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ORIGINAL RESEARCH

# A Systematic Review of Virtual Reality Features for Skill Training

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**Abstract**
The evolving complexity of Virtual Reality (VR) technologies necessitates an in-depth investigation of the VR features and their specific utility. Although VR is utilized across various skill-training applications, its successful deployment depends on both technical maturity and context-specific suitability. A comprehensive understanding of advanced VR features, both technical and experiential, their prospective impact on designated learning outcomes, and the application of appropriate assessment methodologies is essential for the effective utilization of VR technologies. This systematic literature review explored the inherent associations between various VR features employed in professional training environments and their impact on learning outcomes. Furthermore, this review scrutinizes the assessment techniques employed to gauge the effects of VR applications in various learning scenarios. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used to systematically select 50 empirical VR studies sourced from three (03) academic databases. The analysis of these articles revealed complex, context-dependent relationships between VR features and their impact on professional training, with a pronounced emphasis on skill-based learning outcomes over cognitive and affective ones. This review also highlights the predominantly subjective nature of the assessment methods used to measure the effects of VR training. Additionally, the findings call for further empirical exploration in novel skill training contexts encompassing cognitive and affective learning outcomes, as well as other potential external factors that may influence learning outcomes in VR.

**Keywords** Simulators · Professional training · Head mounted display · Assessment · Learning

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## 1 Introduction

Virtual Reality (VR) is a computer-generated simulation technology that combines computer graphics, artificial intelligence (AI), sensor technology, and parallel processing technology (Chavez & Bayona, 2018). First emerging in the 1960s, VR has evolved into a wide range of modalities such as Head Mounted Displays (HMDs), creating a more immersive experience in comparison to Cave Automatic Virtual Environment (CAVE VR) systems because of the higher sensory stimuli it offers (Slater & Sanchez-Vives, 2016). Other non-immersive VR systems facilitate user interaction in traditional interfaces by allowing the user to look into the virtual environment from outside instead of being surrounded by it; for example, in desktop screens and web-based environments with mice and keyboards (Zeng & Richardson, 2016).

VR has evolved from its origins in entertainment to serving many innovative purposes including education and training. Its use in professional training, which emphasizes mastering the complex skills essential for applying learned principles in real-world vocational and professional contexts, stands out as a notable application (Renganayagalu et al., 2021). Various industries, including aviation, processing, healthcare, energy, space, industrial robotics programming, and seafarer training, have enthusiastically adopted VR for professional training (Kaplan et al., 2021; Mallam et al., 2019; Moglia et al., 2016; Nathanael et al., 2016; Nazir et al., 2015). This shift has prompted research to explore new VR technologies and features to enhance their efficiency in various professional training contexts. For example, a literature review by Jensen and Konradsen (2018) identified a few cognitive and motor skill training situations where using HMD VRs would be beneficial over other alternatives. Suh and Prophet (2018) proposed a framework that examined the interplay among technological stimuli, cognitive and affective reactions, and individual differences in VR applications within the domains of business, marketing, and education. Chavez and Bayona (2018) conducted a systematic literature review to identify various VR features and their impacts on the learning process. Radianti et al. (2020) explored immersive VR platforms in the context of professional training largely focusing on a range of learning theories, as well as design elements of VR applications and learning contents. In recent systematic reviews, Matovu et al. (2022) examined the impact of various sensory and actional design features of VR on science teaching and learning, while Gu et al. (2023) explored the influence of different technical features of VR on autonomy, human-computer interaction, and presence during training.

However, existing research on VR features and their application in professional training has not thoroughly explored the specific effects of VR features on different types of professional skill training and their corresponding learning outcomes, indicating a gap in the literature in this area. The absence of insight into whether different VR features positively or negatively affect specific types of skill training served as the motivation for this review. Understanding the specific effects of VR features on diverse skill training and associated learning outcomes, along with knowledge of suitable methods for evaluating these effects, would enhance the applicability of VR for more targeted learning strategies. Therefore, the results of this systematic literature review could inform future VR hardware and software development to cater more effectively to specific educational and training requirements.

### 1.1 Theoretical Background

A thorough comprehension of VR's foundational influence on learning processes is required to understand its effect on training. This encompasses recognizing pertinent learning theories, pinpointing which learning types excel with VR, and selecting the best-suited VR technologies. While research has delved into VR's multifaceted role in training, the findings are often disparate and tailored to specific contexts (Baceviciute et al., 2022; Dalgarno & Lee, 2010; Makransky & Lilleholt, 2018; Makransky & Petersen, 2019).

In order to elucidate the mechanism behind learning in VR, Loke (2015) unveiled 11 theories in a comprehensive review of 80 studies. These theories include experiential learning, situated learning and self-efficacy, along with constructivist learning theories. While constructivism is often the primary theoretical foundation for learning in virtual environments (Mikropoulos & Natsis, 2011), other learning mechanisms, such as reflection, verbal interactions, mental operations and vicarious experiences, are equally relevant within VR training. However, there is no "one theory fits all" due to their reliance on specific technical and experiential VR features, such as avatars, interactivity, presence, immersivity, fidelity, and user embodiment to explain the learning process in VR. Makransky and Lilleholt (2018) also demonstrated how VR features play a mediating role between technology and essential cognitive-affective factors germane to learning in an empirical context.

Similarly, in an effort to analyse learning outcomes from a pedagogical perspective, Kraiger et al. (1993) delineated a framework that categorizes the outcomes into three distinct types: cognitive, skill-based, and affective. This framework is grounded in the earlier works of Bloom et al.'s (1956) taxonomy of cognitive learning and Gagne's (1984) theories of affective learning. Studies focusing on VR training have sporadically addressed these learning outcomes, taking advantage of VR's ability to facilitate 3D spatial representation, immersive experiences, real-time and intuitive manipulation of virtual worlds within a single multisensory visual interaction system (Mikropoulos & Natsis, 2011).

These learning theories and associated constructs, outdated by advances in learning technologies, often require revisits to consider emerging educational methods and technologies (Hammad et al., 2020). In exploring the effect of VR technology on learning, Makransky and Petersen (2019) identified two learning paths, affective and cognitive learning, where the learning process is more closely linked with VR features than their usability. In empirical studies, the 3D features of VR have been found to be beneficial for higher-level cognitive learning outcomes, whereas interactivity and haptic feedback are considered beneficial for active skill-based learning (Allcoat & von Mühlenen, 2018). Hoffmann et al. (2014) noted that the use of avatars in virtual environments can enhance affective learning outcomes such as goal setting. Furthermore, experiential VR features that induce subjective psychological responses, including presence and immersion, are intrinsically linked to the overall learning process (Shin, 2017). Dalgarno and Lee (2010) proposed an expanded learning model for interactive 3D virtual environments. This model indicates how VR technologies featuring representational fidelity and learner interaction facilitate the construction of identity and a sense of presence for learners, which results in different learning benefits, including spatial knowledge representation, experiential learning, engagement, contextual learning and collaborative learning. Extant literature also emphasizes the need to effectively evaluate the impact of

VR on learning to gauge its effectiveness (Kaplan et al., 2021; Merchant et al., 2014), allocate resources properly (Sitzmann, 2011), evaluate learners' experiences (Radianti et al., 2020), and understand the broader applicability of VR-based training (Slater & Wilbur, 1997).

However, despite the potential benefits of VR in enhancing learning outcomes (e.g., cognitive, skill-based, or affective), there remains a significant gap in empirical research and a lack of understanding about how specific VR features, both technical and experiential, affect the different types of skill training (e.g., procedural skills, spatial skills etc.) and associated learning outcomes. Therefore, a systematic analysis of VR features' utility relative to diverse learning outcomes is crucial for optimizing VR training interventions.

### 1.2 The Aim of this Study

Considering the existing theoretical gap and absence of a comprehensive framework delineating the relationship between the varied technical and experiential features of VR and their respective impacts on different skills training in a professional context, this systematic literature review sought to aggregate empirical evidence. Specifically, it aimed to elucidate how distinct VR features influence diverse learning outcomes and skill training within professional domains. In addition, this review examined diverse assessment methods in VR-based training to discern the influence of specific features within these training scenarios.

Therefore, the following research questions were formulated:

RQ1: How are technical and experiential VR features operationalized and their effects assessed within professional training contexts?

RQ2: How do these VR features influence different skill training and associated learning outcomes across diverse professional training scenarios?

## 2 Methods

This systematic review included primary sources related to the use of VR in professional training. The review followed The Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol (Moher et al., 2009). Several inclusion and exclusion criteria were determined during the document screening process, as listed below (see Table 1).

**Table 1** Inclusion and exclusion criteria

| Inclusion criteria | Exclusion criteria |
|---|---|
| Peer-reviewed journal articles published in English only | Grey literature (white papers, technical reports etc.) |
| Studies related to professional training using VR | Conference proceedings |
| Comparative research where VR is compared with other methods of training | Studies that did not use VR in a simulated training environment |
| Empirical studies | Review articles |

**Table 2** Search keywords used in databases

| | |
|---|---|
| Search string | (“Virtual realit*” OR “Immersive VR” OR “head mounted display*”) AND (“affordance*” OR “afford*” OR “characteristic*” OR “trait” OR “feature” OR “property” OR “properties”) AND (“simulat*”) AND (“learning” OR “pedagogy” OR “training” OR “education”) |

**Table 3** PICOC criteria of the review. (adapted from Booth et al., 2016)

| PICOC element | Description |
|---|---|
| Population | Professional VR training in safety-critical domains (e.g., aviation, process, maritime or healthcare industries etc.) |
| Intervention | VR simulators, both with HMD and non-HMD devices, are used for training, and their learning outcomes are compared against other methods |
| Comparison | VR is compared against traditional mode of instructions as well as other technologies |
| Outcomes | Learning outcomes from VR training, both self-reported and those measured quantitatively |
| Context | Studies utilizing VR for simulator training in empirical contexts |

## 2.1 Search Methods

The PRISMA framework is used to reduce bias with predefined approaches that enhance clarity and transparency while ensuring the replicability of data collection (Booth et al., 2016). Three (03) academic databases, Web of Science, Scopus, and Education Resources Information Center (ERIC), were used to operationalize the search using a search string (see Table 2).

The search was performed on the 5th of June 2023 in the databases without defining any time limit. All abstracts of the documents were screened based on the predefined inclusion and exclusion criteria. Qualitative synthesis of the documents followed the PICOC criteria during data extraction, as mentioned in Table 3.

## 2.2 Data Extraction

The document search returned 1673 records, of which 348 were identified as duplicates through conditional formatting in Excel, following Kwon et al. (2015). The abstracts of the remaining 1325 records were screened based on the inclusion and exclusion criteria. Consequently, 183 full-text records remained for further screening. The first author performed a full-text review of all the 183 studies. An inter-rater reliability check was performed while each author reviewed the dataset and articles independently. Subsequently, a crosscheck was performed to verify whether the results conformed to each other. After completing the process, a final set of 50 articles was selected for further analysis. The document selection process is depicted in the PRISMA flow diagram (see Fig. 1).

All 50 studies were qualitatively synthesized corresponding to the research questions, categorizing professional domains and identifying common VR features across diverse training contexts. We extracted the emphasis on specific VR features from each study.

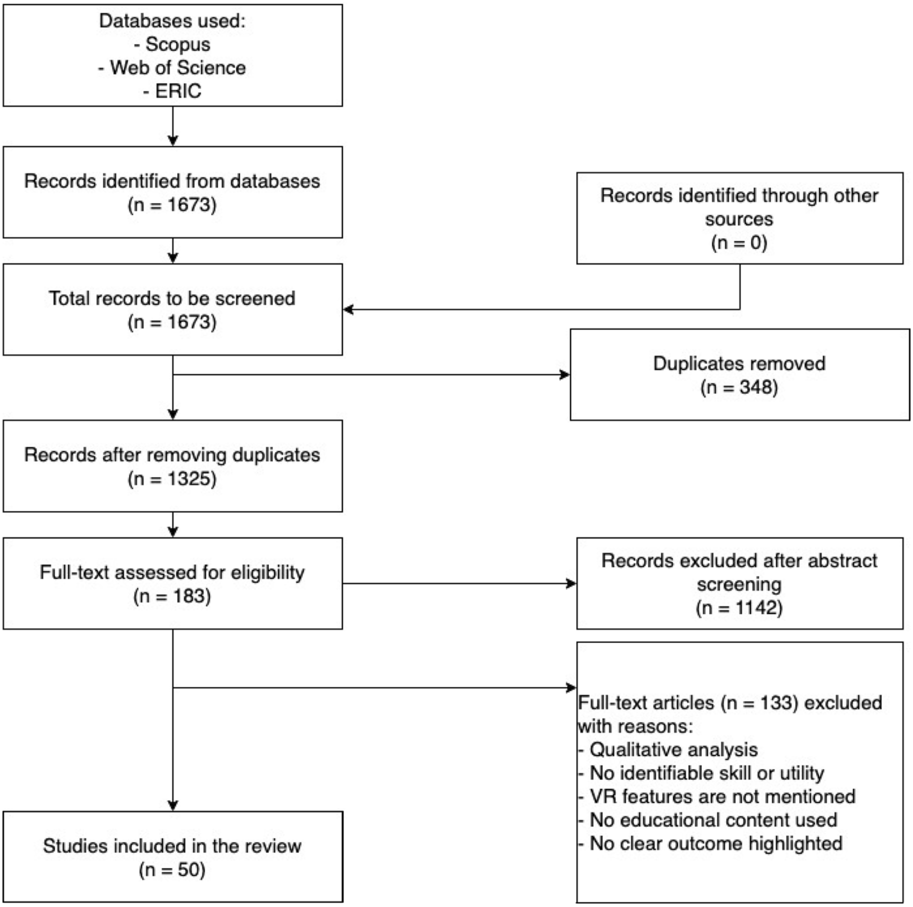


**Fig. 1** PRISMA flow diagram adopted from Page et al. (2021)

Qualitative synthesis was used to reveal the learning outcomes in these studies, which encompassed skill-based, cognitive, and affective domains. Our analysis also explored how VR features influence specific types of skill training in each study's experimental context. We also examined the methods used to evaluate and measure the outcomes of various VR features in each experiment, resulting in a comprehensive understanding of their operationalization and effects in professional training scenarios, allowing for a nuanced and detailed analysis.

## 3 Results

### 3.1 VR Features

The examination of 50 studies revealed a myriad of VR features and their effects in a range of professional training contexts. In this review, healthcare-specific VR studies were the most prevalent (60%), followed by education-related studies (26%). A miscellaneous

**Fig. 2** Breakdown of different domains from the reviewed articles

category, comprising a diverse range of VR applications, accounted for the remainder. This included police, forestry, sports, process industry, driving, language, and organizational training, each at 2% (see Fig. 2).

The technological features of VR, as identified, primarily pertain to hardware-oriented aspects, such as stereoscopic display, haptic feedback, 3D visuals, user interaction, immersivity, high-fidelity environments, multisensory integration, computer-generated real-time feedback, wider field of view, and avatars. Conversely, the experiential features identified were user-perceived and distinct from VR hardware-oriented features. These encompassed user autonomy, an enhanced sense of presence, user embodiment, exercise repeatability, and a safe environment.

It was found that not all features are concurrently used in a single VR system; instead, a common practice is to employ a mixture of different VR features in context-dependent applications. The results indicate that haptic feedback and stereoscopic displays are the most utilized VR features followed by interaction capabilities and 3D visuals as portrayed in the identified studies (see Fig. 3).

3D visuals, interactivity and haptic feedback remain the most common technical features of VR whereas stereoscopic displays, wider field of view, and multi-sensory integration appears to be the differentiating factors between HMD and non-HMD VR systems (see Table 4).

### 3.2 VR for Skill Training with Various Learning Outcomes

The domain-specific professional training studies identified in this review largely utilized VR for motor skill training (45%), followed by Non-Technical Skills (NTS) (15%), spatial skills (6%), problem-solving skills (2%), technical skills (8%) and procedural skills (8%), recognition and identification skills (6%), teaching skills (4%), perceptual cognitive skills (2%), and language learning skills (4%) (see Fig. 4).

This literature review identified a spectrum of VR effects on different skill training, such as *positive*, *negative*, *neutral*, or *mixed*, depending on the specific VR features

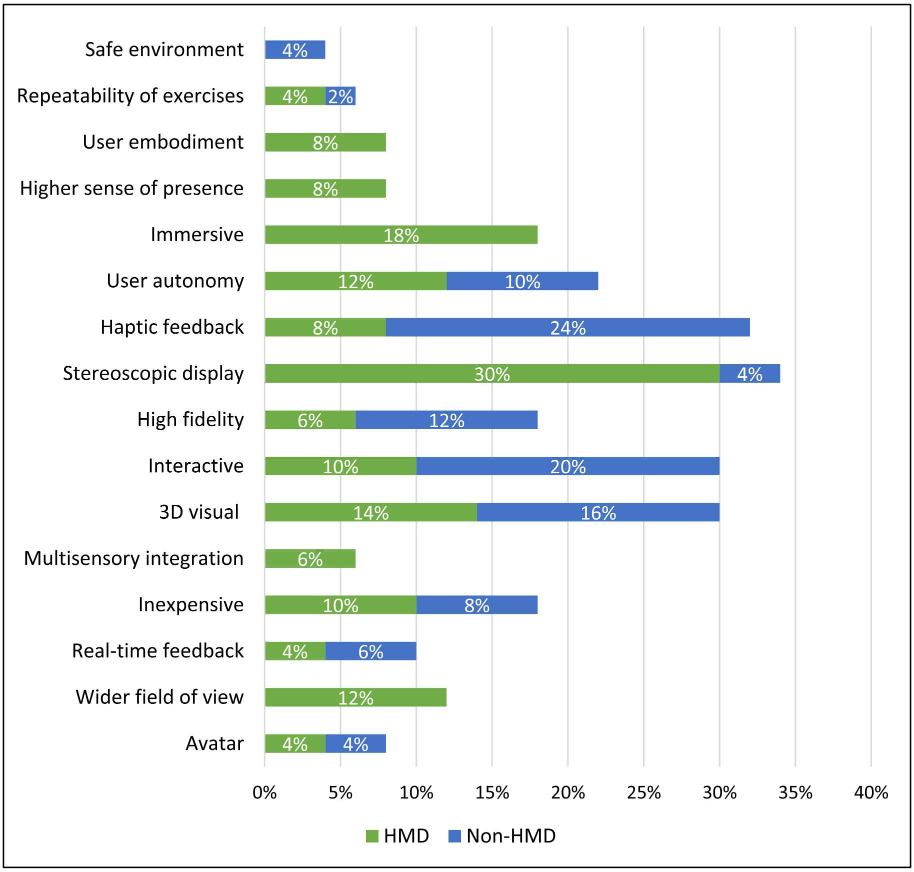


**Fig. 3** Technical and experiential features of VR in HMD and non-HMD modalities (Here, the y-axis represents the identified VR features while the x-axis represents their frequency of being focused within the identified studies)

employed. Here, we define the terms as follows: a ‘positive effect’ denotes an increase in learning outcomes from VR training; a ‘negative effect’ implies a reduction in learning outcomes; a ‘neutral effect’ signifies no observable difference between VR and other learning methods. Finally, a ‘mixed effect’ represents a situation where multiple VR features act together, with some being beneficial and others being non-beneficial for the learning outcome. A detailed account of the feature-specific effects of VR on various skill trainings across different domains is provided in Table 4.

By categorizing learning outcomes into skill-based (encompassing technical, procedural, motor, recognition, and identification tasks), cognitive (including spatial, problem-solving, teaching, language, and other perceptual skills), and affective (e.g., NTS) categories, it can be observed that VR training prioritizes skill-based outcomes, yielding largely positive results. Cognitive outcomes were associated with less frequent VR applications, while affective outcomes were least associated with VR training (see Fig. 5).

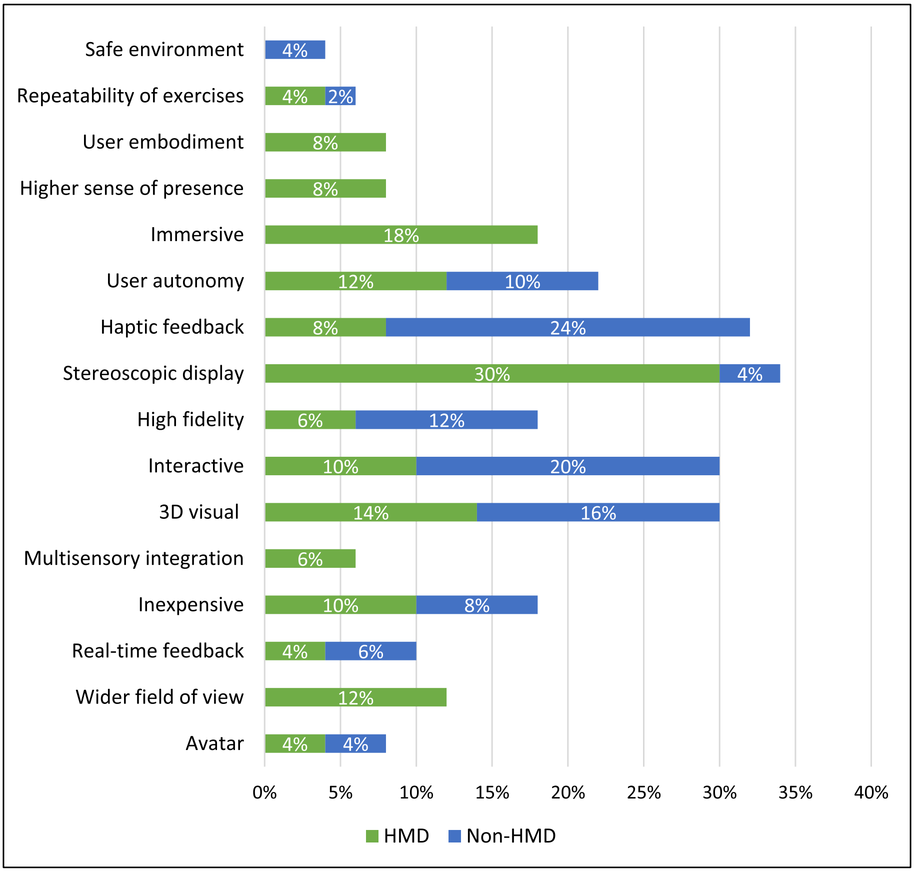
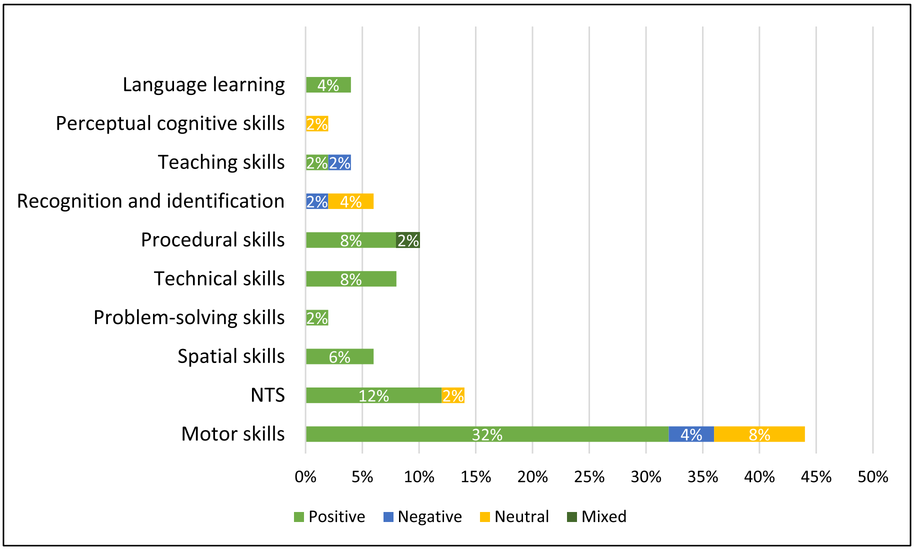


**Fig. 3** (continued)

## 3.3 Assessing the Effects of VR Training

Measuring the effects of VR training has been a widely discussed topic in the literature, where the challenges of providing an objective and unbiased assessment of these effects have been highlighted (Chou & Handa, 2006; Topalli & Cagiltay, 2019). However, in the analysed studies, the assessment techniques identified were predominantly subjective, relying on methods such as self-rated scores, open-ended questions, Likert-scale surveys, and various types of psychological measures. In contrast, measuring activity or response time, movement data (e.g., eye-tracking), rate of task completion, etc. are some of the under-utilized objective assessment methods that have been employed in VR training (see Table 4).

*Positive (+), negative (−), neutral (=) and mixed effect (◌) of different VR features in comparison to the alternative training methods.



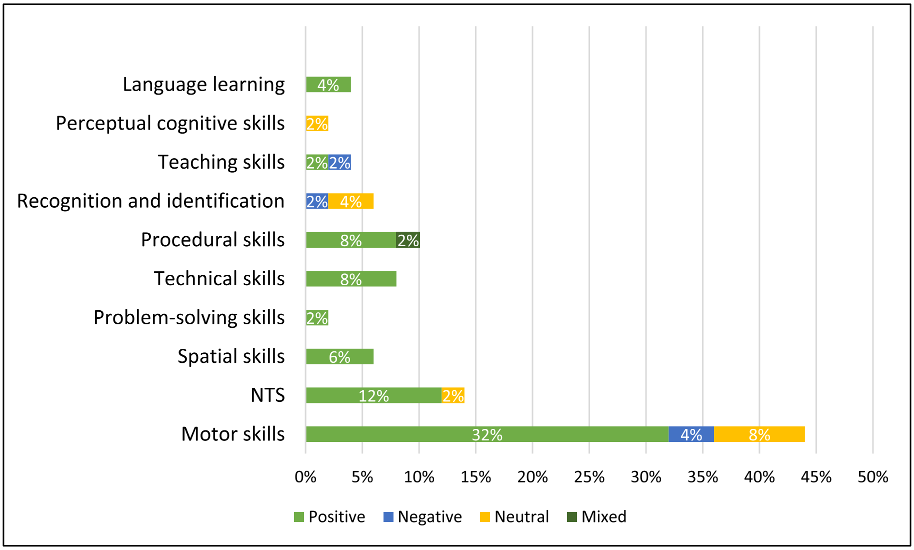


**Fig. 4** *Effect of VR training on identified skills* (Here, the y-axis represents different skills, while the x-axis represents their frequency of being focused within the identified studies)

## 4 Discussion

This systematic literature review delved into the operationalization of technical and experiential VR features within professional training contexts. Specifically, it examined how various skill trainings are influenced by these VR features and their associated learning outcomes across diverse professional training scenarios. This section is structured into distinct subsections, each addressing specific aspects of the research. Sections 4.1, 4.2, and 4.3 include discussions related to diverse technical and experiential VR features, as well as a

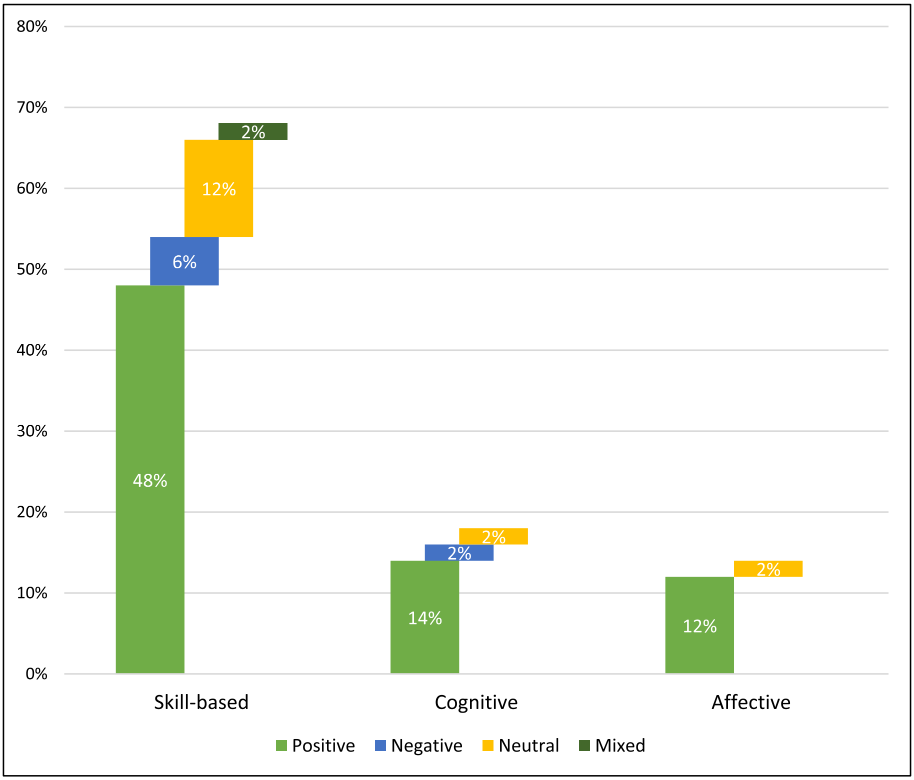


**Fig. 5** VR training for specific learning outcomes (Here, the x-axis represents the type of learning outcomes, and the y-axis represents their frequency of being focused within the identified studies)

comparison of the review's findings with existing literature. Section 4.4 highlights several implications in the areas of theory, methodology, and pedagogical practice related to the findings of this study. Finally, Sect. 4.5 and 4.6 discuss potential future research directions and the inherent limitations of this literature review, respectively.

## 4.1 Technological Features of VR and Their Effect on Skill Training

This study identified several major technological features of VR that are widely used in professional training contexts, including stereoscopic displays, haptic feedback, 3D visuals, interactive interfaces, immersivity, high fidelity, multisensory integration, real-time feedback, and avatar representation. The split in technological characteristics between HMD and non-HMD VR manifests a clear distinction in their respective capabilities. For example, stereoscopic display and wider field of view characterise the significance of visual experience in HMD VRs, whereas interactivity and haptic feedback distinguish non-HMD VRs for their suitability for enhanced motor experiences (see Fig. 3). However, the presence of any specific VR feature can affect skill training in multiple ways, as observed in this literature review. In other words, certain technical and experiential features appear to support specific types of skill training more effectively than others. The intricate nature of these relationships can also be highly contextual (see Table 5).

**Table 4** Relationship between VR features and trained skills

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 1. | Immersive<br>User embodiment (first person perspective) | HMD | eMagin Z800 3DVisor | Psychomotor skills | Psychophysical skills | + | Post-test cognitive questionnaires, open-ended questions | Parmar et al. (2016) |
| 2. | Higher sense of presence | HMD | Oculus Rift™ | Communication skill (non-technical skill: NTS) | Education | + | Self-rated scores, analysis of voice frequency | Remacle et al. (2021) |
| 3. | Stereoscopic display,<br>Wider field of view,<br>User autonomy,<br>Inexpensive,<br>Immersive | HMD | Oculus Rift DK2 | Classroom management skill,<br>NTS | Pedagogy (teacher education) | + | Latency measurement: video-based measurements of the end-to-end latency using a frame-counting method | Lugrin et al. (2016) |
| 4. | Stereoscopic display,<br>High fidelity | HMD | VR4 HMD | Complex spatial skills (visuospatial capabilities) | Architecture education | + | Comparing time elapsed in navigation using both modalities | Grant & Magee, (1998) |
| 5. | Stereoscopic display,<br>3D visual,<br>Inexpensive,<br>Repeatability of exercises | HMD | Unspecified | Procedural skill,<br>surgical skill (psychomotor skills) | Healthcare | + | Evaluators, timed verbal questions, Likert scales | Lohre et al. (2020a) |
| 6. | Stereoscopic display,<br>Wider field of view,<br>User autonomy,<br>3D visual | HMD | HTC Vive | Problem solving skill | Engineering education | + | Success rate and completion time were measured | Wu et al. (2020) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 7. | Stereoscopic display,<br>Immersive,<br>Haptic feedback,<br>User autonomy | HMD | VIDA Odonto | Anaesthesia procedure (technical and procedural skills) | Healthcare | + | Time and accuracy measurements, qualitative simulator sickness questionnaire | Collaço et al. (2021) |
| 8. | Stereoscopic display,<br>Multisensory integration | HMD | Lenovo Mirage Solo | Learning strategy | Education psychology | + | Questionnaire | Klingenberg et al. (2020) |
| 9. | Stereoscopic display,<br>Spatial representation,<br>Multisensory integration | HMD | Lenovo Mirage | Cognitive and affective learning | Organizational training | + | Pre-session and post-test survey questionnaire | Baceviciute et al. (2022) |
| 10. | Stereoscopic display,<br>Immersive | HMD | nVisor SX60 (by Nvis Inc) | Learning relative motion concepts | Education | + | Epistemological belief questionnaire,<br>relative motion problem solving questionnaire (RMPSQ), | Kozhevnikov et al. (2013) |
| 11. | Stereoscopic display,<br>Inexpensive,<br>High fidelity,<br>Interactive | HMD | Oculus Rift | Surgical oncology skills (movement and time efficiency) | Healthcare | + | Objective measurement (time, movement measures), and self-assessment scores | Bing et al. (2019) |
| 12. | Stereoscopic display,<br>Interactive,<br>3D visual,<br>Haptic feedback,<br>User autonomy | HMD | HTC Vive | Recognition and identification skill | Healthcare | - | Post-test measures (recognition test) | Liebermann et al. (2021) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 13. | Stereoscopic display,<br>3D visual,<br>Haptic feedback | HMD | HTC Vive | Root canal detection (identification skill) | Healthcare | = | Post-demonstration questionnaire | Reymus et al. (2020) |
| 14. | Stereoscopic display,<br>Repeatability of exercises | HMD | Oculus Rift | Hand positioning skills (motor skills) | Healthcare | = | Likert scale, free text response | Sapkaroski et al. (2020) |
| 15. | User embodiment,<br>Avatar,<br>3D visuals | HMD | OpenSimulator with Kinect | Teaching skills | Education | + | Survey, video/screen recording and eye tracking | Ke et al. (2016) |
| 16. | Stereoscopic display,<br>Higher sense of presence | HMD | Oculus Rift Development Kit 2 | Driving behaviour (NTS),<br>hazard perception skill | Psychology (driving simulator) | + | Spatial presence (MEC-SPQ) and simulator sickness (SSQ) questionnaire | Malone & Brünken, (2021) |
| 17. | Interactive,<br>Immersive | HMD | Oculus Quest | Declarative knowledge | Education | + | Pre-test (intrinsic motivation scale, self-efficacy scale, knowledge test) and post-test (agency scale, physical presence scale, cognitive load scale, situational interest scale, embodied learning scale in addition to pre-test measures) | Petersen et al. (2022) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 18. | Immersive,<br>Stereoscopic display,<br>Higher sense of presence | HMD | Samsung GearVR | Conceptual and procedural knowledge | Education | - | Cognitive processing using EEG | Makransky et al. (2019) |
| 19. | Immersive<br>Wider field of view,<br>Interactive | HMD | HTC Vive | Language learning | Language training | + | Questionnaires and activity monitoring for cognitive and learning measurement | Legault et al. (2019) |
| 20. | Wider field of view<br>Higher sense of presence<br>Inexpensive | HMD | Cardboard headset | Identification skill | Healthcare | = | Knowledge and attitudes scales | Giordano et al. (2020) |
| 21. | High fidelity,<br>Wider field of view,<br>User autonomy,<br>Eye tracking | HMD | HTC Vive | Perceptual cognitive skills | Police training | = | SIM-TLX, eye tracking (gaze data) analysis using EYEMMV toolbox of MATLAB, | Harris et al. (2021) |
| 22. | Multisensory integration,<br>Real-time feedback,<br>3D visual,<br>Haptic feedback,<br>Inexpensive | HMD | Unspecified | NTS | Healthcare | = | Pre-test, post-test surveys and expert evaluation | Khanal et al. (2014) |
| 23. | User embodiment | HMD | HTC Vive | Remediation of written learning content | Education | + | Advanced EEG measurement techniques, learning tests, and cognitive load measures | Baceviciute et al. (2021) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 24. | Avatar,<br>User embodiment,<br>Real-time feedback | HMD | Microsoft Kinect with OpenSimulator platform | Teaching skills, reflective debriefing | Education | - | Pre-simulation and post-simulation survey on Likert scale | Ke & Xu, (2020) |
| 25. | User autonomy,<br>Immersivity,<br>Wider field of view | HMD | HTC VIVE | Procedural skill | Healthcare | + | Direct observation for procedural skills | Chao et al. (2023) |
| 26. | Interactivity,<br>Stereoscopic display,<br>3D visual,<br>Immersivity | HMD | Samsung GearVR | Language learning | Education | + | Pre-test and post-tests questionnaire | Tai, (2022) |
| 27. | Haptic feedback,<br>Stereoscopic display,<br>3D visual | Non-HMD | Simodont (Nissin Dental Products Europe BV, NieuwVennep, Netherlands) | Procedural skill | Dental | # | Subjective evaluation by experts | Hattori et al. (2022) |
| 28. | 3D visual,<br>Stereoscopic display,<br>Haptic feedback | Non-HMD | CardinalSim | Surgical skill (psychomotor skills) | Healthcare | + | Expert assessment of operative procedures | Won et al. (2018) |
| 29. | Safe environment<br>High fidelity,<br>Interactive | Non-HMD | da Vinci Si VR skills simulator | Surgical skill (psychomotor skills) | Healthcare | - | Analysing physiological response and kinematic movement data on both simulators | Wang et al. (2019) |
| 30. | User autonomy,<br>Real-time feedback | Non-HMD | da Vinci Skills Simulator by Mimic Technologies and Intuitive Surgical | Surgical skill (psychomotor skills) | Healthcare (surgical skill) | + | Pre and post-test measures (qualitative) | Tergas et al. (2013) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 31. | Haptic feedback, Interactive | Non-HMD | VirtaMed ArthroS™ (Zürich, Switzerland) | Arthroscopy skills (psychomotor skills) | Healthcare | = | Between group experiment and questionnaire | Remacle et al. (2021; Vaghela et al. (2021) |
| 32. | Haptic feedback, Interactive | Non-HMD | LapSim | Laparoscopic skills (motor skills) | Healthcare | = | Objective structured assessment scale as post-test measure | Balcı & Ta, (2014) |
| 33. | 3D visual, Interactive | Non-HMD | Simlog Simulation Launcher | Motor skill | Forestry | + | Quantitative measures including time, fall direction and cutting height of timber | Pagnussat et al. (2020) |
| 34. | Haptic feedback | Non-HMD | Unspecified | Objective assessment | Healthcare | + | Identifying performance metrics in VR environment and analysing them using machine learning algorithms | Topalli & Cagiltay, (2019) |
| 35. | User autonomy, Haptic (tactile) feedback, Inexpensive | Non-HMD | Nintendo Wii and PlayStation2 | Laparoscopic skills (motor skills) | Healthcare | + | Pre and post-test measures of different laparoscopic skills | Ju et al. (2012) |
| 36. | User autonomy, High fidelity | Non-HMD | *SEP Robot* by SimSurgery AS; *SurgicalSIM* by SimSurgery and METI | Suturing and knot tying task (motor skills) | Healthcare | + | Pre-post task surveys | Lin et al. (2009) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 37. | 3D visual,<br>Interactive,<br>Real-time feedback | Non-HMD | EndoTower by Immersion Corporation, San Jose, CA | Laparoscopic skills (motor skills) | Healthcare | - | NASA-TLX to measure mental, physical and temporal demand during workload measurement in the respective environments | Stefanidis et al. (2007) |
| 38. | High fidelity,<br>Avatar | Non-HMD | Unspecified | Physical energy management skill (technical and NTS) | Sports | + | Performance was measured against established expert profile | Hoffmann et al. (2014) |
| 39. | Interactive<br>Inexpensive | Non-HMD | VR simulator training platform by World-Viz LLC, CA | Surgical tasks (motor and spatial orientation skills) | Healthcare | + | Time to task completion measure | Chien et al. (2013) |
| 40. | Haptic feedback | Non-HMD | Unspecified | Motor skill | Process | + | Pre & post-test measures (quantitative), psychomotor test | Kaber et al. (2014) |
| 41. | 3D visual<br>Haptic feedback,<br>Interactive | Non-HMD | Simodont | Patient-centred practice,<br>fine motor skill | Dental | + | Qualitative questionnaires | Serrano et al. (2020) |
| 42. | Haptic feedback,<br>High fidelity | Non-HMD | URO-trainer | Motor skills,<br>cognitive skills | Healthcare | + | Questionnaire: evaluation and statistical analysis. Other measures: time and amount of lost blood | Reich et al. (2006) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 43. | Haptic feedback,<br>3D visual | Non-HMD | VR simulator by TraumaVision, Swemac Simulation AB, Sweden | Procedural skills, motor skills, | Healthcare | + | Scientifically validated assessment measure (e.g., tip apex distance of more than 20 mm is considered fail) | Rölfing et al. (2020) |
| 44. | Interactive | Non-HMD | SIMENDO by Delltatech, Delft, The Netherlands | Basic endoscopic skills,<br>motor skills | Healthcare | + | Post-test questionnaires, comparative analysis | Verdaasdonk et al. (2006) |
| 45. | 3D visual<br>Haptic feedback | Non-HMD | Virtual Fracture Carving simulator | Understanding spatially complex surgery (visuospatial and psychomotor skills) | Healthcare | + | Quantitative measures | Pahuta et al. (2012) |
| 46. | Inexpensive,<br>Repeatability of exercises,<br>Avatar,<br>Safe environment | Non-HMD | ICE STORM VR | Teamwork (NTS) | Healthcare | + | Likert scale, NASA-TLX etc. | Abelson et al. (2015) |
| 47. | Interactive,<br>High fidelity | Non-HMD | VIST-C VR simulation system by Mentice AB, Gothenburg, Sweden | Technical,<br>procedural, and management skills | Healthcare | + | Post-test questionnaire | Lonn et al. (2012a) |
| 48. | 3D visual,<br>Haptic feedback,<br>Interactive,<br>Inexpensive | Non-HMD | Prototype of a Computer Airway Simulation System (CASS) | Technical skill, hand-eye coordination (motor skills) | Healthcare | + | Post-test Likert scale | Casso et al. (2019) |

**Table 4** (continued)

| SL | VR features | VR environment | VR devices | Target skill / utility | Domain | Effect* | Method used to assess | Source |
|---|---|---|---|---|---|---|---|---|
| 49. | High fidelity, User autonomy | Non-HMD | PortCAS simulator system | Hand-eye coordination skills, precision, speed (motor skills) | Healthcare | = | Task completion time and muscle effort (collected by physiological instruments) | Zahiri et al. (2016) |
| 50. | Real-time feedback, User autonomy | Non-HMD | DentSim by Image Navigation, New York, NY | Technical skill | Healthcare | + | Different operational parameters (time, margin location scores, wall incline scores) were analysed using ANOVA | Kikuchi et al. (2012) |

Table 5 Mapping of technical and experiential VR features for specific skill training

| Skill | VR modality | Supporting technical features | Supporting experiential features | Reference |
|---|---|---|---|---|
| Psychomotor/ motor skill training | HMD | Immersive<br>Stereoscopic display<br>3D visual,<br>High fidelity<br>Interactive | User embodiment<br>Inexpensive,<br>Repeatability of exercises | Bing et al. (2019), Lohre et al. (2020a), Parmar et al. (2016) |
| | Non-HMD | 3D visual,<br>Haptic feedback<br>Real-time feedback<br>Interactive<br>High fidelity | User autonomy,<br>Inexpensive | Casso et al. (2019), Chien et al. (2013), Ju et al. (2012), Kaber et al. (2014), Lin et al. (2009), Pagnussat et al. (2020), Pahuta et al. (2012), Reich et al. (2006), Rölfing et al. (2020), Serrano et al. (2020), Tergas et al. (2013), Verdaasdonk et al. (2006), Won et al. (2018) |
| Non-technical skill | HMD | Stereoscopic display<br>Higher field of view,<br>Immersive | Higher sense of presence<br>User autonomy,<br>Inexpensive, | Lugrin et al. (2016), Malone & Brünken (2021), Remacle et al. (2021) |
| | Non-HMD | Avatar,<br>Interactive,<br>High fidelity | Safe environment<br>Inexpensive,<br>Repeatability of exercises, | Abelson et al. (2015), Hoffmann et al. (2014), Lonn et al. (2012a) |
| Spatial skill | HMD | Stereoscopic display,<br>High fidelity | | Grant & Magee (1998) |
| Problem-solving skill | HMD | Stereoscopic display,<br>Wider field of view,<br>3D visual | User autonomy | Wu et al. (2020) |
| Technical skill | HMD | Stereoscopic display,<br>Immersive,<br>Haptic feedback | User autonomy | Collaço et al. (2021) |
| | Non-HMD | Interactive,<br>High fidelity<br>3D visual,<br>Haptic feedback,<br>Real-time feedback, | Inexpensive<br>User autonomy | (Casso et al. 2019), Kikuchi et al. (2012), Lonn et al. (2012a) |

**Table 5** (continued)

| Skill | VR modality | Supporting technical features | Supporting experiential features | Reference |
|---|---|---|---|---|
| Procedural skill | HMD | Stereoscopic display,<br>Immersive,<br>Haptic feedback,<br>Wider field of view | User autonomy | Collaço et al. (2021) |
| | Non-HMD | Haptic feedback,<br>3D visual,<br>Interactive,<br>High fidelity | | (Lonn et al. 2012a), Rölfing et al. (2020) |
| Teaching skill | HMD | Avatar,<br>3D visuals | User embodiment, | Ke et al. (2016) |
| Learning skill | HMD | Immersive,<br>Wider field of view,<br>Interactive,<br>3D visual,<br>Stereoscopic display,<br>Multisensory integration | User embodiment | Baceviciute et al. ( 2021, 2022), Klingenberg et al. (2020), Kozhevnikov et al. (2013), Legault et al. (2019) |

First, *Stereoscopic Displays* significantly increase immersion in a simulated environment, providing depth perception of objects to users (Collaço et al., 2021; Colombo et al., 2014). However, perceptual irregularities in VR users may result from conflicts in depth perception among different types of screens (Hoffman et al., 2008; Wood et al., 2021). Stereoscopic displays combined with haptic force-feedback could also make VR systems particularly suitable for motor skill training (Kaber et al., 2014), although individual differences in depth perception capabilities may affect training performance in stereoscopic VR simulators (Hattori et al., 2022).

*Haptic Feedback* activation mechanisms have been probed in various ways in the context of human performance testing. For example, it guides and reduces the information processing load of users and avoids unnecessary actions (Rosenberg, 1993). The advantages of haptic feedback in VR are realized in different contexts, such as increasing the fidelity of synthetic bone simulation (Stirling et al., 2014), assisting psychomotor skill training in endoscopic skull-based surgery (Won et al., 2018), and hip fracture surgery simulation (Rölfing et al., 2020), thereby becoming an indispensable part of laparoscopic surgical training (Liu et al., 2018). Haptic feedback is also presumed to increase the sense of presence and the consequent task performance in VR (Kaber & Zhang, 2011). In addition, haptic feedback is considered one of the defining features of VR that facilitates user embodiment during a reading task (Baceviciute et al., 2021). The coupling of accurate visual and haptic feedback has been realized to improve human performance in VR (Arsenault & Ware, 2000; Richard et al., 1996), especially for novice trainees (Collaço et al., 2021). The increased latency between visuals and haptics may reduce performance in VR (Kaber & Zhang, 2011). Therefore, an instantaneous link between the two is warranted for an enhanced outcome. In contrast, haptic features coupled with other visual features, such as stereoscopic displays and 3D visuals, have been found to have less significance (Reymus et al., 2020) to negative effects (Liebermann et al., 2021) on recognition and identification skills.

*3D Visual Representations* aid in building a more complete mental model than 2D environments (Dede et al., 1999). In addition, it induces empathy among users in real-world environments (Mallam et al., 2017). In the reviewed articles, 3D visuals coupled with other VR features have been reported to have positive effects on procedural (Lohre et al., 2020b), motor (Lohre et al., 2020b), problem-solving skills (Wu et al., 2020), and teaching skills (Ke et al., 2016) in HMD environments, and basic to advanced motor skills (Casso et al., 2019; Pagnussat et al., 2020; Pahuta et al., 2012; Rölfing et al., 2020; Serrano et al., 2020; Won et al., 2018), procedural skills (Rölfing et al., 2020), technical skills (Casso et al., 2019) and visuospatial skills (Pahuta et al., 2012) in non-HMD environments. In rare contexts, 3D visual features coupled with real-time feedback negatively affect motor skill training (Stefanidis et al., 2007) in non-HMD environments. However, the effects on recognition and identification skills can be both positive (Liebermann et al., 2021) and neutral (Reymus et al., 2020) in HMD environments. Interestingly, in terms of NTS training, the effects of 3D representations coupled with real-time haptic feedback and multisensory integration in VR did not differ from those of traditional training methods (Khanal et al., 2014).

*Interactive Features* are more prevalent in non-HMD studies than in HMD studies (see Fig. 3). User interaction in virtual environments is beneficial for motor skill development. The presence of interactive features has been reported to account for a larger increase in motor performance than other features in small VR environments (Arsenault & Ware, 2000). The necessity of interactive features has also been highlighted for technical, procedural, and management skills training (Lonn et al., 2012a) as well as for enhanced embodied representation in VR during language training (Legault et al., 2019) and teacher training (Ke & Xu, 2020). The observed divergence in the applicability of VR interactive features beyond motor skill training may be due to rapid technological developments in the areas of haptics, motion sensing, and tracking. With regard to achieving specific training goals, multisensory integration in interactive virtual environments has a positive influence (Makransky & Petersen, 2019; Mikropoulos & Natsis, 2011). In addition, Shin (2017) highlighted the emotional component of interactivity by discussing the association between users' attitudes and interactive experiences in VR environments, which might have a bearing on learning outcomes.

*Immersivity* is exclusive to HMD environments and positively influences all skill training types identified in this review. The level of immersion in VR is correlated with the "sense of presence" (North, 2014; Witmer & Singer, 1998), which in turn mediates learning outcomes (Bulu, 2012). However, highly immersive environments may increase presence but may not always have positive learning outcomes owing to increased demands on working memory, as observed in the study by Makransky et al. (2019).

*High-Fidelity* VR environments have shown positive effects on all types of cognitive and motor skill training, as observed in this study. In addition, technical, non-technical, procedural, and management skill training recognize the importance of high-fidelity VR environments (Hoffmann et al., 2014; Lonn et al., 2012a). However, high-fidelity realism is not an exclusive requirement for higher learning outcomes because low-cost low-fidelity simulators are as effective as expensive high-fidelity simulators at times (Matsumoto et al., 2002). Inexpensive portable VR simulators show at least a similar or higher learning outcome than other available alternatives in different educational and training contexts (Bing et al., 2019; Chien et al., 2013; Lohre et al., 2020b).

The importance of *Multisensory Integration* in VR is recognized in instructional design and pedagogy, along with other technological features (Baceviciute et al., 2022; Klingenberg et al., 2020). It forms a critical aspect of learning within VR environments by providing opportunities to interact with otherwise intangible and inaccessible objects in a safe environment while still being able to perceive it as if the learner is in a real environment (Klingenberg et al., 2020; Mikropoulos & Natsis, 2011).

*A Wider Field of View* is recognized as a unique feature of HMD VR environments, which affects NTS (Lugrin et al., 2016), problem-solving skills (Wu et al., 2020) and language training (Legault et al., 2019) positively. However, its effect on object identification using cheaper cardboard HMDs (Giordano et al., 2020) or on perceptual cognitive skills using high-end HMDs (Harris et al., 2021) did not make any difference.

## 4.2 Experiential Features of VR and Their Effect on Skill Training

The effects of VR technical features on learning outputs are often mediated by other experiential features. For example, technical features such as immersion, the presence of avatars, and six degrees of freedom correspond to the sense of presence (North, 2014), embodied experience (Ke et al., 2016; Ke & Xu, 2020), and user autonomy (Wu et al., 2020) respectively; all of which positively influence the overall learning outcome, as reported in the literature (Bulu, 2012; Lindgren & Johnson-Glenberg, 2013; Wu et al., 2021). In addition, the flexibility of VR simulators facilitates repeated exercises, which in turn benefits motor skill training and associated learning activities (Köyağasıoğlu & Özgürbüz, 2022), as well as other NTS, such as teamwork training (Abelson et al., 2015). Presence is considered one of the main experiential features and a prime psychological factor in VR learning environments (Mikropoulos & Strouboulis, 2004; Winn & Windschitl, 2000). In this literature review, the effect of sense of presence on different types of behaviour, perceptual, conceptual, and procedural skills training was identified. Simultaneously, the positive effect of presence on driving behaviour, hazard perception skills (Malone & Brünken, 2021), and the potential disassociation between presence and learning outcomes in immersive environments (Makransky et al., 2019) are also depicted in the literature.

## 4.3 Measuring the VR Effects

Although VR learning environments are being explored as alternative solutions across a plethora of learning contexts, the lack of appropriate metrics for evaluating learning outcomes poses a challenge for VR educators (dos Santos Nunes et al., 2016; Ralph et al., 2017). Janßen et al. (2016) exposed the complex nature of measuring performance in VR which is related to the complexity in measuring individual differences of users and other associated variables such as immersion, presence, flow, gaming experience etc. Qualitative measures of performance assessment are prevalent in the literature, as identified in this review. Hybrid methods have also been proposed; for example, Ralph et al. (2017) developed an assessment rubric combining presence, immersion, and flow questionnaires. Dos Santos Nunes et al. (2016) proposed a model to automatically predict learning outcome by monitoring the participants behaviour in VR and the difference in the types of interaction among the participants. The different objective measurement techniques cited in this study include measuring task completion time, movement, success rate, physiological measures (e.g., EEG), and the specific output of actions performed in VR. Suh and Prophet (2018) proposed the need for method-triangulation, including qualitative, quantitative, and neuropsychological (e.g., ECG) measures, by citing the limitations for each when applied individually to evaluate VR experiences. Novel measurement techniques include utilizing AI and machine learning in healthcare VR simulators (Mirchi et al., 2020; Yilmaz et al., 2022), which require further empirical investigation before they can be employed in other domain-specific contexts.

## 4.4 Implications of this Review

The findings of this systematic literature review reveal an intricate relationship between VR features and training contexts, bearing substantial theoretical, methodological, and pedagogical implications.

### 4.4.1 Theoretical Implications

Extant literature highlights the association of specific VR features with diverse learning outcomes: 3D representation with higher-order learning and haptic and interactive elements with active skill-based learning (Allcoat & von Mühlenen, 2018; Van der Meijden & Schijven, 2009). Additionally, avatars contribute to affective outcomes, while experiential attributes such as presence and immersion are foundational to the learning process (Shin, 2017). Understanding these intricate relationships between VR features and varied learning outcomes is essential for enhancing training efficiency. Furthermore, knowledge of the distinct influences of VR features on learning processes can inform the design of VR applications, thereby optimizing them for educational effectiveness (Radianti et al., 2020). This review addresses this need by aggregating empirical evidence to develop a comprehensive framework for VR features and skill training within a given context.

The perceived effects of a few selected VR features (e.g., immersion, interaction, and presence) on learning outcomes in different educational contexts and controlled environments have been conceptually investigated in literature (Ai-Lim Lee et al., 2010; Barrett et al., 2021; Makransky & Lilleholt, 2018). The results of these investigations predominantly showed a linear relationship, suggesting a positive perceived effect, ranging from low to high. However, this literature review revealed the intricate nature of the interrelationships between these VR features and targeted skill acquisition, showcasing a range of effects—positive, negative, neutral, and mixed—in the context of professional training. These findings underscore the nuanced impact of individual VR features across different contexts.

Furthermore, literature underscores the significance of multiple external factors in VR learning environments. These factors include personal differences, age, gender (Salzman et al., 1999), prior knowledge, experience, and motivation (Dengel & Mägdefrau, 2020) as well as learners' spatial abilities and learning styles (Ai-Lim Lee et al., 2010). Simultaneously, instructional design principles such as guidance, feedback, control, and pre-training are emphasized as essential mediators for effective VR training (Moreno & Mayer, 2007). This literature review revealed that the effects of VR on different types of skill training differ based on the hardware used, specifically HMD and non-HMD devices. Such findings may explain the nonlinear impact of distinct VR features on skill training and could serve as a guide to anticipate VR outcomes in specific contexts.

It is important to recognize that a specific VR feature's absence of association with a skill does not necessarily imply a lack of correlation. Instead, it may reflect a lack of evidence from the studies identified in this review.

### 4.4.2 Methodological Implications

One of the primary objectives of VR training is to provide precise sensory stimuli that mimics an authentic work environment. This aims to expose trainees to life-like experience (Bowman & McMahan, 2007; Lonn et al., 2012b). Consequently, it is crucial to identify the VR features that elicit responses aligned with the realism needed for specific skill training, thereby promoting optimal training transfer. In essence, the effectiveness of VR training is anchored in immersion benefits, which are intrinsically linked to immersion elements, namely the specific features of VR (Makransky & Petersen, 2021). The mapping of VR features to specific skill training in this review could assist in identifying the immersion elements, potentially enhancing learning outcomes in these contexts.

Assessing the effects of VR training is challenging, largely because of reliance on subjective measures (Cummings & Bailenson, 2016; Slater, 2004). Despite these challenges, subjective measures remain prevalent, as is highlighted in this review. This underscores the importance of devising standardized, objective approaches to evaluate VR training efficiency across various learning outcomes. In addition, understanding the requisite immersion levels in VR through proper assessment of specific outcomes can not only enhance training effectiveness, but also reduce learners' mental workload (Chao et al., 2017).

### 4.4.3 Pedagogical Implications

The findings highlight the pronounced efficacy of VR in skill-based learning outcomes, in contrast to its limited impact on cognitive and affective learning (see Fig. 5). Such insights can guide VR training design in professional contexts, indicating a potential preference for using VR in skill and competency training rather than conceptual instruction.

An important aspect of VR training is that sometimes it does not support actual learning as much as it induces enjoyment, motivation, or engagement (Makransky et al., 2019; Parong & Mayer, 2018; Zhao et al., 2022). As a reason for this, researchers point towards the "novelty effect" where students may find VR interesting at first but long-term learning retention remains questionable (Allcoat & von Mühlenen, 2018; Mikropoulos & Natsis, 2011). However, by tailoring VR environments and associated features to match the cognitive and perceptual demands of the intended learning outcomes, the "novelty effect" can be harnessed to promote sustained deep learning rather than superficial engagement (Dalgarno & Lee, 2010). In addition, learner characteristics have an underlying link with learning experiences in VR. For example, spatially adept individuals may acquire greater benefits from VR's 3D visual features (Lee & Wong, 2014), while those inclined towards experiential learning styles could find the immersive, interactive elements of high-fidelity VR particularly advantageous (Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011). Age and development level are also crucial factors in VR training, as younger learners may be enticed by VR's game-like immersion compared to adult learners (Parong & Mayer, 2018). Incorporating this knowledge with the review findings can refine strategies for adaptive VR learning environments in professional training, allowing educators to customize VR experiences according to learners' needs and optimize outcomes.

Empirical research suggests that overloading VR environments with features can detract from the optimal learning outcomes. Parong and Mayer (2018, 2020, 2021) emphasized the need to mitigate non-essential VR features that introduce extraneous cognitive load, thereby enhancing the focus on actual learning goals. This review can facilitate strategic resource allocation to prioritize essential VR features by elucidating the impact of specific VR features on different learning outcomes. For instance, in *spatial skill training*, stereoscopic display may be more critical than haptic feedback. Likewise, less immersive non-HMD VR might not be as suitable for *spatial skill training*, yet it can effectively address *motor skill training*. Such mapping of VR features detailed in this review (see Tables 4 and 5) offers pivotal insights for trainers and VR system designers, guiding hardware selection—be it HMD or non-HMD—aligned with specific skill training contexts.

## 4.5 Future Research Directions

Advances in VR technology have reshaped education and training, underscoring the need to study the intersection of learner characteristics, VR features, and learning outcomes in various theoretical contexts. VR exhibits a significant potential for enhancing skill-based learning outcomes across a range of domains. However, a notable gap persists in the empirical validation concerning the effectiveness of VR for cognitive and affective learning outcomes across all domains. Future studies should strive to uncover innovative, widely deployable features and pedagogically apt VR training solutions that address all types of learning outcomes (cognitive, skill-based, and affective) while also mitigating negative physiological impacts (e.g., cybersickness or eyesight problems). Moreover, refining assessment techniques, possibly through hybrid methods that blend subjective and

**Table 6** Potential research questions in educational VR research

| Research area | Potential research questions |
|---|---|
| Investigating VR effects outside experimental conditions | What are the long-term effects of VR training in authentic professional environments, accounting for varied samples to ensure generalizability? |
| Advancing pedagogical applications in VR | What are the best practices for learning and evaluation in VR environments considering the pedagogical requirements? |
| Integrating state-of-the-art features in VR | What strategies can be employed to optimize the integration of advanced technologies, such as biometrics, neural interfaces, and artificial intelligence, into VR systems to enhance learning outcomes? |

objective assessments or advanced solutions, such as AI, is crucial for accurately measuring the learning impact of VR. Comprehensive empirical studies are necessary to elucidate the interplay among the factors that mediate learning outcomes in VR environments as technology progresses.

Future research in VR training should examine both practical and technologically relevant concerns with a pedagogical focus, addressing, but not limited to, the following key questions (see Table 6):

### 4.6 Limitations of this Study

Given the exclusive focus of the selected studies in this review on professional training, the complexity depicted in the relationship between VR features and learning outcomes remains highly contextual, excluding other educational scenarios such as non-professional or child education. In addition, the study did not account for potential mediators, such as learners' age, their technological literacy (Van Laar et al., 2017), and the novelty effect of VR (Makransky et al., 2019), which could influence learning outcomes and therefore, potentially affect the applicability of the findings.

The analysis in this review draws from empirical studies that may encompass varied reporting qualities, study designs, and construct conceptualizations. In particular, the varied interpretations of VR features and learning outcomes across studies adds to this complexity. Excluding conference articles may have led to the omission of significant empirical research. A possible publication bias—favouring reports with positive VR effects (Sutton et al., 2000)—could have skewed our review analysis. While the selected studies reported VR training effects at the 5% significance level, discerning specific VR feature effects required qualitative interpretation. The wide scope of this review, covering simulations from basic desktops to immersive applications across various domains, might limit its direct applicability to individual VR systems. These aspects serve as characteristics of our findings, necessitating careful interpretation of the results within the context of the identified limitations.

## 5 Conclusion

This systematic review comprehensively investigated the operationalization of VR features in professional training contexts, their influence on specific skill training and learning outcomes, and the assessment techniques used to measure learning effects in VR.

The results underscored the diverse applications of VR across multiple domains, notably in healthcare and formal education, identifying an array of technological and experiential VR features relevant to skill training. It remains established that VR simulators significantly enhance motor skills, yet the specific contribution of a few individual VR features, such as immersivity, fidelity and interactivity remain ambiguous in this context. The primary intent of this review was to deconstruct the VR features employed in each study. In doing so, we aimed to provide a comprehensive summary of all features and elucidate their associations with skill training.

This review sheds light on the significant role of haptic feedback, 3D visuals, interactivity, and unique multisensory integration offered by VR environments in facilitating effective learning. Although this study underscores the pronounced influence of VR on skill-based learning outcomes, it simultaneously emphasizes a comparatively subdued effect on cognitive and affective learning outcomes, thus underscoring the need for additional empirical research focusing on VR training in contexts that target these outcomes. Furthermore, the review revealed the complexity of measuring the effects of VR on learning, noting the prevalent use of subjective measures and the potential for quantitative, hybrid, and other state-of-the-art measures (e.g., AI) to create a comprehensive assessment framework.

The findings from this review pave the way for a user-focused adaptive learning approach that harnesses the power of VR technology and has the potential to significantly enhance professional training outcomes. It is envisaged that the findings of this literature review will offer pivotal insights into the technical and experiential aspects of VR for the system designers and education providers alike.

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**Data Availability** This manuscript has no associated data in a data repository. However, the data related to the literature review can be provided upon suitable request to the corresponding author.

**Conflict of Interest** We, the authors, declare no conflicts of interest regarding the research, data, or financial involvement that could potentially influence the objectivity or impartiality of this scientific article.

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