Examining the Use of Virtual Reality (VR) Technology in Health and Safety Training within Hazardous Work Environments: A Scoping Review

Avni Jain

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Abstract

Hazardous working environments in industries such as oil and gas, mining, chemical, construction, and firefighting pose significant risks to employees' health and safety, for which an effective training program is required. Conventional training methods often fail to adequately prepare employees for the dangers and complexities of these environments. Virtual reality (VR) technology has emerged as a promising solution that simulates real-world scenarios without exposing trainees to real-life consequences. This dissertation uses a systematic literature review approach to assess the efficacy of VR technology in hazardous working environments. The review collates and synthesises 20 peer-reviewed journal articles using qualitative, quantitative, and mixed methods. The articles examine the effectiveness of VR on knowledge acquisition and retention, engagement, and sense of presence. The review findings identify benefits such as enhanced user engagement, sense of presence, motivation, and knowledge retention, which are higher in immersive VR environments than non-immersive ones. The review identifies limitations, including a lack of longitudinal research, challenges in transferring acquired skills to real-world applications, and demographic factors such as age, gender, and digital literacy. Insights from this review aim to guide future research and improve the practical use of VR technology in health and safety training in hazardous work environments.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Author's signature: **Avni Jain** Date: 14/08/2024

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Chapter 1: Introduction

Hazardous working environments are typical in mining, oil and gas, chemical, and construction industries. These industries involve high-risk tasks, exposure to dangerous elements, and complex operations, which usually make them prone to accidents and occupational hazards. The health and safety of employees should be the priority for any organisation in these industries (Abotaleb et al., 2023; Chan et al., 2023). For instance, employees in the oil and gas industry face risks such as explosion, fire, exposure to toxic gases, and harsh conditions at the plant site (Haridoss, 2017). As an example, the workforce responsible for well drilling, an area of high risk, reports hundreds of fatalities or accidents annually during the drilling operation, whether on the land surface or seabed (Asad et al., 2022). Similarly, the construction industry experiences statistically alarming numbers of injuries and fatalities every year (Feng et al., 2023). This poor track record is due to the involvement of high-risk activities such as working at elevated heights and in complex and frequently changing environments (Jacobsen et al., 2022). According to the International Labor Organization (ILO), approximately 60,000 fatal accidents happen annually at construction sites (Habibnezhad et al., 2021).

Furthermore, mining operations, particularly in confined spaces and on unstable ground, expose workers to severe risks such as malfunctioning machinery, exposure to harmful dust and gas, and the possibility of structural collapses, which can occur without warning and pose life-threatening dangers (Fajar, David, et al., 2022; Feng et al., 2023). This high level of risk is reflected in the fact that at Kompania Weglowa S.A., Europe's largest coal mining company, miners are injured in 18% of all workplace accidents (Grabowski & Jankowski, 2015). Such collapses, including trench failures, were a major cause of mining-related fatalities in the United States, resulting in 332 deaths between 2011 and 2018 (Feng et al., 2023). Similarly, in the chemical industry, employees face significant threats from hazardous substances, including chemical spills, explosions, and exposure to toxic materials and gases, further emphasising the high-risk nature of these working environments (Chan et al., 2023). Therefore, safety training is necessary and constitutes an integral component of a safety management system for organisations in hazardous working spaces (Chan et al., 2023).

Thus, there is an increasing need to enhance the effectiveness of safety training for employees in these hazardous working environments (Pedram et al., 2021). So, to effectively minimise casualties, the workforce should be trained to acquire life-saving skills and injury/illness prevention, develop necessary mental preparedness and gain firsthand experience of the dangers they might encounter at the time of an actual emergency (Backlund et al., 2007). Conventional training methods include classroom lectures, videos and printed safety manuals. These methods involve a unidirectional flow of information in which a trainer teaches or guides trainees. The advantage of this approach is that a considerable amount of information can be delivered to trainees quickly. However, conventional methods can be ineffective because trainees learn passively, which can lead to boredom and decreased attention spans

(Blair & Seo, 2007; Fivizzani, 2005). Other standard safety training methods include on-the-job and hands-on training or real-life drills where trainees get exposure to practical activities, encouraging active participation in the learning process and enhancing decision–making skills through experiential learning (Bhide et al., 2015). Experiential learning is "the process whereby knowledge is created through the transformation of experience" (Kolb, 1984, p.41). However, real-life drills present considerable limitations such as time, cost, and safety constraints (Hsu et al., 2013). For instance, if the trainee makes a mistake during real-life drills, it could have costly or even fatal consequences.

Due to challenges associated with experiential learning in conventional training programs, learning approaches related to technology have grown significantly (Fromm et al., 2021). In these approaches, the trainee's interaction with the objects, trainer, and colleagues is facilitated by information technology (Alavi & Leidner, 2001). Virtual Reality (VR) is a promising alternative for training in hazardous working environments because it does not present the health and safety constraints of traditional methods. Originally, VR was defined by Sutherland (1965, p. 508) as "Ultimate display", comparing it to an inter-dimensional window similar to the "wonderland into which Alice walked" (Pedram et al., 2021, p. 1). Arguably, VR's greatest strength lies in its ability to simulate experiences which closely resemble real-life events (Pedram et al., 2020). This simulation-based training method allows the trainees to gain hands-on experience by actively engaging in safety practices within the realistic virtual working environment (Bhide et al., 2015). This allows them to learn from their mistakes without facing real-life consequences.

Recently, there has been a trend towards employing virtual reality (VR) technology for health and safety training in industries such as mining, oil and gas, construction, fire safety and chemical (Asad et al., 2022; Chan et al., 2023; Feng et al., 2023; Nykänen et al., 2020; Saghafian et al., 2020). Findings on the effectiveness of VR technology in health and safety training in hazardous working environments are inconsistent. Some studies demonstrate positive outcomes (Dhalmahapatra et al., 2021; Pedram et al., 2020; Rey-Becerra et al., 2023). On the other hand, some studies indicate it should be used as a complementary training solution rather than a substitute for traditional training programs (Abotaleb et al., 2023; Pedram et al., 2021).

Thus, through an integrated review (Cronin & George, 2023), I synthesised and evaluated the literature on the effectiveness of VR technology in health and safety training in hazardous working environments to address the following research questions:

RQ 1: How have researchers studied the efficacy of VR technology in health and safety training in hazardous work environments?

RQ 2: What are the key research findings on the efficacy of VR technology within health and safety training in hazardous work environments?

RQ 3: What are the underlying assumptions of the research on the efficacy of VR technology within health and safety training within hazardous work environments?

RQ 4: What are the limitations of the research on the efficacy of VR technology in health and safety training within hazardous work environments?

Chapter 2: Literature Search

2.1 Virtual Reality Technology

Virtual reality is a technology that creates a simulated environment and allows users to immerse themselves in and interact with the 3D world, replicating the real-world scenario (Khandelwal & Upadhyay, 2021). Unlike traditional interfaces, which only display the content, VR places the user in a real-world scenario. It provides sensory experiences such as vision, hearing, and touch (Purnomo et al., 2022). VR environments can be organised into two categories: immersive and non-immersive VR. Immersive VR fully engages the user by providing them with a wider view and flexibility for movement within the virtual environment through head-mounted devices (HMDs) (Pedram et al., 2021). This VR system provides a higher sense of presence and makes the user feel like they are actually in the virtual environment. On the other hand, a non-immersive VR system involves interacting with a 3D virtual environment generated on a computer through a keyboard, mouse or joystick, touchscreen and gloves (Pedram et al., 2021). Though it provides a limited sense of presence, it can offer interactive experiences.

2.2 Training

Training is defined as "planned and systematic activities designed to promote the acquisition of knowledge (i.e. need to know), skills (i.e. need to do), and attitudes (i.e. need to feel)" (Salas et al., 2012, p. 5). The intended result includes cognitive change (improved knowledge), behavioural change (acquisition of new or enhanced skills) and affective change (increased motivation) (Salas et al., 2012). The efficacy of training, known as learning transfer, measures the extent to which the acquired knowledge from real-life or simulation-based training impacts job performance (Saghafian et al., 2020). Other key indicators of training effectiveness are enhanced productivity, reduced errors or accidents and improved employee satisfaction. Several evaluation methods are used to evaluate training effectiveness, including pre- and post-training assessments, skills demonstrations and feedback mechanisms (Saghafian et al., 2020). Moreover, this helps determine the return on investment from training initiatives. Training effectiveness is vital for organisations to optimise employees' capabilities and maintain competitive advantage within their respective industries.

2.3 Related work on VR effectiveness

Virtual Reality (VR) technology is increasingly integrated into employee training, significantly changing how organisations approach learning and development (Feng et al., 2023). It is being adopted for training across various industries, including healthcare, aviation, manufacturing, and customer care (Khandelwal & Upadhyay, 2021). For instance, Bechtel, an engineering company, employs VR technology to train their employees in high-risk environments (Manuel, 2017).

Regarding safety, training plays a crucial role in preparing employees to follow procedures during emergencies or disasters involving high stress levels and negative emotional arousal. Studies have shown that VR is useful for safety training within hazardous industries such as construction, oil and gas, mining, chemical, and aviation (Asad et al., 2021; Chan et al., 2023; Feng et al., 2023; Nykänen et al., 2020). For example, research by Feng et al. (2023) showed that VR training significantly enhances practical performance while dealing with construction excavation hazards, suggesting that knowledge acquired during training can be transferred to work behaviours. In addition, their findings suggest that VR is more effective than health and safety manuals for knowledge retention. Further, a study by Abotaleb et al. (2023) showed that VR can enhance learning outcomes, potentially resulting in lower accident and fatality rates on construction sites.

Research by Liang et al. (2019) showed that VR training increases miners' familiarity with scaling operations and hazard identification, leading to better knowledge retention than conventional instructional media methods. It was also observed that most participants trained through VR could position themselves safely to avoid being hit by loose rocks. In contrast, most participants trained through the conventional method stood in dangerous areas where loose rocks could fall. Furthermore, the study by Dhalmahapatra et al. (2021) on evaluating the efficacy of VR in training electric crane operators showed significant improvement in hazard identification. It was observed that operators identified an additional ten hazard elements after receiving VR training in addition to the 18 hazard elements identified before the training. Similarly, a study by Jeelani et al. (2020) showed that, before VR training, trainees could identify only 31% of potential hazards. However, after undergoing VR training, their ability to identify hazards increased significantly, to 70%. Also, it was observed that trainees' hazard management performance improved by 44%. Similarly, research by Dhalmahapatra et al. (2022) found a 15% improvement in safety performance following VR training. These findings suggest that VR training is effective in improving both hazard management and overall safety performance.

The effectiveness of VR training is often captured by metrics such as sense of presence, engagement, motivation, learning outcomes, knowledge acquisition, knowledge retention and simulation sickness. Immersion, realism and graphics are the key features of VR and play a vital role in achieving these metrics. For instance, research by Pedram et al. (2020) suggested that learning is positively influenced by the features of VR technology, such as realism, co-presence, and the scenario. VR also enhances learning through immersion, presence and flow in the learning experience. However, these metrics can be influenced by the fidelity of head-mounted devices (HMDs) used in immersive VR training. Fidelity is said to be the degree to which the virtual environment conforms to and accurately replicates the real world (Saghafian et al., 2020). A study by Buttussi and Chittaro (2018) showed that HMDs with higher fidelity can more effectively present spatial cues, enabling users to employ a spatial memory strategy for memorising procedures. In addition, it showed that engagement was higher when using higher-fidelity HMD.

While many studies have demonstrated the potential of VR training, others have shown that it does not lead to significant improvement. For instance, a study by Leder et al. (2019) observed that, although immersive VR training was effective in terms of a sense of presence, there was no significant improvement in learning outcomes. Further, research by (Buttussi & Chittaro, 2021) reported that training through an immersive VR headset and a non-immersive smartphone yielded similar results regarding knowledge acquisition and retention. Likewise, Al-Khiami and Jaeger (2023) found that VR training did not lead to increased user learning effectiveness.

Moreover, VR can cause simulation sickness in the participants, which is similar to motion sickness (Nykänen et al., 2020). It can be caused by a visually simulated perception of movement rather than by actual motion (Dhalmahapatra et al., 2021). Symptoms include nausea, dizziness, eye strain and blurred vision. Studies have shown that some users experience simulation sickness, which might affect the efficacy of the training (Abotaleb et al., 2023; Babalola et al., 2023; Pedram et al., 2021; Touloudi et al., 2022). A study by Abotaleb et al. (2023) showed that the occurrence of simulation sickness is often related to the quality of the VR system.

It is noted that most of the research to date has assessed the impact of VR training over the short term and has not assessed long-term effects (Jelonek et al., 2022). Furthermore, research by (Al-Khiami & Jaeger, 2023; Chan et al., 2023) showed that older employees (above 50 years) were unfamiliar with and uncomfortable using VR systems. There is a lack of studies which have explored demographic factors such as age, gender, and technology proficiency. Studies have pointed out limited research on the transferability of skills to real-world scenarios, highlighting the need for more comprehensive and longitudinal studies (Pedram et al., 2021; Pedram et al., 2020). Thus, the study by Abotaleb et al. (2023) stated that the complete replacement of conventional training is impractical and infeasible due to the nascent stage of research in this area.

Therefore, through this systematic review, I comprehensively assesses the effectiveness of VR training in health and safety training in hazardous working environments. My review aims to contribute insights to research and practical applications in this domain by examining the interplay between VR training and its outcomes.

Chapter 3: Methodology

This chapter lays out the systematic approach drawn on to examine the use of virtual reality (VR) technology in health and safety training within hazardous working environments. The research addresses key questions regarding the effectiveness and usability of VR-based training programs in reducing the risks and mitigating safety concerns for employees working in hazardous environments. I followed the Preferred Reporting Instrument for Systematic Reviews and Meta-analyses (PRISMA) to search and collate the literature on the use of VR technology (Rethlefsen & Page, 2022). The methodology entails five steps: (1) developing a review plan and proposal, (2) identification of literature, i.e. searching databases to get a broad range of journal articles to answer my research questions, (3) screening of journal articles, (4) assessing the eligibility of articles selected post initial screening, and (5) eliciting essential data from selected articles and answering the formulated research questions.

3.1. Developing Review Plan & Proposal

This research started with a discussion with my supervisor to formulate a clear plan. We mapped out a review framework comprising the aim, objectives, research questions, and identification of relevant databases (with the help of Steph Clout, Te Mātāpuna Library research librarian), and inclusion and exclusion criteria. We also discussed the techniques for data extraction, synthesis, and reporting. This systemic review aims to examine empirical evidence about the usefulness and effectiveness of VR technology in the health and safety training of employees working in hazardous environments. In due course, after creating the framework, I submitted the research proposal for approval to the PG programme committee, including the entire research roadmap and the project timelines.

3.2 Identification of Literature

The identification process involves scouring databases to get a broad range of journal articles to answer research questions. I have searched three databases - Scopus, Business Source Complete, and Medline - because of their extensive pool of articles across varied disciplines. I also chose Medline because it includes occupational health and safety literature specific to regions like Australia and New Zealand, where health and safety often emphasise hazardous working environments and differ from traditional healthcare settings. This is to ensure that research from these countries, which may use different terminologies, is not overlooked. I limited my search to articles that were (1) peer-reviewed, (2) published between 2015 and 2023 and (3) written in English. I restricted the period of publication because there was limited research before 2015 on the use of VR technology for health and safety training, but thereafter, it came to the attention of researchers due to technological advancements. The search fields are almost the same across all the databases, i.e. they include keywords, titles, and abstract fields. Furthermore, the search string used was nearly the same in all the databases but was modified slightly due to the nature of the database. The search strings which I used were as follows:

1. ("virtual reality" OR "virtual reality technology" OR vr OR oculus) AND ("safety training" OR "health and safety" OR "health & safety")
2. ("virtual reality" OR "virtual reality technology" OR vr OR oculus) AND ("safety training" OR "health and safety" OR "health & safety" OR hazardous OR "hazardous environment" OR "safety management") AND (workplace OR employment OR employee OR organisation OR organization OR office OR workspace OR "job site" OR "work site" OR "plant site" OR "manufacturing site")

I used Endnote reference management software to download all the identified articles (n=224) and for further sequential steps.

3.3 Screening of Journal Articles

In this step, I used a specialised function of Endnote to remove duplicate articles (n=19). Following this, I ran through the remaining 205 articles, screened them by their titles and abstracts, and included those relevant to my research questions. In particular, the articles focused on the efficacy or usage of VR technology for health and safety training of employees exposed to hazardous work settings. This involved training aspects such as knowledge acquisition, knowledge retention, technology acceptance model, satisfaction, and motivation. In addition, during the initial screening, articles were excluded (n=144) in which the study was not on health and safety training of employees within hazardous work environments, or which did not have the full text available. For example, articles about VR training platforms for collaboration with construction robots or articles about only designing VR platforms and their implementation were excluded. After removing these articles, 59 remained (See Figure 1).

3.4 Assessment of Articles for Eligibility

In this step, I conducted an eligibility assessment of the remaining 59 identified articles, by running through their abstracts and, if required, full articles. A further 40 articles were eliminated for various reasons such as (1) articles which did not conduct empirical research on the use of VR in health and safety training, but instead did secondary research such as reviews or conceptual papers; (2) articles focused on other technologies like augmented reality (AR), extended reality (XR), building information modelling (BIM) (n=15); (3) studies comparing the effectiveness of VR and other metaverse technologies such as AR, XR, BIM (n = 1); (4) studies in which participants were students, novices, or not involved in the hazardous working environment. Students and novices do not accurately represent the work experiences of non-student workers, possibly limiting the validity and relevance of the research. Eventually, after excluding these articles, 20 remained, as illustrated in Table 1.

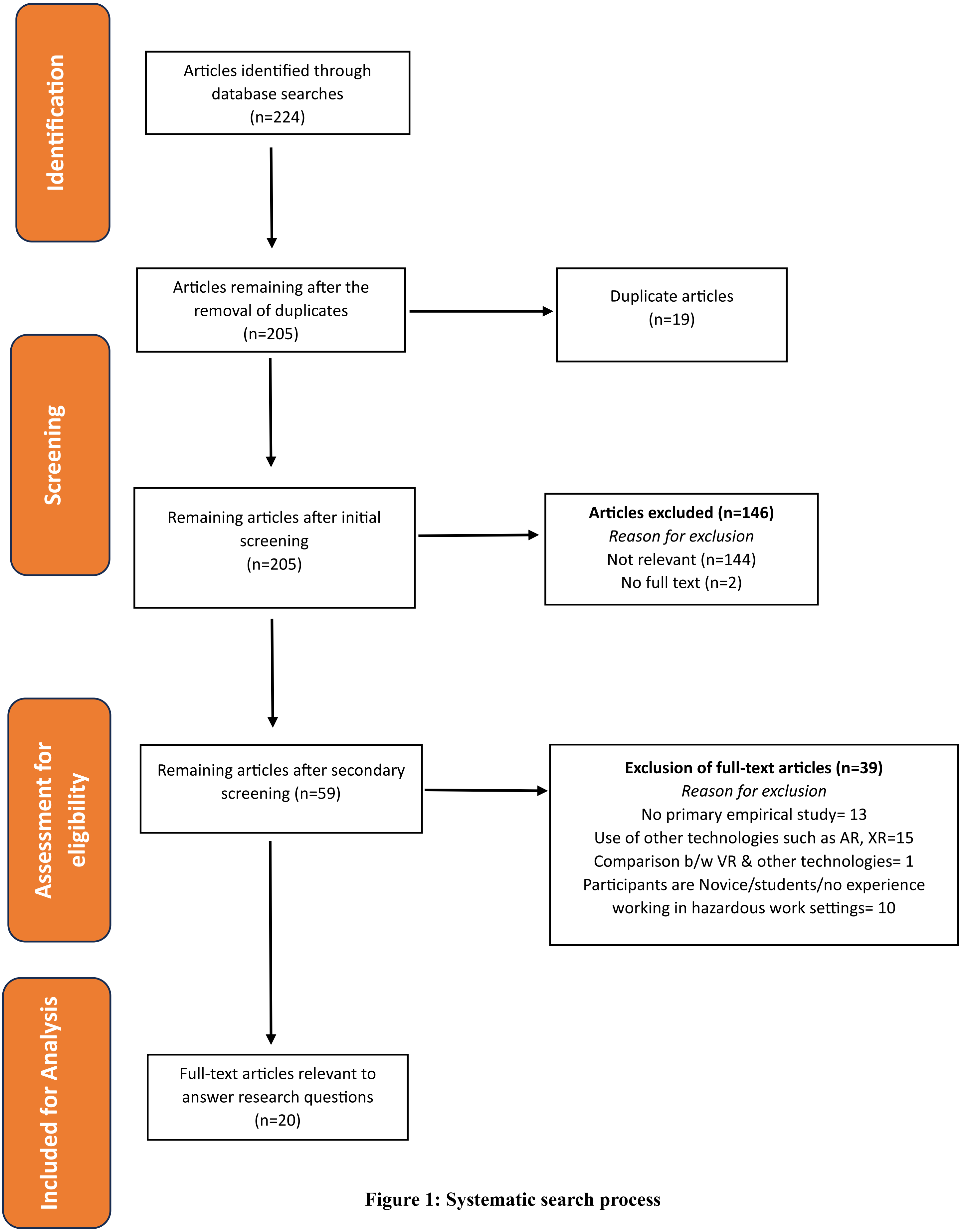

Figure 1: Systematic search process

3.5 Data Analysis

In this final step, I initially extracted the key aspects of each article. Firstly, I used a data extraction table that Arksey and O'Malley (2005) had developed to capture each study's aim, design, method, findings, and implications. By referring to this table, I was able to answer my first two descriptive research questions, i.e. (1) how have researchers studied the efficacy of VR technology in health and safety training in hazardous work environments? and (2) what are the key research findings on the efficacy of VR technology within health and safety training in hazardous work environments? Next, I synthesised and evaluated articles to answer the remaining two evaluative questions, i.e. (3) what are the underlying assumptions of the research on the efficacy of VR technology in health and safety training within hazardous work environments? and (4) what are the limitations of the research on the efficacy of VR technology in health and safety training within hazardous work environments? I applied the methodology proposed by Cronin and George (2023), by thoroughly examining the 20 extracted articles, and thus, I could identify patterns or thematic elements relevant to the last two questions.

Table 1: List of articles referred to in the systematic review

S.No	Article Title	Author	Year	Country/Region	Study Method	Industry
1	An interactive virtual reality model for enhancing safety training in construction education	I. Abotaleb, O. Hosny, K. Nassar, S. Bader, M. Elrifaee, S. Ibrahim, et al.	2023	Egypt	Quantitative	Construction
2	Safer Working at Heights: Exploring the Usability of Virtual Reality for Construction Safety Training among Blue-Collar Workers in Kuwait	M. I. Al-Khiami and M. Jaeger	2023	Kuwait	Quantitative	Construction
3	Effects of Different Types of Virtual Reality Display on Presence and Learning in a Safety Training Scenario	F. Buttussi and L. Chittaro	2018	Italy	Quantitative	Aviation
4	A Comparison of Procedural Safety Training in Three Conditions: Virtual Reality Headset, Smartphone, and Printed Materials	F. Buttussi and L. Chittaro	2021	Italy	Quantitative	Aviation
5	Study of motivation and engagement for chemical laboratory safety training with VR serious game	P. Chan, T. Van Gerven, J. L. Dubois and K. Bernaerts	2023	France	Mixed	Chemical Laboratory
6	Assessment of virtual reality-based safety training simulator for electric overhead crane operations	K. Dhalmahapatra, J. Maiti and O. B. Krishna	2021	India	Quantitative	Steel

7	An integrated TRIZ coupled safety function deployment and capital budgeting methodology for occupational safety improvement: A case of manufacturing industry	K. Dhalmahapatra, A. Verma and J. Maiti	2022	India	Quantitative	Steel
8	The Metaverse to Enhance Safety Campaign toward Shipping Industry (Case Study: The Development and Implementation of Metaverse in Government-Owned Corporation)	M. Fajar, D. David, P. R. Sihombing, H. A. Kekal, I. Aditya, R. Ilham and Y. S. Keswara	2022	Indonesia	Quantitative	Oil & Gas
9	A comparative investigation of usability issues toward virtual reality implementation in a state-owned shipping service enterprise	M. Fajar, Y. Udjaja, A. Chowanda and B. Juarto	2022	Indonesia	Quantitative	Oil & Gas
10	Immersive virtual reality training for excavation safety and hazard identification	Z. Feng, R. Lovreglio, T. W. Yiu, D. M. Acosta, B. Sun and N. Li	2023	New Zealand	Quantitative	Construction
11	Virtual Reality-based pilot training for underground coal miners	A. Grabowski and J. Jankowski	2015	Poland	Quantitative	Mining
12	MINING-VIRTUAL: A comprehensive virtual reality-based serious game for occupational health and safety training in underground mines	S. Gürer, E. Surer and M. Erkayaoğlu	2023	Turkey	Quantitative	Mining
13	Evaluating Virtual Reality Simulations for Construction Safety Training A User Study Exploring Learning Effects, Usability and User Experience	M. Jelonek, E. Fiala, T. Herrmann, J. Teizer, S. Embers, M. König and A. Mathis	2022	Germany	Mixed	Construction

14	Implementing and evaluating novel safety training methods for construction sector workers: Results of a randomised controlled trial	M. Nykänen, V. Puro, M. Tiikkaja, H. Kannisto, E. Lantto, F. Simpura, et al.	2020	Finland	Quantitative	Construction
15	Cost–benefit analysis of virtual reality-based training for emergency rescue workers: a socio-technical systems approach	S. Pedram, R. Ogie, S. Palmisano, M. Farrelly and P. Perez	2021	Australia	Mixed	Mining
16	Investigating the process of mine rescuers' safety training with immersive virtual reality: A structural equation modelling approach	S. Pedram, S. Palmisano, R. Skarbez, P. Perez and M. Farrelly	2020	Australia	Quantitative	Mining
17	Improvement of short-term outcomes with VR-based safety training for work at heights	E. Rey-Becerra, L. H. Barrero, R. Ellegast and A. Kluge	2023	Colombia	Mixed	Construction
18	Evaluating the preliminary effectiveness of industrial virtual reality safety training for ozone generator isolation procedure	H. Stefan, M. Mortimer, B. Horan and G. Kenny	2023	Australia	Quantitative	Ozone Isolation Generator
19	Perceptions of the use of virtual reality games for chemical engineering education and professional training	C. Udeozor, R. Toyoda, F. Russo Abegão and J. Glassey	2021	UK	Mixed	Chemical
20	Incorporating virtual reality technology in safety training solution for construction site of urban cities	Z. Xu and N. Zheng	2021	Australia	Quantitative	Construction

Chapter 4: Findings

This chapter presents the outcomes of the systematic literature review, examining the use of VR technology in employees' health and safety training within hazardous working environments. The chapter is organised into four sections, each of which answers one research question. In the first two sections, I use a descriptive approach to discuss the methodologies and parameters researchers identified to study the efficacy of VR technology. The last two questions use an evaluative approach in which I discuss the underlying assumptions made and outline the limitations in current research.

4.1 RQ1: How have researchers studied the efficacy of VR technology in health and safety training in hazardous work environments?

I have coded the articles based on the study method, type of industry, study designs, constructs, measures, study location and participants' professions.

4.1.1 Study Methods, Designs, Measures, and Constructs

I note that a quantitative approach was used the most (n=15), followed by a mixed approach in which researchers have used quantitative and qualitative methods (n=5). Articles that used quantitative study designs used either experimental study (pre-test and post-test intervention) (n=11) or cross-sectional survey (n=10) as data collection methods. This may be because by using pre- and post-test interventions, researchers can evaluate the immediate effects of VR technology in the context of health and safety training. Also, using a cross-sectional survey provides them with more insights, for example, about user experience and satisfaction, and an understanding of its impact (Stefan et al., 2023). Furthermore, regarding mixed research design, primarily semi-structured interviews (n=3) were chosen for the data collection method, and in only one study was an open-ended survey (n=1) used (Udeozor et al., 2021). This may be because semi-structured interviews allow the researchers to evaluate the user's perception of VR technology compared to conventional training methods (Chan et al., 2023). They also provide profound insights into the user experience, acceptance of technology, and challenges associated with using VR technology. (See Table 2).

I have identified the constructs and measures used in quantitative and mixed methods studies examining the effectiveness of VR technology in health and safety training. As shown in Table 2, the most common measures in the studies were user experience and perception across both quantitative (n=28) and mixed methods (n=10). In the quantitative method studies, most of the articles examined constructs such as motivation (n=6), sense of presence (n=4), engagement (n=4), user experience (n=4), satisfaction (n=4), and motion/simulation sickness (n=4), in user experience and perception measures. The same was true for mixed method studies, i.e. in user experience and perception measures, most of the studies focused on constructs like motivation (n=2), sense of presence (n=2), engagement (n=1), motion/simulation sickness (n=1); or user experience (n=1).

I did identify one more measure — learning and performance — in both quantitative (n=22) and mixed methods (n=4). In quantitative research, researchers mainly focused on knowledge acquisition (n=11) and knowledge retention (n=6). The same was true for mixed methods studies, in that most focused on investigating knowledge acquisition (n=2) and knowledge retention (n=2) constructs. This may be because these two constructs play a vital role in evaluating the effectiveness of VR technology in health and safety training within hazardous working environments. Also, in quantitative research, researchers have investigated safety performance (n=4) and confidence level (n=1) constructs. Another construct assessed in mixed methods studies was safety performance (n=1).

Table 2: Study methods, designs, measures, and constructs in research for the use of VR in health and safety training

Research design	**Quantitative: N= 15**	**Mixed Methods: N= 5**
Unit of analysis	Individual: N= 15	Individual: N=5
Design of Study/ Data Collection Method	Experimental study: N=11 (Pre & post-intervention study) Cross-sectional survey: N=10	Semi-structured interviews: N= 3 Open-ended survey: N=1
Measures and Constructs	**User experience & perception** Sense of Presence: N=4 User Experience: N=4 Motion/Simulation Sickness: N=4 Engagement: N=4 Motivation: N=6 Satisfaction: N=3	**User experience & perception** Sense of Presence: N= 2 User experience: N= 2 Motion/Simulation Sickness: N=1 Engagement: N=1 Motivation: N=2
	Learning & performance Knowledge Acquisition: N=11 Knowledge Retention: N=6 Safety Performance: N=4 Confidence Level: N=1	**Learning & performance** Knowledge Acquisition: N=2 Knowledge Retention: N=1 Safety Performance: N=1

4.1.2 Study Locations and Industry

The research was performed in 14 countries, mainly in Australia (n=4), India (n=2), Italy (n=2) and Indonesia (n=2) (see Fig 2). However, only one study was conducted in each of ten other countries: Egypt, the UK, Poland, France, Columbia, New Zealand, Kuwait, Turkey, Germany, and Finland. This may be for several reasons, such as varied levels of adoption of VR technology, priorities for occupational safety training, and availability of funding. Also, it could be because I limited my search to studies that recruited seasoned professionals from the same industry and only focused on using VR technology.

The studies were focused on the construction industry (n=4) and other industries such as oil and gas (n=2), chemical (n=2), aviation (n=2), mining (n=2) and steel (n=2) (see Fig 3). These industries were most likely chosen because they are known for their hazardous working environments and potential for injuries and fatal accidents. Participants recruited in the studies were from diverse professional backgrounds and across hierarchy levels, such as labourers working at construction sites, pilots, mining engineers, civil engineers, technicians working at chemical laboratories, crane operators and chemical engineers. It is essential to assess the effectiveness of VR technology in these sectors as it would provide a realistic evaluation and help the companies make an informed decision on whether to implement VR for training purposes.

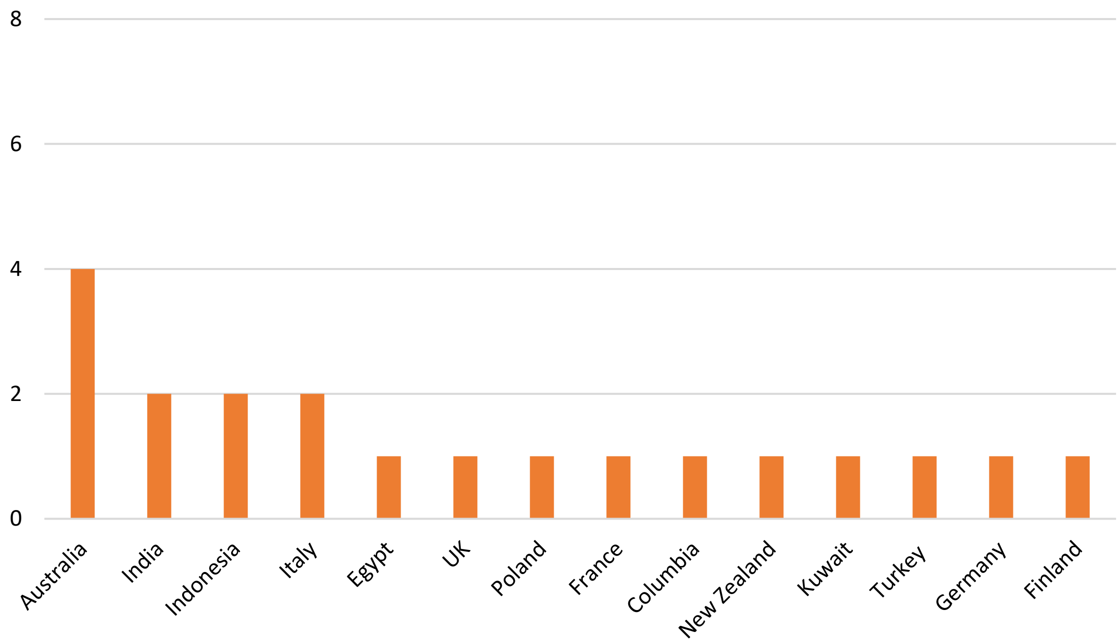

Figure 2: Study locations of the research on the use of VR in health and safety training

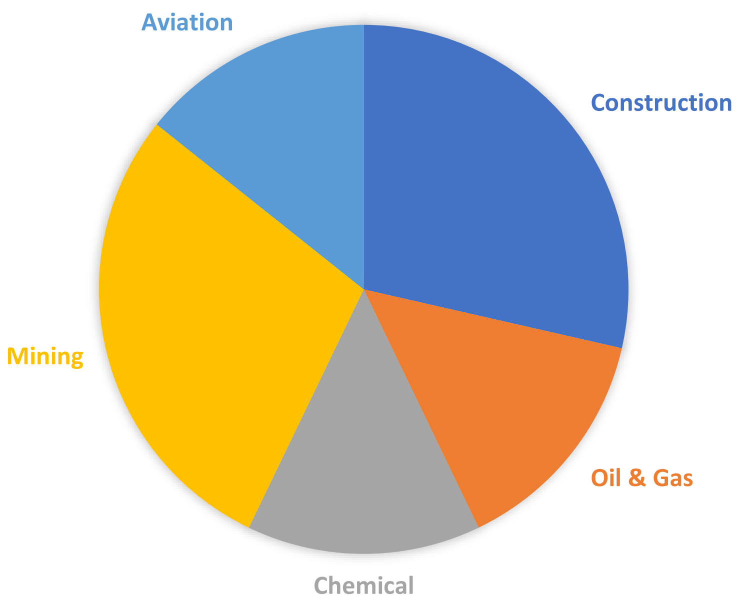

Figure 3: Industry breakdown: The use of VR in health and safety training

4.2 What are the key research findings on the efficacy of VR technology in health and safety training within hazardous work environments?

To summarise the key research findings on the effectiveness of VR technology in health and safety training within hazardous working environments, I developed a nomological network of antecedents and outcomes, as shown in Fig. 4. This network highlights predominant antecedents such as graphics rendering, physical simulation, VR scenes, and visualisation, along with outcomes like knowledge acquisition, knowledge retention, motivation and sense of presence. Also, I have identified the mediators between antecedents and outcomes, such as HMD with narrow FOV and 3-DOF and HMD with wider FOV and 6-DOF. (These terms are explained in 4.2.2 below.) Developing this nomological network aligns with other integrative reviews (Zhang & Parker, 2019).

4.2.1. Antecedents

Scenario Fidelity

The most prominent antecedent in the existing research on the effectiveness of VR in health and safety training is simulation. Simulation is a method used to create artificial environments to mimic real-world scenarios in which users can interact with each other and experience real situations without facing real-world consequences (Pedram et al., 2020). This can include the capability to simulate real-world effects such as gravity, weather shifting, interaction with objects, etc (Xu & Zheng, 2021). It has been seen that simulation plays a critical role in improving the effectiveness of health and safety training by immersing trainees in realistic scenarios that mimic hazardous environments. It is effective because it provides an immediate stimulus that stirs up the trainees' emotions and increases their ability to recognise more risk.

When training is given in an environment where hazards are portrayed as real, the trainees most likely perceive the dangers as real and react accordingly (Buttussi & Chittaro, 2018; Pedram et al., 2021). This emotional response stimulates a sense of vigilance and attention to detail, leading to an engaging and impactful learning experience (Rey-Becerra et al., 2023).

Another reason for its effectiveness is that it allows on-the-job or experiential training in a risk-free environment while still providing a high sense of presence, which is missing in conventional training methods. Moreover, it has been shown that experiencing hazards in simulations can trigger reflection processes, which can bring memories of previously encountered hazards (Jelonek et al., 2022). Encountering these experiences improves trainees' safety awareness and helps them develop strategies to mitigate risks in the future (Xu & Zheng, 2021). In addition, research (Pedram et al., 2021) has shown that 56% of participants feel that VR training is effective as it allows real-time feedback and discussion. The simulation provides immediate feedback on the decisions made by the users within a given scenario.

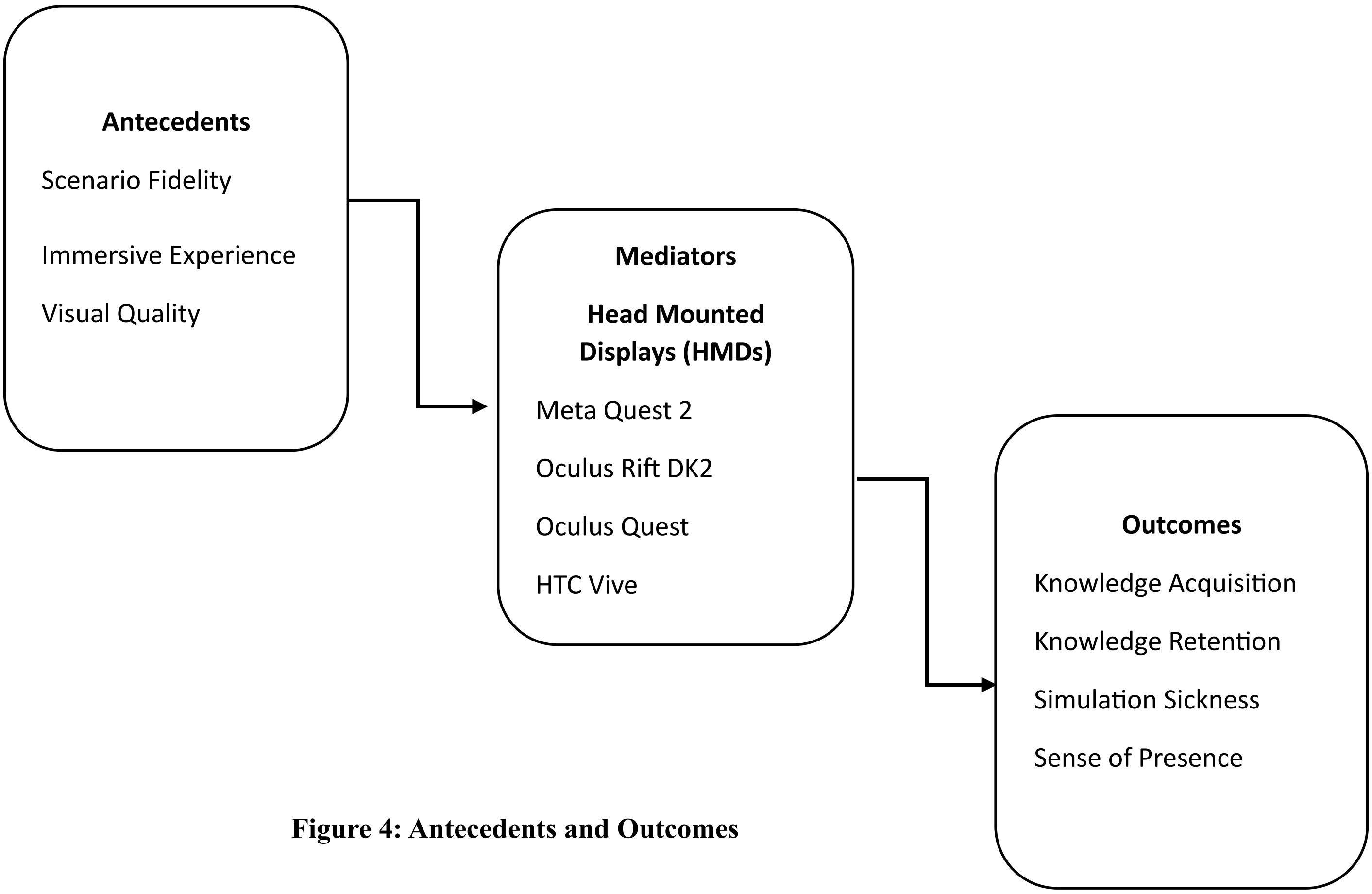

Figure 4: Antecedents and Outcomes

Immersive Experience

Immersion in VR technology is the sensation of being fully present within the virtual environment. Through immersion, users feel physically present in a non-physical world. Immersion seeks to create a 360-degree experience by transporting users into digital three-dimensional environments. This is achieved through graphics, sound effects, and simulation, creating real-world-like conditions (Udeozor et al., 2021). Findings from my review show that immersion plays a vital role in the effectiveness of VR technology in health and safety training within hazardous environments. It gives a sense of "being there" in the virtual world, essential for training in high-risk industries. VR can mimic extreme situations, and users can gain experience by being virtually present in dangerous scenarios without facing real-life consequences. This sense of presence helps trainees to make decisions and learn from their mistakes while remaining safe (Pedram et al., 2021).

Immersion in a VR environment also helps enhance understanding and safety awareness. It helps participants to recognise unpredicted problems, evaluate and anticipate decision-making errors, and identify workplace hazards. Research (Dhalmahapatra et al., 2021) has shown that immersion aids in identifying events that lead to accidents or possible accident paths. For example, this study reported that participants could recognise an additional 10 hazardous elements and 13 initiating mechanisms after VR training. Moreover, it allows trainees to explore a variety of emergency scenarios, which provides an opportunity for them to experience and practise in hazardous situations without having real-life consequences, which is not possible in traditional training methods (Pedram et al., 2021).

Visual Quality

Graphics rendering is a process of generating and displaying visual images in a virtual environment. It creates 3-D graphics, animations, lighting effects and textures, which simulate realistic scenarios and provide an immersive experience (Udeozor et al., 2021). It ensures that virtual environments are visually captivating and accurately represent trainees' perspectives and interactions. Graphics contribute to the enhancement of trainee immersion and engagement. Existing research has found that the quality of graphics rendering plays a crucial role in the acceptance of the technology. It has been reported that users feel VR is an effective training method as it provides them with a real-life experience because of the graphics visualisation (Gürer et al., 2023). However, it has also been reported that, if the quality of graphics is poor, it can lead to simulation sickness, resulting in a negative experience (Abotaleb et al., 2023). Simulation sickness is defined as a trainee feeling discomfort while training in a virtual environment, such as dizziness, nausea, disorientation or eye strain (Pedram et al., 2021). So it is essential to ensure high-quality visuals to minimise the chances of simulation sickness and increase user acceptance.

4.2.2. Mediator

The Head-Mounted Display (HMD) mediates the antecedents and outcomes and is crucial in making VR technology effective in health and safety training within hazardous working environments. HMD is a helmet-shaped device worn on the head with a screen in front of the eyes to provide a virtual experience. It blocks the external environment and makes users feel they are in the virtual environment (Guo et al., 2022). HMDs are differentiated based on their field of vision (FOV) and degree of freedom (DOF). FOV refers to the extent to which a user can see around themselves at any one time, and it is measured in degrees (Buttussi & Chittaro, 2021). DOF refers to the number of directions in which the user's head movement can be tracked, thereby determining the level of freedom and realism in the virtual world (You et al., 2018). An HMD with a wider FOV provides a more immersive experience as the user can see a larger area of the virtual environment.

There are two types of DOF: 3-DOF and 6-DOF. The less sophisticated type, 3-DOF, permits only of rotational movement of the head (Liu et al., 2024). This means that the user can only move their head up or down, left or right, or tilt the head to one side. These movements are known, respectively, as "pitch", "yaw" and "roll". In contrast, the more advanced type, 6-DOF, allows translational movement as well as rotational, meaning the user can move their whole body, whether left or right, forwards or backwards and upwards or downwards, and not merely their head.

The most common HMD devices used in the review are Meta Quest 2, Oculus Rift DK2, Oculus Quest and HTC Vive. The Meta Quest has an FOV of approximately 90 degrees and a tracking system of 6-DOF, which allows trainees to have a wide range of motion and immersive experience. On the other hand, the Oculus Rift DK2 is an older model and offers a narrow FOV of less than 90 degrees and tracking system of only 3-DOF, limiting the trainee's movement and immersive experience (Dhalmahapatra et al., 2021). The Oculus Quest offers the same FOV as the Meta Quest. However, its tracking system is the more sophisticated 6-DOF, providing a wider FOV and a higher degree of freedom for the trainee's movement in the virtual environment (Feng et al., 2023). So it is vital to select the appropriate device based on the desired level of immersion and interaction, as it can significantly impact the user experience and effectiveness of the training.

4.2.3. Outcomes

Knowledge Acquisition

Knowledge is a process that keeps developing and evolving and is built rather than received (Abotaleb et al., 2023). In other words, learners contribute to knowledge acquisition as they interpret their experiences when they encounter cognitive challenges (Abotaleb et al., 2023). Research has shown that VR training enhances learning safety procedures (Buttussi & Chittaro, 2018; Feng et al., 2023; Jelonek et al., 2022). The immersive and interactive environment allows trainees to visualise and interact with the objects within the virtual environment, which facilitates a deeper understanding. This hands-on method helps the trainee understand the complex details that might be difficult to deliver through conventional training methods. Further, it has been reported that the VR model that has a wider FOV and higher DOF proves to be more effective in knowledge acquisition than a model with a narrow FOV that limits the movement of the trainees in the virtual world (Buttussi & Chittaro, 2018). In general, however, VR technology enhances the knowledge acquisition of trainees working within hazardous environments by creating captivating, engaging and practical learning experiences.

Knowledge Retention

Knowledge retention is when newly acquired knowledge is transferred from short-term to long-term memory (Feng et al., 2023). VR has positively impacted knowledge retention in health and safety training in hazardous working environments. The review highlights the studies in the construction and aviation industries that have reported enhancement in knowledge retention while using VR for training because it allows spatial interaction, i.e. interaction among other trainees and objects within the virtual space (Buttussi & Chittaro, 2018; Feng et al., 2023). Moreover, research indicates that knowledge retention tends to diminish with conventional training methods but is retained well with VR training. It is because VR offers a hands-on approach and experiential learning, allowing trainees to explore, engage and assess their actions. The learn-by-doing approach is effective as it offers active participation and real-time feedback (Feng et al., 2023).

Research (Buttussi and Chittaro (2021) has reported that VR training is more effective than safety videos and manuals regarding knowledge retention. Surprisingly, the results were similar whether the VR setup was immersive (via HMD) or non-immersive (via smartphone), and it is because both approaches allowed the trainees to learn by doing. Moreover, the research found that unexpected events and realistic depictions of trainees' mistakes lead to the arousal of negative emotions, which can aid in memory consolidation and retention (Buttussi & Chittaro, 2018). It was observed even in the trainees who used VR systems with narrower FOV or lower DOF.

Simulation Sickness

One shortfall of VR training is that trainees might feel simulation sickness. It differs from motion sickness, as it is caused by the perception of moving in the virtual world. Users may experience symptoms like nausea, dizziness, blurred vision, sweating, excessive saliva production, eye strain, vertigo, vomiting and disorientation (Pedram et al., 2021). However, the review indicates that it is not a significant concern for most trainees, with few experiencing these symptoms, and it depends mainly on the quality of the HMD (Abotaleb et al., 2023; Nykänen et al., 2020; Pedram et al., 2021; Xu & Zheng, 2021). Moreover, it has been found that there is no significant difference in the occurrence of simulation sickness between young trainees and older adults, which suggests age does not play a role in susceptibility (Dhalmahapatra et al., 2021).

Sense of Presence

The sense of presence is the psychological state in which the user feels physically present in the non-physical world (Nykänen et al., 2020). The user feels present in a virtual world due to the features of VR, i.e. physical simulation, immersive experience, and graphic rendering. All these elements work together and portray a realistic and engaging scenario where trainees feel they are in the virtual environment. The existing research has shown that VR enhances the sense of presence in health and safety training within hazardous working environments. It has been reported that when the trainees experience a high sense of presence, they engage profoundly, resulting in improvement in knowledge acquisition and retention, and recognition of hazards (Abotaleb et al., 2023; Buttussi & Chittaro, 2021; Dhalmahapatra et al., 2021; Fajar, Udjaja, et al., 2022; Pedram et al., 2021).

Moreover, research by (Buttussi & Chittaro, 2018) found that a sense of presence is influenced by field of view (FOV) and degree of freedom (DOF). The wider the FOV, the more it allows the trainees to see around them within the virtual environment, enhancing the feeling of immersion required for a sense of presence. Likewise, a higher DOF, specifically 6-DOF, allows translational and rotational movement, which provides a more realistic and engaging experience and enhances the sense of presence.

4.3 RQ3: What are the underlying assumptions of the research on the efficacy of VR technology within health and safety training within hazardous work environments?

4.3.1 Effectiveness through Immersion

A common assumption in the review is that the effectiveness of VR in health and safety training within hazardous environments is attained by immersion, as immersive experiences create more engaging and realistic scenarios. This assumption is derived from various factors observed in my review. The immersive nature of VR allows trainees to practise in a scenario which is a replica of the real world. It enables them to interact within the virtual environment, enhancing the trainee's understanding of safety procedures (Fajar, Udjaja, et al., 2022). In addition, immersion enhances trainee engagement, which leads to knowledge acquisition and retention (Jelonek et al., 2022). Moreover, high levels of immersion are achieved through realistic graphics, visual effects and interactive elements, making the trainee feel they are in the virtual environment (Buttussi & Chittaro, 2021). As a result, an enhanced sense of presence leads to more profound learning experiences because the trainees can interact with the environment (Buttussi & Chittaro, 2018).

However, this assumption reveals several complexities. Though immersion enhances the trainee's engagement, it is not guaranteed to improve learning outcomes. This is because the effectiveness of immersion depends on the quality of the VR setup, which includes the fidelity of graphics and visual effects (Piccione et al., 2019). Research by Buttussi and Chittaro (2021) has shown that more immersive visualisation features, high-quality rendering, and realistic simulations can make training more engaging and lead to better knowledge retention. Also, the VR experience can be ruined if the graphics are of poor quality or have visual inconsistencies, leading to simulation sickness and disengagement (Abotaleb et al., 2023). Symptoms like nausea, disorientation, eye strain and dizziness can make it difficult for the trainees to focus, affecting the learning experience and reducing the sense of presence (Piccione et al., 2019).

Furthermore, immersion is not the sole factor influencing knowledge acquisition and retention. Other factors play a crucial role, such as the instructional design of VR programs and the relevance of content (Joe, 2020; Piccione et al., 2019). Thus, developing a highly immersive VR setup does not lead to better learning outcomes if the training content is not well-structured or if the scenarios do not effectively mimic real-world hazards (Stefan et al., 2023).

4.3.2 User Readiness and Technological Literacy

Another underlying assumption is user readiness and technological literacy, which means all employees are comfortable and familiar with advanced technology to allow them to benefit from VR-based training. This assumption is evident from my review as the studies' primary objectives focus on exploring VR's effectiveness based on learning outcomes, engagement, and sense of presence. However, these studies often overlook factors such as age and workforce background, which play a crucial role in the effectiveness of VR training. For example, not all employees have the same level of experience of or exposure to advanced technology such as older employees who are not tech-savvy and might find it challenging to adopt VR training due to less familiarity with VR interfaces as compared to the younger workforce who have grown up in the era of technology advancement (Chan et al., 2023).

Moreover, employees working in sectors such as mining, oil and gas, and construction, which are characterised by hazardous working environments where the majority of the workforce is likely involved in manual labour, might not be familiar with the technology or might exhibit low digital literacy (Al-Khiami & Jaeger, 2023). Because of this, the efficacy of VR training can be affected: if the trainee struggles while using the VR system and spends more time trying to understand how to use the VR setup instead of focusing on the training content, this can lead to stress, frustration and disengagement (Al-Khiami & Jaeger, 2023). Also, employees less accustomed to gaming or virtual environments might not find VR engaging, potentially impacting their learning experience (Chan et al., 2023). Moreover, there could be resistance to the change from the employees who are used to traditional training methods. Adapting to a new training approach requires a shift in mindset, which everyone might not be ready to welcome (Balint et al., 2020).

4.3.3 Transferability of Skills

One more underlying assumption is that skills and knowledge acquired during VR training can seamlessly be transferred to real-world scenarios. It means that it prepares the employees to face challenges in hazardous situations. Most of the studies focussed on the effectiveness of VR training based on knowledge acquisition, knowledge retention, engagement and sense of presence (Buttussi &

Chittaro, 2018, 2021; Fajar, Udjaja, et al., 2022; Feng et al., 2023; Jelonek et al., 2022; Nykänen et al., 2020; Pedram et al., 2020). However, these studies have overlooked the critical aspect of skills transfer and applying it to real hazardous situations. Though VR training provides high levels of immersive and authentic experience, it may not entirely replicate the challenges, complexities and unpredictable scenarios in a real-world situation (Pedram et al., 2021). For instance, it is difficult to imitate genuine hazardous situations and elements in a virtual setting, such as physical sensations including smell, heat, ventilation, mud, uneven ground, and immediate consequences of mistakes (Pedram et al., 2021).

Moreover, effective learning depends on the trainers' acceptance of and proficiency in the technology. If the trainers are reluctant, uncomfortable, have a negative perception of the technology or are sceptical about its effectiveness, it will negatively influence the viewpoint and thought process of the trainees (Pedram et al., 2021). On the other hand, if trainers are comfortable and have a positive view of the technology, it will provide better experiences and quality feedback and lead to effective learning (Pedram et al., 2020). Furthermore, VR cannot replace actual drills or conventional training (Abotaleb et al., 2023). It can complement real-life drills to practise real-life dangerous situations but is less suited to gaining factual knowledge about safety and cannot replace the need for practical experience (Chan et al., 2023; Nykänen et al., 2020). Real-life drills play an essential role as they provide exposure to the physical and psychological demands of hazardous situations, which is necessary for preparation while working in hazardous environments (Pedram et al., 2021).

4.4 RQ4: What are the limitations of the research on the efficacy of VR technology in health and safety training within hazardous work environments?

4.4.1 Lack of Longitudinal Studies

In my literature review, most studies focused on short-term outcomes such as knowledge acquisition, engagement, and sense of presence. While these metrics provide a profound insight into how the technology fits the purpose and is essential for initial evaluations, they fail to provide an in-depth understanding of the effectiveness of the technology in the long term regarding aspects such as knowledge retention and transfer of skills (Al-Khiami & Jaeger, 2023; Feng et al., 2023; Pedram et al., 2021). There is a scarcity of longitudinal studies that can track the impact of VR training on practical performance over extended periods, knowledge retention, and sustained application of skills (Feng et al., 2023). This gap limits the assessment of the effectiveness and potential of VR training in health and safety in hazardous working environments.

4.4.2 Inadequate Consideration of Workforce Diversity

One of the limitations of my literature review is the lack of consideration within the literature of a diverse workforce. Many studies have not considered factors such as varied levels of technology literacy and acceptance of technology among demographic groups. For example, one study (Al-Khiami & Jaeger, 2023) shows older employees are less acquainted with the technology and exhibit low digital literacy. VR training was a stressful experience for them due to a lack of familiarity with using a headset and hand controller. It can lead to an inaccurate assessment of the effectiveness of VR training as the challenges they encounter are not addressed adequately. Moreover, in hazardous working environments such as oil and gas, construction, mining, etc., where the employees perform manual or labour-intensive tasks, they often have different learning styles, and they would be more comfortable with technology, which is easier to use and has a simple hardware configuration (Abotaleb et al., 2023; Al-Khiami & Jaeger, 2023). However, all these aspects have not been sufficiently considered in the literature. This lack of inclusivity will lead to only a partial understanding of the effectiveness of VR training.

4.4.3 Technological Variability

The technological quality, including hardware and software, influences the effectiveness of VR training (Buttussi & Chittaro, 2018). In the literature review, studies (Dhalmahapatra et al., 2021; Feng et al., 2023) have used various VR devices with different specifications in terms of field of view (FOV), degree of freedom (DOF) and interactivity. VR devices which provide high-fidelity simulations tend to be more effective in achieving the outcomes of a sense of presence, and engagement (Buttussi & Chittaro, 2018). However, studies (Buttussi & Chittaro, 2018, 2021) have shown no significant difference in the outcome of knowledge retention with a varied level of display fidelity. This technological inconsistency makes it difficult to evaluate and draw a concrete conclusion about the effectiveness of VR training.

Chapter 5: Discussion and Conclusion

5.1 Discussion

This systematic review shows that VR technology holds substantial potential to improve the health and safety outcomes of employees working in hazardous environments such as oil and gas, mining, construction, and chemical industries. It underscores VR technology's ability to create immersive and realistic training scenarios that enhance users' sense of presence, engagement, knowledge acquisition, and knowledge retention (Abotaleb et al., 2023; Buttussi & Chittaro, 2018; Nykänen et al., 2020; Stefan et al., 2023). These immersive experiences allow employees to practice critical skills in a risk-free environment, preparing them better for real-world scenarios without facing real-life consequences (Pedram et al., 2020).

This review shows that several key factors, such as the fidelity of head-mounted devices, quality of graphic rendering, and adaptability of training content to diverse user profiles, influence the effectiveness of VR training (Abotaleb et al., 2023; Feng et al., 2023; Stefan et al., 2023; Xu & Zheng, 2021). This highlights the importance of developing high-quality VR systems that closely mimic real-world conditions. Moreover, it is crucial to develop inclusive training programs considering factors such as diverse workforce demographics, including older employees, those in labour-intensive roles, and those not well versed in advanced technology.

Given these insights, it is evident that maximising the benefits of VR training requires prioritising the use of high-fidelity VR systems and ensuring that the training content is accessible and relevant to all trainees (Al-Khiami & Jaeger, 2023). This involves investing in high-fidelity VR systems and continuously refining training programs based on feedback and performance metrics. Enhancing the effectiveness of VR training can lead to improved safety and performance in hazardous environments.

The importance of acting on these findings stems from VR training's potential to reduce workplace accidents and enhance safety outcomes significantly. Implementing high-quality VR training programs can lead to a more competent and prepared workforce capable of handling complex and dangerous situations with greater confidence and skill. This will benefit the employees and the overall safety culture within high-risk industries.

On the other hand, failing to act on these insights risks continuing the limitations of conventional training methods, which often fail to prepare employees for the realities of hazardous environments. Without effective training, this can lead to higher accident rates, increased injuries, and potentially fatal accidents.

5.1.1. Theoretical Contributions

The theoretical frameworks discussed in this review include concepts such as immersion, graphic rendering, and simulation with a specific emphasis on experiential learning theory. Experiential learning theory helps explain how VR training enhances learning outcomes through an increased sense of presence, engagement, realistic simulations and hands-on practice. However, this review reveals gaps in these theories. For instance, these concepts address immediate learning outcomes and engagement but do not fully explain the long-term retention of skills and knowledge acquired through VR training or the transferability of these skills in real-world scenarios.

Future theoretical frameworks should focus on integrating these aspects more comprehensively. Improving current models or developing new models to include factors that influence the long-term retention of skills learned through VR could give a more holistic understanding. Also, existing theories could be expanded to better account for the dynamic and interactive nature of VR environments, considering factors of how continuous interaction with high-fidelity simulations impacts learning over time.

Moreover, it is important to explore how demographic differences and digital literacy influence the effectiveness of VR training. New or revised theorisation could show the specific conditions under which VR training is more effective by considering how older employees or those not well versed digitally might experience and benefit from VR differently. This could be achieved by tailoring the VR programs or by designing simpler hardware configuration VR systems to accommodate diverse learner profiles and hence maximising the effectiveness of training across different demographics.

5.1.2. Practical Contributions

From a practical perspective, this review highlights several key contributions to implementing VR training in hazardous working environments. Firstly, it underscores the importance of high-fidelity VR systems that can accurately replicate real-world conditions, which enhances the realism and effectiveness of training (Al-Khiami & Jaeger, 2023; Xu & Zheng, 2021). Secondly, the review emphasises the importance of designing and implementing VR programs with user-friendly hardware configurations, ensuring all the trainees can benefit from it regardless of age and digital literacy (Al-Khiami & Jaeger, 2023). Furthermore, the review suggests that VR can complement conventional training programs but cannot replace hands-on experience and real-world drills (Abotaleb et al., 2023; Chan et al., 2023; Nykänen et al., 2020).

So by identifying and addressing these contributions, organisations can maximise the use of VR technology in the health and safety training of employees working in hazardous environments. Also, they can improve the safety training outcomes and reduce the incidence of errors and accidents.

5.2. Conclusion

This systematic review examines research on the efficacy of VR training in health and safety in hazardous working environments. The literature review identifies VR as a powerful training tool which can enhance knowledge acquisition, knowledge retention, sense of presence, engagement and user experience due to its immersive and realistic nature (Abotaleb et al., 2023; Al-Khiami & Jaeger, 2023; Gürer et al., 2023; Pedram et al., 2020; Stefan et al., 2023). However, it revealed a couple of assumptions and limitations within the current research. These are the beliefs that employees can seamlessly transfer the skills learned in a VR environment to real-world scenarios, assuming that the personnel are technologically capable and ready to adopt VR. Also, it often overlooks employee diversity, such as varying age groups and levels of technological proficiency.

Moreover, this systematic review highlighted the crucial role of the fidelity of VR devices, comprising elements such as immersion, graphic rendering and simulation, which enhance the sense of presence and engagement (Abotaleb et al., 2023; Buttussi & Chittaro, 2018, 2021; Pedram et al., 2020; Stefan et al., 2023). At the same time, the impact on learning outcomes is still inconclusive. Therefore, VR training in health and safety in hazardous working environments looks promising, but its full potential depends on addressing these assumptions and limitations.

5.3. Future Research

In this systematic review, most studies explore the impact of VR training for a short period, i.e. a maximum of 1 month. Thus, future research should focus on the long-term impact of VR training on whether the knowledge acquired from training can be effectively translated into practical action over an extended period (Al-Khiami & Jaeger, 2023; Chan et al., 2023; Feng et al., 2023; Pedram et al., 2020). It is crucial to accurately evaluate the benefits of VR safety training, as immediate performance measurement is often impossible due to the unpredictability of hazardous working environments (Pedram et al., 2021). Moreover, this review showed that merely immersive capabilities do not significantly enhance learning outcomes; rather, they depend on other factors such as interaction fidelity or training content (Nykänen et al., 2020). Therefore, future studies should examine the relationship between key characteristics of the virtual learning experience (Nykänen et al., 2020). Furthermore, in the review, few studies focused on workforce diversity. Thus, there is a need for more inclusive studies that consider the diversity of the workforce, such as age, gender, and technological proficiency, to evaluate the effectiveness of VR training for all users (Al-Khiami & Jaeger, 2023; Feng et al., 2023; Pedram et al., 2020; Rey-Becerra et al., 2023).

References

*Abotaleb, I., Hosny, O., Nassar, K., Bader, S., Elrifaee, M., Ibrahim, S., El Hakim, Y., & Sherif, M. (2023). An interactive virtual reality model for enhancing safety training in construction education. *Computer Applications in Engineering Education*, *31*(2), 324-345. https://doi.org/10.1002/cae.22585

*Al-Khiami, M. I., & Jaeger, M. (2023). Safer working at heights: Exploring the usability of virtual reality for construction safety training among blue-collar workers in Kuwait. *Safety*, *9*(3), 63. https://doi.org/10.3390/safety9030063

Alavi, M., & Leidner, D. E. (2001). Research commentary: Technology-mediated learning—a call for greater depth and breadth of research. *Information Systems Research*, *12*(1), 1-10. https://doi.org/10.1287/isre.12.1.1.9720

Asad, M. M., Sherwani, F., Hassan, R. B., Sahito, Z., & Khan, N. (2021). Workforce safety education and training for oil and gas industry: a conceptual framework for virtual reality-based HAZFO expert 2.0. *Journal of Engineering, Design and Technology,* *20*(5), 1122-1131. https://doi.org/10.1108/JEDT-08-2020-0330

Babalola, A., Manu, P., Cheung, C., Yunusa-Kaltungo, A., & Bartolo, P. (2023). A systematic review of the application of immersive technologies for safety and health management in the construction sector. *Journal of Safety Research*, *85*, 66-85. https://doi.org/10.1016/j.jsr.2023.01.007

Backlund, P., Engstrom, H., Hammar, C., Johannesson, M., & Lebram, M. (2007, July 4-6). *Sidh—a game based firefighter training simulation.* 2007 11th International Conference Information Visualization (IV'07), Zurich, Switzerland. https://doi.org/10.1109/IV.2007.100

Balint, B.-N., Stevens, B., Dudfield, H., & Powell, W.. (2020, November 30-December 4). *Exploring the characteristics of immersive technologies for teamwork.* Virtual Interservice/Industry Training, Simulation, and Education Conference, Orlando, Florida.

Bhide, S., Riad, R., Rabelo, L., Pastrana, J., Katsarsky, A., & Ford, C. (2015, May 30-June 2). *Development of virtual reality environment for safety training*. IIE Annual Conference. Proceedings. Nashville, Tennessee.

Blair, E., & Seo, D.-C. (2007). Safety training making the connection to high performance. *Professional Safety*, *52*(10). https://www.jstor.org/stable/45457667

*Buttussi, F., & Chittaro, L. (2018). Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE transactions on visualization and computer graphics*, *24*(2), 1063-1076, Article 7817889. https://doi.org/10.1109/TVCG.2017.2653117

*Buttussi, F., & Chittaro, L. (2021). A comparison of procedural safety training in three conditions: Virtual reality headset, smartphone, and printed materials. *IEEE Transactions on Learning Technologies*, *14*(1), 1-15, Article 9239901. https://doi.org/10.1109/TLT.2020.3033766

*Chan, P., Van Gerven, T., Dubois, J.-L., & Bernaerts, K. (2023). Study of motivation and engagement for chemical laboratory safety training with VR serious game. *Safety Science*, *167*, 106278. https://doi.org/10.1016/j.ssci.2023.106278

Cronin, M. A., & George, E. (2023). The why and how of the integrative review. *Organizational Research Methods, 26*(1), 168-192. https://doi.org/10.1177/1094428120935507

*Dhalmahapatra, K., Maiti, J., & Krishna, O. B. (2021). Assessment of virtual reality based safety training simulator for electric overhead crane operations. *Safety Science*, *139*, Article 105241. https://doi.org/10.1016/j.ssci.2021.105241

*Dhalmahapatra, K., Verma, A., & Maiti, J. (2022). An integrated TRIZ coupled safety function deployment and capital budgeting methodology for occupational safety improvement: A case of manufacturing industry. *Process Safety and Environmental Protection*, *165*, 31-45. https://doi.org/10.1016/j.psep.2022.06.067

*Fajar, M., David, D., Sihombing, P. R., Kekal, H. A., Aditya, I., Ilham, R., & Keswara, Y. S. (2022). The metaverse to enhance safety campaign toward shipping industry (case study: the development and implementation of metaverse in government-owned corporation). *International Journal of Emerging Technology and Advanced Engineering*, *12*(8), 1-11. https://doi.org/10.46338/ijetae0822_01

*Fajar, M., Udjaja, Y., Ang, D., Chowanda, A., Juarto, B., & Yulianto, Y. (2022). A comparative investigation of usability issues toward virtual reality implementation in a state-owned shipping service enterprise. *ICIC Express Letters, Part B: Applications*, *13*(5), 545-552. https://doi.org/10.24507/icicelb.13.05.545

*Feng, Z., Lovreglio, R., Yiu, T. W., Acosta, D. M., Sun, B., & Li, N. (2023). Immersive virtual reality training for excavation safety and hazard identification. *Smart and Sustainable Built Environment, 13*(4), 883-907. https://doi.org/10.1108/SASBE-10-2022-0235

Fivizzani, K. P. (2005). The evolution of chemical safety training. *Chemical Health & Safety*, *12*(6), 11-15. https://doi.org/10.1016/j.chs.2005.08.005

Fromm, J., Radianti, J., Wehking, C., Stieglitz, S., Majchrzak, T. A., & vom Brocke, J. (2021). More than experience?-On the unique opportunities of virtual reality to afford a holistic experiential learning cycle. *The Internet and Higher Education*, *50*, 100804. https://doi.org/10.1016/j.iheduc.2021.100804

*Grabowski, A., & Jankowski, J. (2015). Virtual reality-based pilot training for underground coal miners. *Safety Science*, *72*, 310-314. https://doi.org/10.1016/j.ssci.2014.09.017

Guo, H., Bakdash, J. Z., Marusich, L. R., & Prabhakaran, B. (2022). Augmented Reality and Mixed Reality Measurement Under Different Environments: A Survey on Head-Mounted Devices. *IEEE Transactions on Instrumentation and Measurement, 71*. https://doi.org/10.1109/TIM.2022.3218303

*Gürer, S., Surer, E., & Erkayaoğlu, M. (2023). MINING-VIRTUAL: A comprehensive virtual reality-based serious game for occupational health and safety training in underground mines. *Safety Science*, *166*, Article 106226. https://doi.org/10.1016/j.ssci.2023.106226

Habibnezhad, M., Shayesteh, S., Jebelli, H., Puckett, J., & Stentz, T. (2021). Comparison of ironworker's fall risk assessment systems using an immersive biofeedback simulator. *Automation in Construction*, *122*, 103471. https://doi.org/10.1016/j.autcon.2020.103471

Haridoss, S. (2017). Health and safety hazards management in oil and gas industry. *International Journal of Engineering Research and Technology*, *6*(6), 1058-1061.

Hsu, E. B., Li, Y., Bayram, J. D., Levinson, D., Yang, S., & Monahan, C. (2013). State of virtual reality based disaster preparedness and response training. *PLoS Currents*, *5*.

Jacobsen, E. L., Solberg, A., Golovina, O., & Teizer, J. (2022). Active personalized construction safety training using run-time data collection in physical and virtual reality work environments. *Construction Innovation*, *22*(3), 531-553. https://doi.org/10.1108/CI-06-2021-0113

Jeelani, I., Han, K., & Albert, A. (2020). Development of virtual reality and stereo-panoramic environments for construction safety training. *Engineering, Construction and Architectural Management*, *27*(8), 1853-1876. https://doi.org/10.1108/ECAM-07-2019-0391

*Jelonek, M., Fiala, E., Herrmann, T., Teizer, J., Embers, S., König, M., & Mathis, A. (2022). Evaluating virtual reality simulations for construction safety training: A user study exploring learning effects, usability and user experience. *i-com*, *21*(2), 269-281. https://doi.org/10.1515/icom-2022-0006

Joe, M. D.'N. (2020). *Instructional Design Techniques used to develop virtual reality-based Safety Training in an Industrial Environment* [Doctoral dissertation, Walden University].

Khandelwal, K., & Upadhyay, A. K. (2021). Virtual reality interventions in developing and managing human resources. *Human Resource Development International*, *24*(2), 219-233. https://doi.org/10.1080/13678868.2019.1569920

Kolb, D. A. (1984). *Experience as the source of learning and development*. Prentice Hall.

Leder, J., Horlitz, T., Puschmann, P., Wittstock, V., & Schütz, A. (2019). Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, learning, and decision making. *Safety Science*, *111*, 271-286. https://doi.org/10.1016/j.ssci.2018.07.021

Liang, Z., Zhou, K., & Gao, K. (2019). Development of virtual reality serious game for underground rock-related hazards safety training. *IEEE Access*, *7*, 118639-118649. https://doi.org/10.1109/ACCESS.2019.2934990

Liu, B., Ding, L., Wang, S., & Meng, L. (2022). Misleading effect and spatial learning in head-mounted mixed reality-based navigation. Geo-spatial Information Science *27*(2), 408-422. https://doi.org/10.1080/10095020.2022.2137063

Manuel, A. (2017). Keep well @ work. *MHD Supply Chain Solutions*, *47*(3), 42.

*Nykänen, M., Puro, V., Tiikkaja, M., Kannisto, H., Lantto, E., Simpura, F., Uusitalo, J., Lukander, K., Räsänen, T., Heikkilä, T., & Teperi, A.-M. (2020). Implementing and evaluating novel safety training methods for construction sector workers: Results of a randomized controlled trial. *Journal of Safety Research*, *75*, 205-221. https://doi.org/10.1016/j.jsr.2020.09.015

*Pedram, S., Ogie, R., Palmisano, S., Farrelly, M., & Perez, P. (2021). Cost–benefit analysis of virtual reality-based training for emergency rescue workers: A socio-technical systems approach. *Virtual reality*, *25*(4), 1071-1086. https://doi.org/10.1007/s10055-021-00514-5

*Pedram, S., Palmisano, S., Skarbez, R., Perez, P., & Farrelly, M. (2020). Investigating the process of mine rescuers' safety training with immersive virtual reality: A structural equation modelling approach. *Computers and Education*, *153*, Article 103891. https://doi.org/10.1016/j.compedu.2020.103891

Piccione, J., Collett, J., & De Foe, A. (2019). Virtual skills training: the role of presence and agency. *Heliyon*, *5*(11). https://doi.org/10.1016/j.heliyon.2019.e02583

Purnomo, F. A., Purnawati, M., Pratisto, E. H., & Hidayat, T. N. (2022). *Archery training simulation based on virtual reality.* (pp. 195-198) 1st International Conference on Smart Technology, Applied Informatics, and Engineering (APICS), Surakarta, Indonesia. https://doi.org/10.1109/APICS56469.2022.9918716

Rethlefsen, M. L., & Page, M. J. (2022). PRISMA 2020 and PRISMA-S: common questions on tracking records and the flow diagram. *Journal of the Medical Library Association, 110*(2), 253-257. https://doi.org/10.5195/jmla.2022.1449

*Rey-Becerra, E., Barrero, L. H., Ellegast, R., & Kluge, A. (2023). Improvement of short-term outcomes with VR-based safety training for work at heights. *Applied Ergonomics*, *112*, 104077. https://doi.org/10.1016/j.apergo.2023.104077

Saghafian, M., Laumann, K., Akhtar, R. S., & Skogstad, M. R. (2020). The evaluation of virtual reality fire extinguisher training. *Frontiers in Psychology*, *11*, 593466. https://doi.org/10.3389/fpsyg.2020.593466

Salas, E., Tannenbaum, S. I., Kraiger, K., & Smith-Jentsch, K. A. (2012). The science of training and development in organizations: What matters in practice. *Psychological Science in the Public Interest*, *13*(2), 74-101. https://doi.org/10.1177/1529100612436661

*Stefan, H., Mortimer, M., Horan, B., & Kenny, G. (2023). Evaluating the preliminary effectiveness of industrial virtual reality safety training for ozone generator isolation procedure. *Safety Science*, *163*, Article 106125. https://doi.org/10.1016/j.ssci.2023.106125

Sutherland, I. E. (1965). The ultimate display. *Proceedings of the IFIP Congress,* pp. 506-508.

Touloudi, E., Hassandra, M., Galanis, E., Goudas, M., & Theodorakis, Y. (2022). Applicability of an immersive virtual reality exercise training system for office workers during working hours. *Sports*, *10*(7), 104. https://doi.org/10.3390/sports10070104

*Udeozor, C., Toyoda, R., Russo Abegão, F., & Glassey, J. (2021). Perceptions of the use of virtual reality games for chemical engineering education and professional training. *Higher Education Pedagogies*, *6*(1), 175-194. https://doi.org/10.1080/23752696.2021.1951615

*Xu, Z., & Zheng, N. (2021). Incorporating virtual reality technology in safety training solution for construction site of urban cities. *Sustainability (Switzerland)*, *13*(1), 1-19, Article 243. https://doi.org/10.3390/su13010243

You, D., Seo, B.-S., Jeong, E., & Kim, D. H. (2018). Internet of Things (IoT) for seamless virtual reality space: Challenges and perspectives. *IEEE Access*, *6*, 40439-40449. https://doi.org/10.1109/ACCESS.2018.2829194

Zhang, F., & Parker, S. K. (2019). Reorienting job crafting research: A hierarchical structure of job crafting concepts and integrative review. *Journal of Organizational Behavior*, *40*(2), 126-146. https://doi.org/10.1002/job.2332

Note: An asterisk (*) indicates references used in the literature review.