factors should also be addressed in pre-briefing (Rudolph et al., 2014). We will next provide recommendations for IVR safety training design and pedagogy.

5.1. Recommendations for IVR safety training

First, our findings suggest that high interactivity can support both affective and cognitive safety training outcomes at least partially due to the increased opportunities of embodied learning (Castro-Alonso et al., 2024; Johnson-Glenberg, 2017, 2019). The learners could walk freely on the training area in both experimental conditions. The interviewees' positive remarks reflected their embodied and experiential learning experiences, particularly in the high interactivity scenarios. The hands-on involvement and participation in the training scenario events are likely to have an impact on the learners' perceived agency and safety learning outcomes (Casey et al., 2021; Roussou, 2004). Whereas strictly scripted instructional scenarios may allow for more control for the scenario designer, giving the learners more control over their learning experience seems likely necessary for achieving affective safety training goals. Greater scenario adaptivity to meet the learners' instructional needs, brought on by software and hardware development, could also contribute to more agentic and effective IVR safety training experiences.

Second, the differences in the learners' individual cognitive ability to manage incoming information should be acknowledged (Lawson & Mayer, 2024). The learners reported low ECL in both conditions, which may be interpreted as a successful design of the IVR environment, control interface, instructional delivery, or a combination of these (Albus & Seufert, 2023; Sweller, 2020). However, self-report measures may not capture the mental effort exercised by the learners (Khorasani et al., 2023; Lawson & Mayer, 2024). Several interviewees expressed having difficulty in focusing on the learning content regardless of the scenario interactivity level (see also Khorasani et al., 2023). The learners need to be actively supported in managing their cognitive loads to enable the learning outcomes. We encourage considering the learners' background, level of expertise, and previous IVR experience, and pre-briefing the learners prior to entering an IVR training scenario (Dieckmann et al., 2007; Miguel-Alonso et al., 2023).

Third, high interactivity was associated with increased GCL. Our qualitative findings indicate that engaging and challenging the learners to perform their familiar safety procedures, checks and tasks in the IVR scenarios supports their generative cognitive processing, possibly due to motivational effects (Albus et al., 2021; Mayer, 2014). More research is needed to explore the implications for training transfer, as only short-term learning gains were detected in this study. Based on our findings, we recommend accounting for the influence of the organization and team culture on the learners' and trainers' expectations and attitudes during the IVR scenario development, training implementation, and outcome evaluation (Billett, 2013, 2021; Casey et al., 2021; Moore et al., 2012; Parchoma, 2014; Vygotsky, 1978).

5.2. Limitations and future considerations

A possible novelty effect (Clark, 1983) on the self-reported outcomes cannot be ignored when conducting research on advanced learning technologies such as IVR. The novelty effect is particularly strong with learners who have not encountered the learning technology prior to participating in the study; it influences the learning outcomes by increasing the learner motivation and engagement (Huang, 2020). In the current study, training interventions were carried out for the participants who had relatively little prior IVR experience, particularly in O1. The participants performed two IVR scenarios during their training session, but the training intervention was not repeated with the same participants. The presence of some novelty effect cannot be ruled out in the study results.

Factorial analysis could not be performed on the cognitive load measures due to the small number of questionnaire items. All the items were based on previously published studies, but some meaning may have been lost in translation. Apart from the online interviews, the data collection was carried out in two work organizations, and it was subject to the availability and working shifts of the staff. In O2, the organization-specific scenario contents did not match the participants' work duties and backgrounds as expected. For O2, the study sample was considerably smaller than for O1, which had implications for statistical power. Thus, the comparison of results between the two organizations is difficult.

Embodied learning emerged as a focal angle on the interactivity and learning outcomes in this study (see Petersen et al., 2022). We propose that the learners' perceived embodiment and spatial presence should be studied further along cognitive load and learning outcomes. The learners may prefer learning by doing and experience enhanced learning retention in the high interactivity scenarios (Johnson-Glenberg, 2019; Metcalfe, 2017; Roussou, 2004), but some previous studies indicate that the learners' assessment of their own learning may be inconsistent with the actual learning gains (Fokides & Antonopoulos, 2024; Khorasani et al., 2023). We therefor advocate for developing and applying a more comprehensive approach to measuring the IVR training outcomes and transfer (see Albus et al., 2021; Khorasani et al., 2023; Luo et al., 2021). Larger sample sizes would be desirable for robust statistical analysis. IVR has been studied often using samples of students; instead, we engaged in design-based research with two work organizations. Continuing the working life research collaboration will ensure the contextual relevance of IVR safety training study, and hopefully lead to societal benefits such as increased workplace safety.

6. Conclusions

This mixed-methods study aimed to investigate the learners' sense of agency, cognitive load, and safety learning outcomes by comparing high and limited learner-IVR interactivity in training scenarios. Increased GCL was detected in high interactivity condition. Short-term safety knowledge outcomes were detected in both conditions in O1, but proactive safety behavior self-efficacy increased only in the high interactivity condition. Our qualitative findings suggest that the embodied involvement allowed by high interactivity may support the learners' sense of agency and self-efficacy. Challenging the learners to reflect on their familiar work safety procedures and tasks may add motivational benefits. These conclusions need to be confirmed by further research with larger samples. Nevertheless, we recommend giving the learners more control and autonomy over their IVR learning experience to achieve affective safety training goals in particular. We suggest supporting the learners' cognitive processing by, for example, ensuring the learning tasks' relevance, pre-briefing the learners, and acknowledging their cognitive differences. Considering the sociocultural and contextual aspects of IVR training design, implementation and evaluation is also recommended.

Statement on open data and ethics

This study has been reviewed and approved by the Finnish Institute of Occupational Health's Ethical Committee. Informed consent was obtained from all study participants and they could withdraw their participation at any time. The privacy rights of human subjects within this study are observed through secure storage of all data associated with this study in appropriate protected repositories. The research data is not publicly available due to the data privacy agreement.

CRediT authorship contribution statement

Anu Lehikko: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review

& editing. **Mikko Nykänen:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft. **Kristian Lukander:** Conceptualization, Funding acquisition, Methodology, Project administration, Validation, Writing – review & editing. **Jose Uusitalo:** Software, Writing – original draft. **Heli Ruokamo:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported in part by the Finnish Work Environment Fund grant numbers 210177 and 210182; Fortum Power and Heat; and Stereoscape Ltd. We would like to express our gratitude to the occupational safety and training personnel at both target organizations for their co-operation and efforts during the study. We would also like to thank Dr Maria Tiikkaja and the Virtuario™ VR training platform development team at the Finnish Institute of Occupational Health.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cexr.2024.100066.

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III

Lehikko, A., & Nykänen, M, & Ruokamo, H. (2025). Previous VR Experience Increases Embodiment in Immersive VR Safety Training: An Exploratory Mixed-Methods Study. *Virtual Reality*, *29*, 126. https://doi.org/10.1007/s10055-025-01196-z

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Virtual Reality (2025) 29:126
https://doi.org/10.1007/s10055-025-01196-z

ORIGINAL ARTICLE

Previous VR experience increases embodiment in immersive VR safety training: an exploratory mixed-methods study

Anu Lehikko[1] · Mikko Nykänen[2] · Heli Ruokamo[1]

Received: 24 November 2024 / Accepted: 3 July 2025 / Published online: 30 July 2025
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Abstract
Immersive virtual reality (IVR) appears to hold much potential for educational use in occupational safety training, but the best practices for its pedagogically viable design and application remain unclear. We performed an empirical mixed-methods study on the effects of IVR interactivity design and learner characteristics on the learners' extraneous cognitive load (ECL), sense of spatial presence, and sense of embodiment. The research questions were: (1) "Do learner–IVR interactivity or learner characteristics influence the learners' perceptions of spatial presence, ECL, and embodiment in IVR safety training?" and (2) "What kind of factors influence the learners' training experiences, and how can they be addressed in IVR safety training design?" Two experimental groups were compared using IVR training scenarios designed for either high or limited interactivity. Sixty-eight learners participated in training interventions in two work organizations. Data was collected by questionnaires, video recordings, and interviews. No significant differences between the interactivity conditions were found in statistical analyses. Upon examining the effects of learner characteristics, we found that learners with previous VR experience reported significantly higher embodiment compared with VR novices due to higher self-rated body ownership. The qualitative analysis of the interview data revealed that the VR novices discussed issues related to ECL and a diminished sense of spatial presence more frequently. We offer recommendations for the design and application of IVR for safety training based on the findings.

Keywords Immersive virtual reality · Interactivity · Spatial presence · Embodiment · Extraneous cognitive load · Safety training

1 Objectives

For the last decade, academics and educators have been studying the possibilities of immersive virtual reality (IVR) (Embamby et al. 2018; Hamilton et al. 2021; Pelargos et al. 2017; Safikhani et al. 2022; Wrzus et al. 2024). During the IVR learning experience, the learner is surrounded by a computer-generated virtual environment; it can be accessed and manipulated by appropriate immersion-enabling technologies such as head-mounted displays (HMDs) and hand controllers (Jensen and Konradsen 2018). The IVR learning media appears to support learner engagement and motivation, which makes it well-suited for professional education contexts such as occupational safety training (Abich et al. 2021; Buttussi and Chittaro 2018, 2021; Bödding et al. 2025; Casey et al. 2021; Liu et al. 2022; Makransky and Lilleholt 2018; Makransky and Mayer 2022). However, the media comparison study designs dominating the research field have been affected by methodological weaknesses, leading to conflicting empirical evidence (Lawson and Martella 2023). Shifting the focus onto learning design and learner-treatment interaction studies has been advised in order to discover the best practices and design guidelines for educational IVR (see Buchner and Kerres 2023; Lawson et al. 2024; Luo et al. 2021; Mulders 2023). Mixed-methods research, intervention studies, and design-based research approaches have been recommended in literature reviews (Checa and Bustillo 2020; Luo et al. 2021; Radianti et al. 2020).

✉ Anu Lehikko
alehikko@ulapland.fi

[1] University of Lapland, P.O. Box 122, 96101 Rovaniemi, Finland

[2] Finnish Institute of Occupational Health, Työterveyslaitos, P.O. Box 40, 00032 Helsinki, Finland

Individuals' cognition and perception are focal topics in the study of IVR environments, where the user's perception of their immediate physical environment is replaced by a sensory illusion of being surrounded by an artificial three-dimensional space (Cummings and Bailenson 2016). Wirth et al. (2007) proposed that user's sense of spatial presence is rooted in the sense of self-location—the illusion of being physically and spatially located within the virtual environment—and the perception of action possibilities in the virtual environment. Kilteni et al. (2012) specified that self-location refers to the relationship between one's self and one's body, and that it is just one subcomponent of the user's sense of embodiment: the feeling of having and controlling a body in the IVR. The other subcomponents are user's sense of agency—the subjective experience of intention and motor control—and sense of body ownership: the sensation of possessing a virtual body. Embodiment can be understood to represent the user's perception and experience of the interaction between their cognitive system and the environment (see Castro-Alonso et al. 2024; Heeter 2000).

Current cognitive theories of IVR learning, such as the Cognitive Theory of Multimedia Learning (Mayer 2014) and the Cognitive Load Theory (de Jong 2010; Sweller 2020), apply the concept of *cognitive load*—the demand on the learner's cognitive resources, such as the amount of memory resources and cognitive effort involved in the learning situation. Germane cognitive load is associated with the essential processes of learning. Intrinsic cognitive load is impacted by the complexity of the learning content; previous familiarity with the topic may reduce the learner's intrinsic load. The complexity of the IVR interface and the instructional content presentation may interfere with the learner's ability to process the content during the learning event, generating extraneous cognitive load (ECL) that is considered detrimental to learning—and avoidable by improving the design (Castro-Alonso et al. 2019; de Jong 2010; Kirschner et al. 2018; Schnotz and Kürschner 2007; Sweller 2020, 2023). Distractions originating from the learners' actual physical environment during the learning experience may also contribute to the ECL (Petersen et al. 2022). Evans et al.'s (2024) empirical findings in the context of secondary school education indicate that ECL-inducing instruction may harm the students' autonomous motivation and learning engagement. The Cognitive Load Theory suggests that the instructional methods that initially reduce the learners' cognitive load lose effectiveness with their growing expertise (Schnotz and Kürschner 2007; Sweller 2020).

The possibility for embodied interactivity with and within the environment has been discussed as one of the main learning advantages of IVR, alongside its capability for immersion (Abich et al. 2021; Castro-Alonso et al. 2024; Johnson-Glenberg 2019; Makransky and Petersen 2021; Skulmowski and Rey 2018; Roussou 2004). Petersen et al.'s (2022; see also Makransky and Petersen 2021) Cognitive Affective Model of Immersive Learning is a theoretically and empirically grounded conceptual framework that proposes the existence of relationships and interactions between the key design concept of interactivity and the learners' sense of presence, embodiment, and ECL (see Fig. 1).

According to Petersen et al. (2022), the learners' sense of physical presence is positively influenced by interactivity and negatively influenced by ECL. In turn, presence is theorized to enhance the learner's experience of embodiment—considered by the same authors to have an adverse effect on the learning gains. Physical presence is considered to incorporate the spatial dimension of existing in virtual space (Makransky et al. 2017; Petersen et al. 2022). Previous research indicates that embodiment perceptions may also depend on learners' characteristics, such as their gender (Peck and Good 2024) or previous experiences (Barsalou 2020). The connection between individual-level variables

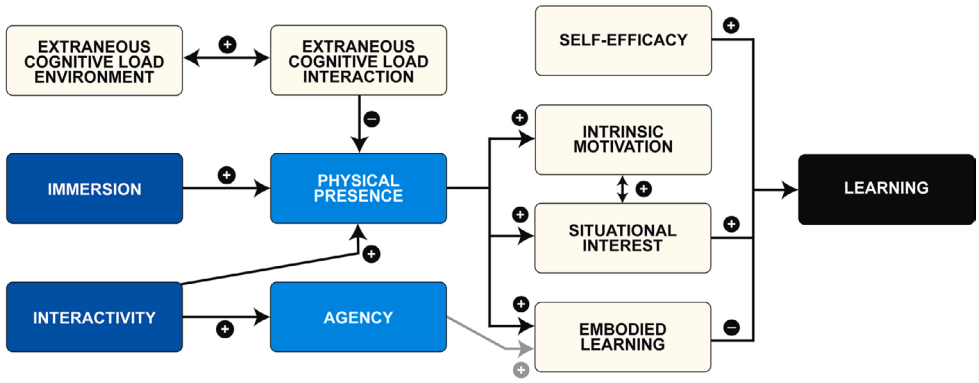

Fig. 1 The Cognitive Affective Model of Immersive Learning (Petersen et al. 2022), reproduced under CC-BY license

and the individual's involvement with media content has been established in media research (see, e.g., Perse 1998; Slater et al. 2009; Wirth et al. 2007). Recently, Laine et al. (2024) discovered in their empirical study that the learners without previous gaming experience experienced significantly more challenges related to the use of functions and controllers in problem-solving centered IVR sessions.

Occupational safety training outcomes and training transfer to daily work practices are not just influenced by the affordances or constraints of the learning media but also by the learners' previous experiences, attitudes, and beliefs that affect their interpretation of the events (Bandura 1997; Billett 2013; Lewin 1947). In IVR safety training, the learners may be expected to buy-in to the experience in a similar way to experiential simulation settings; buy-in is also affected by the learners' previous experiences and individual characteristics (Dieckmann et al. 2007; Muckler 2017; Wirth et al. 2007). In this study, we sought to advance the research on interactivity and learner characteristics in the contexts of IVR safety training and single-user IVR that is accessed by a head-mounted display (HMD) and hand controllers. A mixed-methods exploratory design was applied. Data were collected before, during and after training interventions, and analyzed using appropriate statistical and content analysis methods. Our qualitative findings enabled us to better understand the quantitative results, provided insight on the learners' perceptions and experiences of the training situation, and highlighted training design issues. The findings will contribute to the iteration of a pedagogical model for IVR safety training (Lehikko et al. 2025) in design-based research. The model aims to provide a framework for a pedagogically viable IVR application for safety training practitioners and training providers across industrial sectors and educational contexts.

2 The theoretical framework

2.1 Interactivity

Interactivity is understood as the level of control and immediacy of reciprocal action (Steuer 1992) that are enabled for the IVR user by the software and hardware design: It influences the learner's senses of presence and agency within the virtual environment and impacts on their cognitive processing of the learning content (Dalgarno and Lee 2010; Makransky and Petersen 2021; Petersen et al. 2022). High interactivity may enhance the users' embodied perception of the available affordances, which refers to the action possibilities offered to the IVR user by design (Gibson 2014; Heeter 2000; Klingenberg et al. 2024). According to Conrad et al.'s (2024) literature review, IVR learning environments appear to be most effective in the context of action-oriented learning settings and procedural learning objectives. Currently, the limitations of the consumer-level IVR technologies curb the options for interaction and interface design for procedural learning that involves psychomotor skill development (see, e.g., Klingenberg et al. 2024). For instructional design, interactivity is the key feature for enabling tasks and actions that support learner engagement. The learner–IVR interactivity design affects the availability and range of pedagogical choices and actions within the IVR scenario, and the scenario's suitability for achieving various learning goals. For instance, the design may enable learning by doing—which is not just preferred by many learners but may also be essential for achieving specific learning objectives—or simply learning by observing (see Buttussi and Chittaro 2024; Klingenberg et al. 2024; Roussou 2004; Slater 2017; Won et al. 2023).

2.2 ECL

Perception results from organization: The learner must select the relevant stimuli and make sense of it, which may be taxing in an immersive environment that is rich with distracting factors (Lawson and Mayer 2024; Wirth et al. 2007). ECL arising from, for instance, unintuitive controls, unsuccessful interaction design, or external distractions is considered especially harmful in terms of learning (Lawson and Mayer 2024; Skulmowski and Xu 2022)—and influenced by the IVR design (Baceviciute et al. 2020; Sweller 2020). The content delivery methods (text overlay, text boxes, audio, etc.) may also generate ECL (see, e.g., Skulmowski and Xu 2022). The ECL originating from non-IVR sources, such as external noise or other distractions, should also be recognized and addressed in research and education settings (Petersen et al. 2022). Parong and Mayer (2021) noted that emotional arousal may also induce ECL. Maintaining focus on the learning content can be challenging, especially for an inexperienced IVR user who is simultaneously learning to interact with the system and perform the expected actions in a training scenario (see Klingenberg et al. 2024; Skulmowski 2024; Sweller 2020). Signaling can be used to indicate the relevant learning content to the learners (Albus and Seufert 2021; Castro-Alonso et al. 2019; Skulmowski and Rey 2020); signifiers may be used to help them perceive the available actions in the virtual environment (Gibson 2014; Norman 2013). Tutorials can be used to pre-train the learners to operate the IVR environment and understand its semiotics prior to entering the learning scenario (see, e.g., Chauvergne et al. 2023; Miguel-Alonso et al. 2023). On the basis of their experiments, Lawson and Mayer (2024) proposed that the learners' individual executive function (i.e., their ability to focus their attention on the

IVR content) has an effect on their experienced ECL and the learning outcomes.

2.3 The sense of spatial presence

IVR environments are considered capable of enabling their users with a sense of presence (Slater 2003; Slater and Wilbur 1997). The *sense of spatial presence* refers to the learner's feeling of being convincingly surrounded and immersed in the IVR environment; it is affected by distraction factors such as isolation and interference awareness. Spatial presence has been associated with spatial learning outcomes: It may indicate deeper immersion and thus reduced ECL from the IVR equipment and interface (Parong et al. 2020). The spatial dimension of the presence construct represents the core experience of "being there" within the spatial and temporal constraints of the IVR (Heeter 2000; Schubert et al. 2001). Wirth et al. (2007) theorized that spatial presence is evoked by the users' automatic and involuntary attention, and their controlled attention to the media. The users' mental models have significance: It is possible to vividly imagine one's body and possible actions even in the context of a less immersive media. The attentional processes and sensory inputs enable the user to establish a spatial situation model that, in turn, allows the user to choose over their primary ego reference frame (PERF)—the physical or the virtual. Spatial presence only emerges if the user chooses the mediated PERF (Wirth et al. 2007), which as a concept bears resemblance to Makransky et al.'s (2019) self-presence.

Spatial presence is considered an essential factor in IVR learning (Makransky and Petersen 2021; Petersen et al. 2022), but its exact significance for learning achievements is still unclear. High interactivity may enable engaging features that may increase the learners' spatial presence, but also inflict cognitive load (Makransky et al. 2019; Parong and Mayer 2021). Several factors hampering the users' sense of presence were identified in Jensen and Conradsen's (2018) review study: visual presentation defects such as lagging graphics, sitting body position, awareness of other people watching, and anxious or reserved personality traits. In this study, we consider spatial presence to represent the experiential counterpart of the immersive learning media as is conventional in the field, but we also acknowledge the role of the learner's internal processes in the presence experience, such as the application of imagination during the learning event and the suspension of disbelief (see Muckler 2017; Slater et al. 2009; Slater and Wilbur 1997; Wirth et al. 2007).

2.4 The sense of embodiment

The *sense of embodiment* encompasses the learner's perception of having and controlling a body in the IVR environment (Kilteni et al. 2012; Petersen et al. 2022). It is connected to the representational fidelity of the environment: The sense of embodiment is vulnerable to incongruent mapping of the learner's virtual and physical movements (Makransky and Petersen 2021; Bovet et al. 2018; Pritchard et al. 2016). Kilteni et al. (2012, p. 376) differentiated between the sense of self-location—for instance, inside an avatar—and sense of spatial presence in the virtual space when discussing the dimensions of embodiment, but they also stated that first-person perspective "serves as sensory evidence toward one's self-localization inside the virtual body". Based on their empirical results, Ogawa et al. (2020) proposed that body ownership may even be evoked with abstract self-avatar representations. The IVR environment used in the current study provided abstracted renditions of the hand controllers to cue the user on the location and movements of their hands and arms.

Embodiment has been generally considered beneficial for IVR learning outcomes (Castro-Alonso et al. 2024; Johnson-Glenberg 2019). Recently, some empirical studies (e.g., Khorasani et al. 2023; Klingenberg et al. 2024; Petersen et al. 2022) have challenged this view. In safety training, embodiment may support the learner in focusing on the learning task, increasing training engagement (see Buttussi and Chittaro 2021; Casey et al. 2021; Gao et al. 2019; Wirth et al. 2007). The body ownership component may influence IVR training effectiveness, especially when the training objectives extend beyond declarative goals (Kilteni et al. 2012; Radhakrishnan et al. 2021). Some adverse effects have been discovered in high-risk conditions, where a threat to the learner's virtual body may hinder his or her performance (Shin et al. 2021). Thus, the effect of embodiment on the learning outcomes may depend on the learning objectives, tasks, and contexts, and it may have special significance for IVR safety training design.

2.5 Research questions

The aim of this exploratory field study was to examine the factors that contribute to the learner's experiences in IVR safety training and influence their ratings of the studied constructs, with a primary focus on learner–IVR interactivity and learner characteristics. The research questions (RQ) were:

RQ1. Do learner–IVR interactivity or learner characteristics influence the learners' perceptions of

spatial presence, ECL, and embodiment in IVR safety training?

RQ2. What kind of factors influence the learners' training experiences, and how can they be addressed in IVR safety training design?

3 The method

An exploratory mixed-methods design was applied (Creswell and Plano Clark 2017). We studied the effect of interactivity on the ECL, sense of spatial presence and embodiment that were perceived by the learner. A high level of interactivity between the learner and the IVR environment was hypothesized to increase their sense of spatial presence (H1), ECL (H2), and sense of embodiment (H3) (Dalgarno and Lee 2010; Johnson-Glenberg 2019; Kilteni et al. 2012; Sweller 2020). Learner characteristics were studied by using an exploratory approach. We performed analyses to examine the effect of the learner's gender and previous familiarity with VR. Qualitative data from stimulated recall interviews (STRI) were analyzed to gain insight on the learner's experiences. The preliminary results on the sense of presence and ECL were presented in 2023, and the quantitative results on ECL were presented separately for each participant organization in 2024 (Lehikko et al. 2023, 2024).

Fig. 2 A snapshot from the valve work scenario in 1st person perspective. The learner is standing next to a building. A van is parked on the street on the left. The learner's left hand is slightly raised: A virtual tablet hovers above a blue shape that indicates the position of the hand controller. A pink laser pointer is emitted from the controller. A text box hovers in a small distance, reading: "You have arrived at the worksite, and you start putting up the barriers. You have a tablet in your hand with a map of the worksite for reference." (Picture courtesy of Finnish Institute of Occupational Health)

3.1 The experiment design

3.1.1 IVR equipment, scenarios, and tutorials

The IVR scenarios were built on an IVR training platform provided by the Finnish Institute of Occupational Health using the Unity game engine and 3D graphics tools. Meta Quest 2 wireless HMDs and hand controllers were used to access the IVR environment, which was consistently operated from the first-person perspective. The scenarios were installed on the HMDs in advance. Performing the scenarios required a four-by-four-meter floor area that was flat and free of physical obstructions. The learners could freely walk in the training area due to the wireless setup and 1:1 mapping of their physical movements.

A valve work theme was selected as the thematic backdrop for the IVR scenario as it bore no direct link to the work procedures in either of the participating organizations (see Fig. 2).

By introducing the participants in both organizations to an unfamiliar work setting, we intended to bring them to level in terms of their previous knowledge on the procedures at hand, which may have influenced their cognitive load (see Schnotz and Kürschner 2007; Skulmowski and Xu 2022; Sweller 2023). The main objective in the scenario was to identify occupational hazards encountered during the valve repair process, working from the premise that the general readiness to observe hazards in the work environment is a transferable competency that is useful regardless of the learners' work context. The scenario started in a garage, where the corrective protective work wear was selected. The learner practiced setting up the work site with the aid of miniatures. Next, the location changed to a city street setting where traffic signs and cones were placed before the valve work began. There was occasional passing traffic and pedestrians.

Two scenario versions were developed in order to meet the experimental conditions of high and limited interactivity (Steuer 1992) for a between-groups comparison study design. The same learning content and learning objectives were maintained across the script versions. In the high interactivity condition, the script proceeded by alternating information spots and learning tasks that required the learners to interact with virtual objects. The scenario included some multiple-choice events that enabled making errors and receiving feedback accordingly (Metcalfe 2017). The learners were addressed in second person singular. In the

low interactivity condition, the learners were presented with information concerning the correct procedure instead of the tasks. The scenario script was advanced by interacting with instructional text boxes only. The information was presented in passive voice. The participants were randomized into two experimental groups prior to the training interventions. They performed either the high interactivity version of the valve work scenario (Group A) or the limited interactivity version of it (Group B).

The learners could advance the scenario events at their own pace without a timer or a time limit; each scenario took 15–20 min to complete. A brief tutorial preceded each scenario in order to familiarize the learners with the IVR (Meyer et al. 2019; Sweller 2020). The instructional voice-over and text in the tutorial were modified to reflect the interactivity condition in the scenario. The tutorial content remained the same across the versions: The learner walked around the training area and used their hand controllers to click on a few text boxes in order to advance the script. The signaling principle was applied in order to guide the learners in the tutorials and scenarios (Norman 2013). The location changes both between the tutorial and the scenario, and within the scenario were performed by using fade out, fade in transitions.

The learners also performed a second scenario in the training session. These scenarios were designed and scripted in collaboration with the target organizations to meet their safety training needs; the themes were x-ray luggage inspection and a bridge crane lifting operation. The learning objectives were similar in both organization-specific scenarios: They involved identifying work hazards, using protective equipment, and participating in a work procedure that involved safety checks. The interactivity conditions were reversed between the first and the second scenario to expose all learners to both conditions; however, the questionnaires administered after the scenarios did not share any measures (see Lehikko et al. 2024).

3.1.2 The participants and training procedure

All 68 study participants were recruited on the basis of informed consent by the contact persons in the two collaborating organizations: a government services organization (n = 46) and an energy company (n = 22). All research activities involving the participants occurred during their paid working hours. Twenty-two occupational safety training sessions were held for groups of two to four learners at the participant organizations in 2022. The training sessions followed a pedagogical model where experiential IVR practice is performed individually between pre- and post-briefings in small groups (Lehikko et al. 2025). The sessions were facilitated by the participant organizations' training personnel. The training sessions started with a trainer-facilitated introduction to the training topic and the training structure. A research group member briefed the learners on the IVR equipment, showed them how to adjust it, and ensured that they could wear it comfortably. The learners were advised to ask for assistance if they felt they needed it at any stage, and they were instructed to start the tutorial that continued onto the first scenario. Upon scenario completion, the learners returned the IVR equipment and were guided to another room to fill out a questionnaire. The learners were advised not to discuss their experiences with each other during the scenarios and questionnaires. The process was repeated for a second tutorial, scenario, and questionnaire. The session ended with a trainer-facilitated debriefing in the group setting. Each training session took approximately two hours to complete. The IVR briefing and IVR scenario phases were performed in large spaces that accommodated all the training participants at once. The arrangement made it easier to observe the learners for data collection and their safety.

3.2 Data collection and analysis

3.2.1 Quantitative data

Quantitative data were collected via online questionnaires. Baseline questionnaire (T1) data were collected from 76 participants two to four weeks prior to the training. Due to attrition, 68 persons participated in the training sessions. Eight baseline respondents who did not participate were excluded from the analyses. Sense of presence, ECL, and sense of embodiment measures were administered in a questionnaire (T2A) after the first, valve work themed IVR scenario (see Fig. 3.).

The seven-point Likert scale for the sense-of-spatial-presence measure was based on the Igroup Presence Questionnaire (IPQ) created by Schubert et al. (2001), referencing Witmer and Singer (1994, 1998). Four items from the Spatial Presence subscale of the IPQ were used (e.g., "I felt present in the virtual space," $\alpha = 0.75$). ECL was also measured using a seven-point scale (Klepsch et al. 2017) with two items ("The design of this task was very inconvenient for learning"; "During this task, it was exhausting to find the important information"; $r_{sb} = 0.59$).

The seven-point sense-of-embodiment scale was adapted from the measure developed by Gonzalez-Franco and Peck (2018). It had five items: two for body ownership and three for motor agency ($\alpha = 0.73$). The body ownership items were adapted to reflect the IVR environment design with no visible avatar, where simplified virtual renditions of the controllers indicated the hand and arm movements to the learners (e.g., "I felt as if the virtual controller was a natural part of me"; "It felt as if the virtual controller was

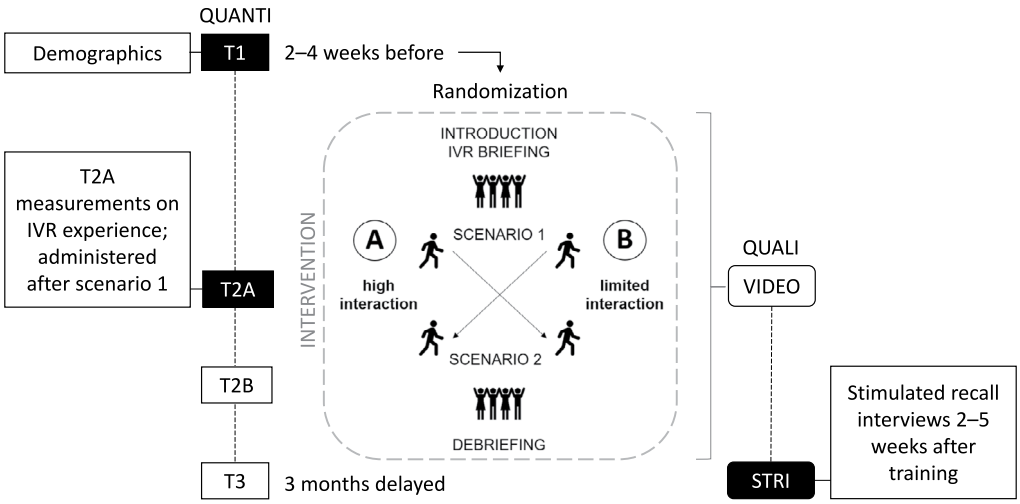

Fig. 3 Training intervention design and data collection. Black labels indicate the data sources of the current study: T1 for the demographics, T2A for IVR related measurements, STRIs for qualitative data

somebody else's"). The motor agency items were similarly adapted for the hand controllers (e.g., "The movements of the virtual controllers were caused by my movements"). All scales were bipolar, ranging from "Totally disagree" (1) to "Totally agree" (7).

Data from both organizations were combined and the questionnaire data were analyzed using statistical methods in SPSS (IBM, US). Questionnaire responses for the key measures were tested for normality in Shapiro–Wilk tests and were found to deviate from normal distributions ($p<0.01$). Hence, non-parametric Mann–Whitney tests were applied in the between-groups analyses.

3.2.2 Qualitative data

Qualitative data were collected from eight training groups by video recordings, observations, and stimulated recall interviews (STRIs) with individual learners. The selection of the dates for qualitative data collection was based on logistic arrangements. The discussion phases were recorded using 360-degree cameras. Other digital video cameras, such as webcams, were used to record the IVR briefing and scenario phases. Individual learners' IVR scenarios were also recorded by their HMDs. The research group selected moments that appeared to be significant for learning from the video material on the basis of the learner actions and vocalizations. To limit the STRI's duration, only one to three video clips per participant were selected and edited into video clips. A thematic STRI protocol, structured according to the training phases, was prepared in advance (see Appendix A).

Online interview arrangements were made after receiving the interviewees' email addresses from the contact person in the respective organization. Twenty-three STRIs were performed 2–5 weeks after the interviewee's training session using the Microsoft Teams online conference tool and recorded by a digital audio recorder. The variance in the interview delay was due to the interviewees' availability and work shifts. Cameras were kept on or off during the interview according to the participants' wishes. The interviewer described the training phases and scenario contents to the interviewee according to the STRI script. Due to technical issues, one interview was performed by telephone, and the video clips could not be displayed to the participant. The training events were discussed verbally instead. Nine interviewees were from Organization 1 (O1) and fourteen from Organization 2 (O2): Out of these, six (67%) and seven (50%) persons, for O1 and O2 respectively, had no previous VR experience (Fig. 4).

The total percentage of novice VR users was 56.5% of all the interviewees. Twelve persons were from experimental interactivity Group A and eleven from Group B. The recorded audio data totaled 18 h 39 min and averaged 49 min per interview.

The audio recordings were transcribed manually by persons employed in a professional transcription service. The transcripts totaled 112,413 words. The transcripts were checked against the audio recordings, and discrepancies and transcription errors were eliminated (Creswell and Plano

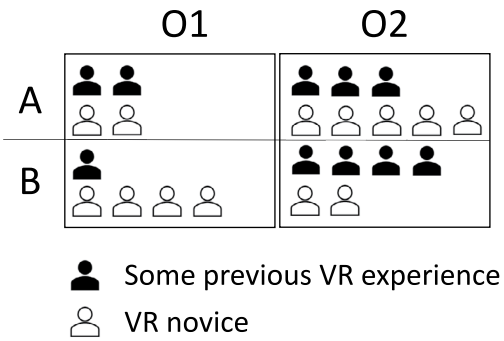

Fig. 4 Interviewees by experimental condition (A/B), organization (O1/O2), and VR experience

Table 1 Qualitative content analysis frame for ECL, spatial presence, and embodiment themes

Theme	Coding reference
Extraneous cognitive load	The learner talks about their ability to access information and to operate the IVR environment (Klepsch et al. 2017; Sweller 2020)
Sense of spatial presence	The learner comments on his or her feelings of being "inside" the IVR environment (Lee 2004; Slater & Wilbur 1997)
Sense of embodiment	The learner discusses their physical, embodied actions and interactions in the IVR scenario context (Pritchard et al. 2016)

Clark 2017). All transcripts were read several times to form a general idea of the contents before starting the analysis procedure. The interviewees made references to their IVR experiences throughout the STRIs; therefore, the content analysis was performed on the full transcript. This approach allowed us to include their comments on both scenarios in the analysis, which enriched the available data.

The transcripts were subjected to both theory- and content-driven content analyses (McDonalds et al. 2019) in the NVivo (1.4, Lumivero, US) analysis software. A framework was prepared in advance for theory-driven content analysis. The themes were selected in accordance with the key constructs and the research question (see Table 1).

The analysis themes were identified in the text using the coding framework. One or more sentences expressing a coherent idea were used as units of analysis (Creswell and Plano Clark 2017). All the analysis themes were discovered in the STRIs. Content-driven analyses was then applied to form thematic subcategories, and to identify negative and positive sentiments in the coded material. In some instances, they were both present in one unit of analysis. For instance, Learner #6 talked about both a high and low sense of presence when discussing why they had decided to walk through a virtual 3D object instead of going around it: The learner explained that they had felt so totally immersed in the start of the scenario that they needed to "awaken" themselves from it. As the coding progressed, the subcategories were edited, occasionally combined or renamed. Coding frequencies were examined using cross-coding matrices between categories and sentiments, and the background factors (such as the experiment group or previous VR experience). The first author performed all the interviews and the initial content analyses. Coding and categorizing were validated by another researcher. Excerpts were selected from the interview transcripts to illustrate the findings (Creswell and Plano Clark 2017).

4 Results

4.1 Demographics

Participants who completed the baseline questionnaire but did not attend the training were excluded from the demographics (see Table 6 in Appendix B). No statistically significant baseline differences (background variables) were detected between the randomized experimental groups A and B. In the between-organizations comparison, the sample size differed noticeably with 46 participants from O1 versus 22 participants from O2. The samples also differed in gender balance and the participants' previous VR experience. The participants' reported age range was 27–65, with a mean age of 41.4. All the training participants indicated either female or male gender in the baseline questionnaire. In O1, 52.2% of the sample were females, in contrast to 18.2% of the O2 sample being females. In terms of previous VR experience, the O2 participants reported more frequent VR use. Less than a third (31.8%) of the O2 respondents had never used VR before, in comparison to over half (54.3%) of the O1 participants. No O1 participants had participated in VR-based workplace learning previously, in contrast to 36.4% of the participants from O2. The percentage of VR novices in the total sample was 47.1%. To form the VR experience comparison groups, the sample was split between the VR novices and those with some experience.

4.2 ECL

4.2.1 Quantitative results on ECL

Upon examining the cognitive load, no significant difference was found for self-reported ECL between the experimental groups (n = 68, 28 females); H1 was not supported. The results were skewed towards the lower end of the scale, indicating a low self-rated ECL (see Table 2).

No differences were discovered in comparisons of groups based on gender ($p = 0.83$, $g = 0.08$, 95% CI [−0.37, 0.55])

Table 2 Extraneous cognitive load across conditions

Measure	High interactivity[a]	Limited interactivity[b]	Mann–Whitney Tests	Hedges'	95% CI	
	Mean (SD)	Mean (SD)	*p*	*g*	LL	UL
ECL	1.84 (0.78)	1.51 (0.54)	.06	0.49	0.01	0.96

[a]$n=33$, [b]$n=35$

LL = lower limit, UL = upper limit

or VR experience ($p=0.38$, $g=0.28$, [−0.19, 0.75]). Thirty-two respondents had no previous VR experience.

4.2.2 Qualitative findings on ECL

Altogether, there were more negative sentiments than positive sentiments associated with the coded units on the ECL theme. However, some positive remarks about the scenario's instructional features were made in eight STRIs. The learners expressed that they enjoyed the ***alternating information spots and learning activities*** scripted into the high interactivity versions.

> I think it was really fun because it had a bit of theory in it, where you read texts, but in between you had… small [activities]. (Learner #1)

Some learners made positive comments on the ***combination of instructional text and audio*** in both the high and low interactivity contexts. The simplicity and responsiveness of the interface, and the possibility of ***proceeding at one's own pace*** were brought up, especially in the limited interactivity scenarios. In total, five learners mentioned that the IVR had felt easy to operate.

> Yes, it was quite simple to use. Which was a good thing—that there wasn't any pointless extra hassle… with it. (Learner #2)

Thirteen interviewees described getting stuck or slowed down during the scenarios. ***A lack of instructions*** was indicated by eleven persons. For instance, two persons failed to find a virtual checklist that supported task completion in the high interactivity versions of the valve work scenario: The checklist was "attached" to the left controller during the task and visible when lifted into one's field of vision. This functionality had not been introduced in the tutorial that only covered the basic interactions, nor was it explained during the scenario:

> Could you tell me more precisely what that checklist is and how to find it?… Can you tell me how you can use that list for help or something? (Learner #20)

In the limited interactivity versions, the interviewees described ***difficulties in understanding the instructions and carrying out actions,*** such as finding the instructional text boxes to click on in order to advance in the scenario script. They felt that these difficulties reduced their ability to focus on the learning material.

> I was probably more concerned with what to do next and where I have to click; maybe that took [my attention away from the task]. (Learner #4)

Nine persons discussed differences between the scripted content and a real-world task or setting. To summarize, several interviewees commented positively on the alternating theory and action that were scripted into the high interactivity scenario (Roussou 2004; Slater 2017) and the combined text and audio instruction (Baceviciute et al. 2020). However, some learners had experienced problems with interpreting the instructional content and advancing in the script regardless of the interactivity condition. Negative comments concerning the instructional arrangements and interactions were frequent in the interview data: There were 91 negative comments identified in total (in contrast to 21 positive remarks) on the ECL-related topics.

The learning tasks in the high interactivity condition required task-specific guidance. Many learners from this group expressed that they felt that they would have benefited from more detailed instruction. Surprisingly, learners in the limited interactivity condition reported similar issues: Several of them had difficulty understanding how to advance in the scenario or where to find the next instructional item to click on. Thus, although the quantitative results implied otherwise, some ECL was evidently inflicted by the instructional design, diverting the learners' attention away from the learning content (Lawson and Mayer 2024).

4.3 Sense of spatial presence

4.3.1 Quantitative results on the sense of spatial presence

The spatial presence results were skewed toward the upper end of the scale in both conditions. However, no significant differences were found between the treatment groups (n = 68, 28 females; see Table 3).

Table 3 Sense of spatial presence across conditions

Measure	High interactivity[a]	Limited interactivity[b]	Mann–Whitney Tests	Hedges'	95% CI	
	Mean (SD)	Mean (SD)	*p*	*g*	LL	UL
SoSP	5.77 (0.78)	6.00 (0.96)	.12	−0.24	−0.72	0.22

[a]$n=33$, [b]$n=35$

LL = lower limit, UL = upper limit

H2 was therefore not supported. No differences were detected in gender group comparison ($p=0.46$, $g=-0.28$, 95% CI [−0.76, 0.19]) or VR experience ($p=0.39$, $g=-0.22$, [−0.69, 0.24]) based comparisons for spatial presence. Thirty-two respondents had no prior VR experience.

4.3.2 Qualitative findings on the sense of spatial presence

All the interviewees commented on topics related to their spatial presence in the IVR environment, and positive factors were identified in 21 STRIs. Eleven learners described ***a state of deep immersion*** by mentioning "being in another world," losing the track of time, and forgetting their actual physical surroundings and the presence of other people in the room. Seven of them were in a high interactivity condition, four were in a limited interactivity condition. The comments were not specifically related to either scenario but directed generally at the IVR experience.

> You sometimes even kind of forgot that you are in a VR world. You get immersed in that world quite deeply straight away. (Learner #1)

Ten learners described ***a feeling of familiarity with the virtual surroundings***; most of these remarks were connected to the organization-specific scenarios. One learner suggested that the similarity between the IVR and reality lowers the threshold for acting on similar hazards in their actual work environment. All but one of these remarks concerned the limited interactivity scenario.

> I did recognize that place… It felt quite real, knowing where you were and what you had to do. (Learner #10)

Also, ten interviewees remarked on how ***moving around physically seemed to enhance the credibility*** of the IVR environment. Six of them commented thus in regard to the high interactivity context.

> You clearly have to take steps… or to be in a certain place and move there by walking; maybe that increases the feeling of reality somehow. (Learner #14)

In Group B, the participants' positive comments were similar, but they often referred to the authenticity of the feeling of physical space surrounding them in the scenario. They suggested that ***movement and the presence of animated objects***, such as the vehicles passing the valve work site, added to the illusion:

> When I was moving in that space… I went carefully behind the van to see if there was anything there… Somehow it felt real, even though you saw it was [computer graphics]. (Learner #19)

> Of course, when… we are in the middle of traffic… it is a situation that feels genuine, [because] there are those moving factors in that world. (Learner #5)

Seven learners expressed a ***strong buy-in***: The tasks they were performing and the objects they interacted with had felt real for them. Three of them made this observation in regard to the high interactivity context.

> I saw real things sometimes, even though it was virtual; there were those crosswalks… and a person arrived. So, I saw it like… [it was] real sometimes. I got into it, which is probably not bad: seeing yourself [to be] in the real situation. (Learner #11)

We also identified elements that led to a compromised physical presence. Ten learners in total remarked that they could ***hear sounds and voice-over from outside their scenario,*** coming from other trainees' HMDs. Eight of them were from O2. Eight learners admitted being distracted by it, trying to find out what part of the scenario the others were in and comparing it with their own performance. Hearing others finish their scenarios made two learners feel that they should hurry up and go faster:

> When there were many people [training] in the same room, you started to hear the sounds of the others, what stage [of the scenario] they were in… That was the only thing that disturbed [my] ability to concentrate. (Learner #18)

> when I heard [from other person's VR sounds] that they had finished, and [I realized that] I still have lots to do, I tried to go more quickly. (Learner #12)

Table 4 The sense of embodiment across conditions

Measure	High interactivity[a]	Limited interactivity[b]	Mann–Whitney Tests	Hedges'	95% CI	
	Mean (SD)	Mean (SD)	*p*	*g*	LL	UL
Sense of embodiment	5.65 (0.79)	5.67 (0.84)	.91	−0.55	−1.03	−0.06

[a]$n=32$, [b]$n=34$

LL = lower limit, UL = upper limit

Table 5 The sense of embodiment for participants with no previous VR experience vs. those with some VR experience

Measure/component	No experience	Some experience	Mann–Whitney Tests	Hedges'	95% CI	
	Mean (SD)	Mean (SD)	*p*	*g*	LL	UL
Sense of Embodiment[a]	5.43 (0.93)	5.87 (0.63)	.03	−0.55	−1.03	−0.06
Body Ownership[b]	5.09 (1.19)	5.72 (0.91)	.02	−0.60	−1.08	−0.11
Motor Agency[c]	5.67 (0.93)	6.00 (0.64)	.23	−0.38	−0.86	0.10

[a]No experience $n=31$, some experience $n=35$

[b]No experience $n=32$, some experience $n=35$

[c]No experience $n=31$, some experience $n=36$

LL = lower limit, UL = upper limit

Ten learners expressed having generally ***low buy-in*** during the scenarios. They did this, for example, by drawing comparisons to gaming or mentioning purposefully walking through virtual objects.

> I knew that [the moving object] would come towards me, I stayed in the way on purpose. (Learner #17)

Eight learners talked about specific ***perceptual discrepancies between the real world and the IVR environment***, such as the limited field of vision, which made the virtual experience less credible, or physical sensations that did not match the visuals. Four of these learners felt that the graphics quality was too low to create a convincing illusion. The real and the virtual had clashed in the form of bodily sensations for two learners.

> I was supposed to step over to the sidewalk. I did… and then I realized that I couldn't really step up [higher], that it's just this [virtual] world. (Learner #6)

One person remarked that the scenario lacked spoken interaction between people, which made the soundscape differ from the real-world work task.

The qualitative analysis revealed that similar factors may have influenced the learners' sense of presence regardless of the interactivity condition: their degree of immersion and scenario buy-in. Their perception of movement in the 3D space may have supported the presence illusion (see Johnson-Glenberg 2019; Pritchard et al. 2016). Domain-specific interest evoked by the familiar tasks and environments possibly provided some motivational benefits that supported the learners' controlled attention to the immersive media and contributed to their spatial presence (Slater et al. 2009; Wirth et al. 2007). Nevertheless, external distractions originating from their physical environment diverted some learners' attention (Parong et al. 2020). The distractions stemming from the training arrangements were also a source of ECL (Petersen et al. 2022) and were likely to interfere with the learners' ability to select and process the relevant learning content (see Lawson and Mayer 2024).

4.4 Embodiment

4.4.1 Quantitative results on embodiment

The embodiment measurements were skewed towards the higher end of the scale in both conditions. No significant difference was found in a between-conditions comparison (n = 66, 27 females); H3 was thus not supported (see Table 4).

No differences were found upon gender-based comparison ($p=0.96$, g = 0.00, 95% CI [−0.49, 0.49]). In the comparison based on VR experience, a stronger sense of embodiment ($p=0.03$, g = −0.55, [−1.03, −0.06]) was discovered for the learners with previous experience. Upon further examination, the difference was found to stem from the body ownership component of the measure. No significant difference was observed in the motor agency component (see Table 5).

Multiple linear regression was performed to test if ECL, spatial presence or VR experience predicted body ownership ($R^2=0.336$, $F(3, 63)=10.61$, $p<0.001$) (see Figs. 5 and 6).

Pearson correlation coefficients were computed to examine the linear relationships between the variables. Negative correlations were discovered between ECL and body ownership—$r(65)=-0.46$, $p<0.001$—and between ECL and spatial presence—$r(65)=-0.30$, $p=0.005$. Positive correlations were found between spatial presence and body

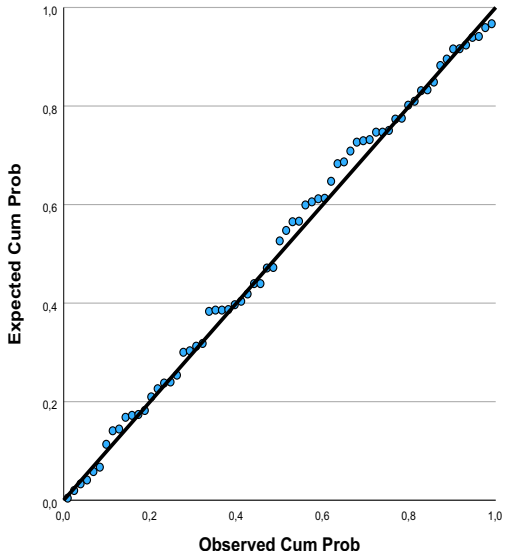

Fig. 5 Normal P-P plot of linear regression for body ownership

ownership—$r(65)=0.40$, $p<0.001$—and between previous VR experience and body ownership—$r(65)=0.29$, $p=0.008$. No additional linear relationships were discovered between VR experience and other variables. VR experience ($\beta=0.209$, $p=0.049$), ECL ($\beta=-0.357$, $p=0.002$) and spatial presence ($\beta=0.265$, $p=0.016$) were found to predict the body ownership score. Multiple linear regression was also performed on the same variables with spatial presence as the dependent variable ($R^2=0.179$, $F(3, 63)=4.59$, $p=0.006$). Only body ownership was discovered to significantly predict spatial presence ($\beta=0.332$, $p=0.016$) in this regression.

Mediational analyses were performed using the Hayes PROCESS macro (e.g. Igartua and Hayes 2021) (Fig. 7).

A mediational analysis—for spatial presence as the dependent variable and body ownership as the mediator—revealed that VR experience ($\beta=0.499$, $p=0.037$) and ECL ($\beta=-0.689$, $p=0.000$) had significant effects on body ownership, which in turn had a significant effect on spatial presence ($\beta=0.262$, $p=0.017$). ECL had a non-significant direct effect ($\beta=-0.200$, $p=0.227$) on spatial presence in the presence of the mediator. The Sobel test confirmed that body ownership significantly mediated the relationship between ECL and spatial presence ($z=-2.09$, $p=0.03$).

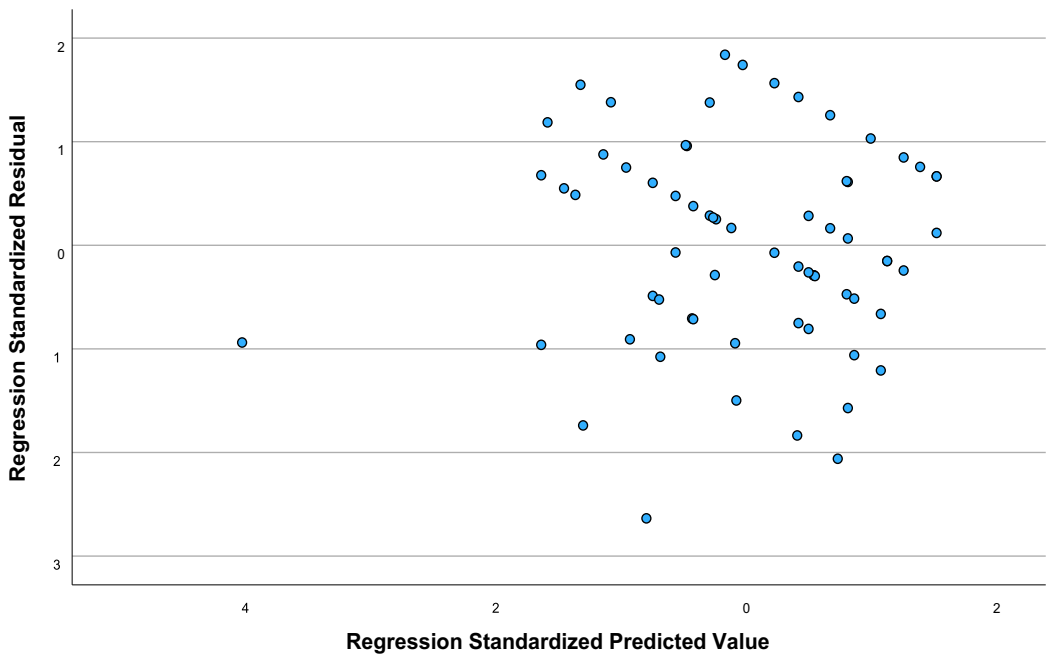

Fig. 6 Scatterplot for linear regression for body ownership. One outlier exceeds Cook's distance

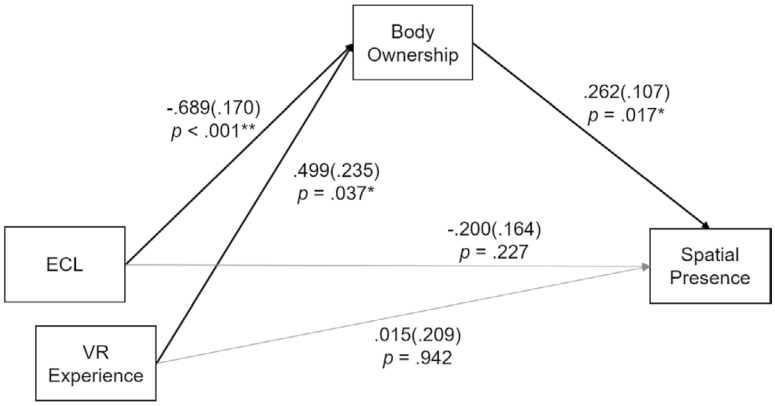

Fig. 7 Mediational model with ECL as the independent variable, VR experience as a covariant, body ownership as a mediator, and spatial presence as the dependent variable. Unstandardized coefficient, standard error, and p-value are reported for each path. Significant effects are represented by darker connectors

4.4.2 Qualitative findings on embodiment

In the qualitative data, there was a strong overlap between the interviewees' remarks on their sense of spatial presence and descriptions of their embodied actions in the IVR. The interviewees talked about looking around in the virtual environment and performing the tasks and operations typical for similar real-world environments. Discussing ***convincing spatial illusions*** overlapped with the expressions of increased presence (see Kilteni et al. 2012). The coding matrix analysis revealed that the learners often made references to their ***physical actions*** in the contexts of equipment, interface, or instructional issues—contributing to the ECL—and diminished presence, such as in the case of low scenario buy-in. Thirteen learners explicitly discussed their positions, actions or sensations in relation to the virtual space; this was interpreted to signal ***body ownership***. Interestingly, six interviewees brought up their perceptions of the available physical space within the scenario, often in the context of their own or other people's bodies.

> It was quite small, that room with the x-ray machine... if there had been any passengers [in the room], it would have been too small. Luckily, there was only the machine, me, and the [virtual] colleague… (Learner #9)

The scenarios had not been scripted to cause discomfort or distress to the learners, but the proximity of large, moving virtual objects appeared to diminish four learners' sense of physical safety:

> I was situated in a way that I was kind of entrapped in there. That's what I think I felt. (Learner #13)

> And then suddenly, when you look in that direction, there's a car; like, uh-oh, my head is in the lane and there is a van coming towards me. Is my head about to come off? That was a good whoopsie-daisy moment. (Learner #1)

The interviewees' remarks on possible physical danger, which sometimes appeared in tandem with the spatial contexts, appear to be aligned with the proposed body ownership and self-location components of the sense of embodiment; the references they made to their bodily actions within the IVR may reflect the agentic component of the construct (Kilteni et al. 2012). The number of spatial and bodily references was surprisingly high considering that the learners had no visible avatars or virtual bodies in the scenarios. Some learners also expressed that they had deliberately resisted the embodiment illusion which can be understood as a deliberate choice in the favor of the real-world ego reference frame (Wirth et al. 2007).

To better understand the quantitative results concerning the correlations of the key constructs and the learners' previous VR experience, we examined the interviewees' background attributes for the qualitative data. Matrix analyses indicated that the VR novices, in particular, had struggled with issues concerning the equipment and the interface, such as ***adjusting to the controls and movement*** in the IVR. They had also experienced ***pressure from the scripted instructions***, and appeared to have felt that their ***focus was directed at clicking on the text boxes*** more frequently than more VR-experienced learners. These challenges are similar to the ones reported by Laine et al. (2024). The mentions of the environment being "easy to use" mostly came from the VR-experienced interviewees. In addition, the VR novices dominated the coded references to spatial presence by a 3:2 ratio, overrepresenting their group. They discussed topics related to ***poor buy-in*** and ***IVR–real world***

discrepancies more frequently compared with their more seasoned colleagues.

5 Discussion

We sought to find out if learner–IVR interactivity or learner characteristics influence the learners' perceptions of spatial presence, ECL, and embodiment in IVR safety training (RQ1). We performed between-group comparisons using two IVR scenario versions that differed in their scripted interactivity: In the limited interactivity version, the learner could only interact with the instructional text boxes, and the storyline did not involve them in the learning tasks. The high interactivity version contained active involvement in learning tasks and the possibility to err in multiple-choice selections. According to the quantitative results, the differences in the interactivity design did not influence the learner's ECL (H1), sense of spatial presence (H2), or sense of embodiment (H3), leaving our three hypotheses unsupported (Tables 2, 3, 4). It should be noted that the reliability for the ECL measure was low (r_{sb} = 0.59). Our qualitative findings indicated that the measure may not have reliably reflected the learners' cognitive effort during the scenario (see Khorasani et al. 2023; Lawson and Mayer 2024).

Additionally, the learners appeared to have experienced similar interface-related and instructional challenges in both experimental conditions, which may have contributed to the lack of pronounced differences between the groups for H1. The results for H2 and H3 could also be interpreted as an indication of successful design and execution of value-added learning media research: The two conditions were similar enough for the participants to rate their spatial presence and embodiment somewhat consistently (see Lawson and Martella 2023; Mayer 2024). According to the qualitative findings, the learners were able to experience deep immersion, spatial presence and buy-in regardless of the scenario's interactivity level.

The key constructs were explored further by grouping the learners by gender and by previous VR experience. No gender effects were found in the between-groups comparisons, but the learners with at least some VR experience were discovered to have reported a significantly stronger sense of embodiment due to higher ratings on the body ownership component of the measure (Table 5). Linear regressions were performed to investigate the relationships between the variables. Significant positive correlations were found between VR experience and body ownership, and between spatial presence and body ownership. The scales for VR experience and the measured constructs were not identical which likely caused some deflation in the calculated Pearson correlation coefficients (Metsämuuronen 2023). In contrast, ECL was discovered to have a significant negative correlation to body ownership and to spatial presence. The detrimental effect of ECL on spatial presence has been established in previous literature (e.g. Makransky and Petersen 2021; Petersen et al. 2022). In mediational analyses, the influence of previous VR experience on body ownership was found to be significant in a mediational model where body ownership mediates the effects of VR experience and ECL on spatial presence (Fig. 7).

Our results indicate that previous VR experience—or not having any—is a focal learner characteristic that should be considered in IVR safety training implementations and designs. The results suggest that the relationships and interactions between ECL, body ownership and spatial presence may warrant further empirical research. We also aimed to discover what kind of factors influenced the learners' training experiences in order to gain insight into how these factors may explain our results, and to incorporate the findings into recommendations for IVR safety training design (RQ2). The qualitative content analysis of the STRI data led to several key findings that, combined with theoretical viewpoints, provide insight into the quantitative data and the results of the mediational analysis. These insights are discussed in the following sections and some recommendations are made to accommodate IVR training for the VR novices in particular.

5.1 Minimize ECL inflicted by interface and instructional design

The VR novices did not self-report significantly more ECL in the group comparison; however, the result may have been influenced by the low reliability of the ECL measure. A matrix analyses of the coded frequencies for ECL related issues revealed that the VR novices struggled with the controls and the logic of operating the IVR scenario more often than those with previous experience. Some of them felt that the mechanics of the interaction (finding and clicking on instructional text boxes) took their focus (Table 6).

The unfamiliar equipment and interface further taxed the VR novices' working memory capacity (see Skulmowski 2024; Sweller 2020). Instructional deficits may have reduced the learners' motivation (Evans et al. 2024) and caused emotional arousal, inflicting ECL (Parong and Mayer 2021). These factors possibly undermined the VR novices' ability and willingness to accept a virtual PERF and apply suspension of disbelief to uphold the spatial illusion (e.g. Petersen et al. 2022; Wirth et al. 2007), reflected in the results of the mediational analysis. ECL may also originate from sources outside the IVR (Lawson and Mayer 2024; Petersen et al. 2022). Learners from both experimental groups reported being distracted by the sounds of other

Table 6 Findings from the STRI's by theme, category and frequency (n = 23; VR novices 56.5%)

Theme	Category	n	f	%
ECL	Instructional issues	19	79	59.5
	Trouble finding next item	13	25	68.0
	Instructions were inadequate	11	22	45.5
	Clicking on text boxes	10	16	75.0
	Content vs reality	9	13	38.5
	Felt pressure from instruction	2	3	100.0
	Equipment and interface issues	14	31	80.6
	Adjusting to controls/movement	9	18	83.3
	IVR control issues	8	9	66.7
	Equipment issues	2	4	100.0
	Pleased with experience	10	20	50.0
	IVR instructed me	8	12	66.7
	IVR felt easy/simple to use	5	8	25.0
Sense of Spatial Presence	Supported presence	21	57	60.0
	Felt fully immersed	11	17	58.8
	Familiar environment	10	17	58.8
	Movement boosted credibility	10	12	66.7
	Strong buy-in	7	11	63.6
	Diminished presence	18	46	58.7
	Heard others' scenario sounds	10	18	33.3
	Poor buy-in	10	17	76.5
	IVR-real world discrepancies	8	10	80.0
Sense of Embodiment	Convincing spatial illusion	19	35	57.1
	Physical action references	17	32	56.3
	Body ownership	13	18	61.1

n = number of interviews with coded units of analysis in category; f = frequency of coded units of analysis within category; % = f percentage of VR novices' coded units of analysis

participants' scenario narrations in the same room, which likely diminished their sense of spatial presence (Parong et al. 2020). The sounds of the other learners' headsets enabled some learners to compare their performance to others, which caused them to proceed more hastily and with less attention to the learning content.

To reduce the ECL inflicted on the learners we recommend **actively eliminating external distractions** during IVR practice. The findings indicated that **instructional clarity** is pivotal regardless of the interactivity design (see Johnson-Glenberg 2019; Laine et al. 2024; Parong and Mayer 2021; Sweller 2020). Both instructional clarity and support for autonomy are pedagogical aspects of the IVR design that influence the learners' motivation (Evans et al. 2024). **Scaffolding should be provided** both inside and outside the IVR environment: The learners may benefit from a combination of pre-briefings and tutorials that cover the interaction methods, instructional scaffolds, and semantics applied in the training scenario (Chauvergne et al. 2023; Johnson-Glenberg 2019; Miguel-Alonso et al. 2023; Mulders et al. 2020).

5.2 Provide attentional and motivational support for body ownership

Previous VR experience was the only learner characteristic included in this study that was found to influence the sense-of-embodiment results, due to the more experienced learners' higher self-ratings for the body ownership dimension of the measure (Table 5). In accordance with the questionnaire items in our study, body ownership translated into perceived fluidity and ease of use of the hand controllers, reflecting the habituation and more efficient functioning of the "embodied interface" between the learners' cognitive system and the virtual stimuli (Heeter 2000). We suggest that body ownership is linked to the primary ego reference frame (PERF) described by Wirth and colleagues (2007); it may thus depend on learner attributes and the IVR features that are connected to attentional guidance. Based on their more frequent mentions of ease of use (Table 6), the learners with prior VR experience appeared to use their cognitive resources more effectively in operating and controlling the embodied IVR experience (see Lawson and Mayer 2024; Skulmowski 2024). Their ability to switch between the physical and the mediated PERF likely contributed to the significant effect of previous VR experience on body ownership found in the mediational analysis. Furthermore, the VR novices expressed low scenario buy-in and brought up the IVR–real world discrepancies more frequently (Table 6). We propose that motivational and attentional factors may have contributed to the insignificant direct effect of VR experience on spatial presence.

Familiar surroundings—in this context, virtual spaces that reminded the learners of their familiar work locations—were frequently referred to in tandem with spatial presence in the interviews. Liu et al. (2023) found that a meaningful emotional connection to the virtual place reduced the participants' negative affect and correlated with their spatial presence. **Real-world based features in scenario design** may increase the learners' domain-specific interest (Wirth et al. 2007) and support their affordance perception according to the signaling principle (Skulmowski and Rey 2020). The familiarity of the spatial cues could add motivational benefits (Mayer 2014) and increase situational interest (see Petersen et al. 2022; Wirth et al. 2007) which helps the learners to maintain attentional focus. We also recommend the instructional practice of **giving VR novices repeated practice sessions to build competence** (see Laine et al. 2024). **Learner-centric facilitation during pre- and post-briefings** may increase training relevance and the learners' motivation (Lehikko et al. 2025; Ryan and Deci 2000), and support buy-in by contributing to the psychological safety of the training situation (Muckler 2017).

Many interviewees discussed feeling convincingly situated within the IVR environment regardless of their experimental group or gender. Despite of the simplified graphics in the IVR environment used in the study—criticized by some learners—movement and animation in the virtual environment appeared to contribute to the spatial illusion even in the limited interactivity condition (Johnson-Glenberg 2019; Pritchard et al. 2016). IVR may elicit strong affective responses and spatial presence in the learners by presenting a captivating sensory environment that speeds up the self-relevant attentional processing of salient virtual events, such as potential threats in IVR (Schöne et al. 2021; Wirth et al. 2007). Based on our findings and the research literature, the body ownership illusion could be supported in interactivity design by utilizing the learners' innate perceptual capacities: for instance, **selectively applying motion and flicker cues** to call attention to specific locations and events (Holcombe 2023; Theeuwes 2010; Wirth et al. 2007).

5.3 Limitations

This study is subject to several methodological limitations. Participant recruitment was not directly performed by the researchers; instead, company contact persons were responsible for this task. This arrangement diminished the researchers' ability to control the outcome of the recruitment process. The small number of participants is a clear limitation for the statistical robustness of the quantitative results. The quality of the measurements may also present a problem. Several authors (e.g., Fokides and Antonopoulos; 2024; Khorasani et al. 2023; Lawson and Mayer 2024) have pointed out that self-reported data in IVR research are subject to validity issues, for instance, due to the variance in the study participants' individual capabilities, and other underlying factors affecting their perceptions and self-assessments. No objective measures, such as skin conductance or heart rate, were employed, and the study did not employ a repeated-measure design.

All measures were based on instruments previously published in English: The items were translated into the learners' native tongue and some meaning or nuance may have been lost in translation (see Endres et al. 2025). Tran et al. (2024) have recommended using the full 14-item IPQ questionnaire instead of selected subscales or items, such as those for spatial presence, to capture all dimensions of the presence construct. The embodiment measure was adapted to suit the avatarless IVR environment which may reduce the comparability of the results to experiments utilizing avatars. The learners' cognitive abilities, such as individual differences in working memory (see Lawson and Mayer 2024), were not measured at baseline. The ECL measure only had two items, and its reliability was low (r_{sb}=0.59). Thus, the quantitative results on the learners' ECL should be treated with caution. The mediational model between ECL, body ownership and spatial presence presented in this explorative study should be considered mostly a thought experiment that needs further empirical validation.

Both individual and contextual factors should be accounted for in the study of IVR learning and training design. In the current study, qualitative data was used to illuminate the facets of the learners' IVR experiences that may have contributed to the quantitative results, and to explain these in the Discussion. STRI data collection was arranged according to the availability of the interviewees over a period of 2–5 weeks after the interventions. However, the interview method was effective for eliciting recollections of their experiences and actions in the IVR scenarios. Overall, the interviewees appeared to remember the training scenarios better than the pre- and post-briefing group discussions. The interview durations remained consistent. The initial coding process was performed by one researcher, and the codes and categories were validated by another research group member. Triangulation by engaging multiple coders from the start would have enabled inter-coder reliability assessments, and may have increased the validity and reliability of the findings.

5.4 Future directions

Currently, the evidence on the role of spatial presence in IVR learning is inconclusive. This study did not discuss learning outcomes and transfer; however, our findings indicate that the constructs of embodiment and spatial presence may be intertwined over the body ownership dimension. Klingenberg et al. (2024) found no favorable effect on learning transfer in their study, but the learners reported higher agency, presence, and embodiment in IVR regardless of the immersion and interactivity conditions. The learner's sense of presence may be crucial for spatial learning (Parong et al. 2020), and the learners' active and embodied involvement is considered to support both declarative and procedural learning outcomes (Castro-Alonso et al. 2024; Conrad et al. 2024). However, Khorasani et al. (2023) discovered in their empirical study that the learners' ability to move around in the IVR when instructed on how to perform a procedural task did not lead to superior learning results when compared with a condition where they were seated. In future research, spatial presence, ECL, embodiment, and body ownership should be scrutinized further in the context of different kinds of learning tasks and objectives in order to discover the best practices and designs to support learning outcomes (see Castro-Alonso et al. 2024; Klingenberg et al. 2024). The study of these constructs could benefit from combining more varied sources of data, such

as physiological measurements and interview data, with a longitudinal research design (see Ratcliffe and Tokarchuk 2021; Skulmowski and Rey 2017).

Based on our findings, assuming body ownership in the virtual environment may be easier for those with previous VR experience. The contributing factors should be examined in future research. Studying the role of learner characteristics and abilities, such as their previous IVR experience and cognitive executive function, is strongly recommended (see, e.g., Buchner and Kerres 2023; Laine et al. 2024; Lawson and Mayer 2024). The learner trait of *absorption*—their disposition for experiential engagement with attentional objects—should also be considered in conjunction with the learners' buy-in, attention and motivation (see Wild et al. 1995; Wirth et al. 2007). The instructional and pedagogical aspects of IVR design, such as learner guidance and motivational elements in the training scenarios, should be examined further. One possible research avenue is to explore whether attentional guidance by using visual and spatial indicators that are familiar from our physical surroundings—such as signs, arrows, lines or footprints placed on the virtual floor—can inflict less ECL, and support the novice users' affordance perception (Gibson 2014; Norman 2013; Skulmowski and Rey 2020). Adaptive signaling that responds to the learners' instructional needs could enable more engaging and relevant learning experiences. The best ways to implement individual adaptive features in the IVR learning environments are yet unclear and should be subjected to empirical study, preferably with larger sample sizes for generalizing the results.

6 Conclusion

The aim of this mixed-methods research was to study whether learner–IVR interactivity or learner characteristics influence the learners' ECL, spatial presence, and embodiment. According to the results, learner–IVR interactivity did not have an effect on the learners' self-ratings on the studied constructs. Learners with previous VR experience reported a significantly stronger sense of embodiment due to their higher ratings on body ownership. Our qualitative findings revealed that a lack of instructional clarity may have contributed to ECL in both conditions. External distractions also inflicted ECL and likely weakened the learners' sense of spatial presence. Furthermore, the VR novices discussed low scenario buy-in and IVR–real world discrepancies more frequently. Based on our findings, we recommend minimizing the sources of ECL and providing instructional support to the VR novices both inside and outside the virtual environment. We conclude that IVR safety training designs should include attentional guidance, motivational elements—such as familiar surroundings—and learner-centric instruction to help the VR novices exercise suspension of disbelief, and support their perceptions of body ownership and spatial presence.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10055-025-01196-z.

Acknowledgements We would like to express our gratitude to all collaborators and staff in the research institutions and the participating organizations, with special thanks to the Virtuario™ VR training development team at the Finnish Institute of Occupational Health.

Author Contributions Conceptualization: Anu Lehikko; Methodology: Anu Lehikko, Mikko Nykänen, Heli Ruokamo; Formal analysis and investigation: Anu Lehikko; Writing—original draft preparation: Anu Lehikko; Writing—review and editing: Anu Lehikko, Heli Ruokamo; Funding acquisition: Anu Lehikko, Mikko Nykänen, Heli Ruokamo; Validation: Mikko Nykänen; Supervision: Heli Ruokamo

Funding This work was supported by the Finnish Work Environment Fund (Grant Numbers 210177 and 210182), Finnish Institute of Occupational Health, University of Lapland, Fortum Power and Heat, and Stereoscape Ltd.

Data availability The research data is not publicly available due to the data privacy agreement.

Declarations

Ethical statement This study has been reviewed and approved by the Finnish Institute of Occupational Health's Ethical Committee.

Competing interests The authors declare no competing interests.

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