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ORIGINAL RESEARCH

Effectiveness of VR Head Mounted Displays in Professional Training: A Systematic Review

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Abstract
Over the past decade, virtual reality (VR) has re-emerged as a popular technology trend. This is mainly due to the recent investments from technology companies that are improving VR systems while increasing consumer access and interest. Amongst many applications of VR, one area that is particularly promising is for pedagogy. The immersive, experiential learning offered by VR provides new training and learning opportunities driven by the latest versions of affordable, highly immersive and easy to use head mounted display (HMD) systems. VR has been tested as a tool for training across diverse settings with varying levels of success in the past. However, there is a lack of recent review studies that investigates the effectiveness, advantages, limitations, and feasibility of using VR HMDs in training. This review aims to investigate the extent to which VR applications are useful in training, specifically for professional skill and safety training contexts. In this paper, we present the results from a systematic review of the effectiveness of VR-based simulation training from the past 30 years. As a secondary aim, the methodological trends of application and practical challenges of implementing VR in training curriculum were also assessed. The results suggest that there is generally high acceptance amongst trainees for VR-based training regardless of the technology limitations, usability challenges and cybersickness. There is evidence that VR is useful for training cognitive skills, such as spatial memory, learning and remembering procedures and psychomotor skills. VR is also found to be a good alternative where on the job training is either impossible or unsafe to implement. However, many training effectiveness studies reviewed lack experimental robustness due to limited study participants and questionable assessment methods. These results map out the current known strengths and weaknesses of VR HMDs and provide insight into required future research areas as the new era of VR HMD's evolve.

Keywords Virtual reality (VR) · Head mounted display (HMD) · Systematic review · Training methods · Effectiveness · Immersive · Education · Pedagogy

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1 Introduction

In recent years, Virtual Reality (VR) has become more prevalent in the consumer marketplace. With the advancements in computing power, display technologies and 3D gaming, Head Mounted Display (HMD) based VR systems are rapidly growing as a consumer product. VR has long been considered as an effective medium for education and training (Pantelidis 2009; Psotka 1995). However, both cost and technological maturity have been major limiting factors for VR proliferation across society, including its utilization for educational and training applications. The introduction of Oculus Rift in 2011 signalled a renewed interest, investment and development in VR HMDs. Since then VR HMDs have become more affordable, easier to use and offer better user experiences. Consumer-grade VR HMDs are now available for less than 500 USD compared to the first commercial HMD VPL eyephone HRX that cost 49,000 USD (IGI consulting 1992) when launched in 1987.

The concept of immersive VR technologies, as we know it today, began in the 1960s when Morton Heilig first introduced Sensorama simulator in 1962 followed by Ivan Sutherland's "The Ultimate Display" concept (Sutherland 1965). Since then, there have been many technological milestones that have expanded the boundaries of VR for individuals to have increased immersive experiences. Throughout the 1970s and 1980s, NASA was the main early adopter of the technology by using VR HMDs in flight simulations and space operations research. The AMES research center at NASA developed VR HMDs for researching telepresence control and telerobotic control for space station operations (Fisher et al. 1987).

The definition of VR has changed throughout these periods based on the context of use and state of technology of that time. Based on the current state of the art, *Virtual Reality (VR) is defined as a computer-generated three-dimensional graphical representation of the real or imaginary environment in which users are immersed through a dedicated headset or an array of display walls.* In addition, wearable sensors could be worn to provide more sensory cues to the user (e.g. binaural audio, vests and gloves with haptics). VR allows users to interact with a computer-generated world, where the user's natural sensory perceptions are fully/partially replaced with a digital alternative. VR is further described by the following three characteristics (Logan 1998):

Interactivity: The graphical image responds in real-time to the user's commands.

Immersion: The user is drawn into the simulation by sensorial experience.

Imagination: the user's imagination is free to explore the simulated world to see, touch, move and experience things in new ways from new perspectives.

Through this experience, users can find creative solutions to problems and new ways of seeing and doing things (Logan 1998). Although physical immersion is a major characteristic of a VR system, there are other forms of VR systems that are non-immersive (Robertson et al. 1993). Termed as "Desktop VR" or "Fish-Tank VR", this non-immersive VR systems contain computer screens, 3D graphics and interacted through computer input devices. In this study, however, we only focus on the immersive VR and specifically VR HMD systems (Fig. 1), as they are currently the most popular, state of the art VR technology. An HMD is the main hardware component of the current VR technology. Unlike computer screens in the Desktop VR, HMDs often work as both input and output device. Inputs include head motion tracking sensors, gyroscopes and accelerometers. The outputs are the two graphical displays (one for each eye). In VR HMDs the point-of-view of the

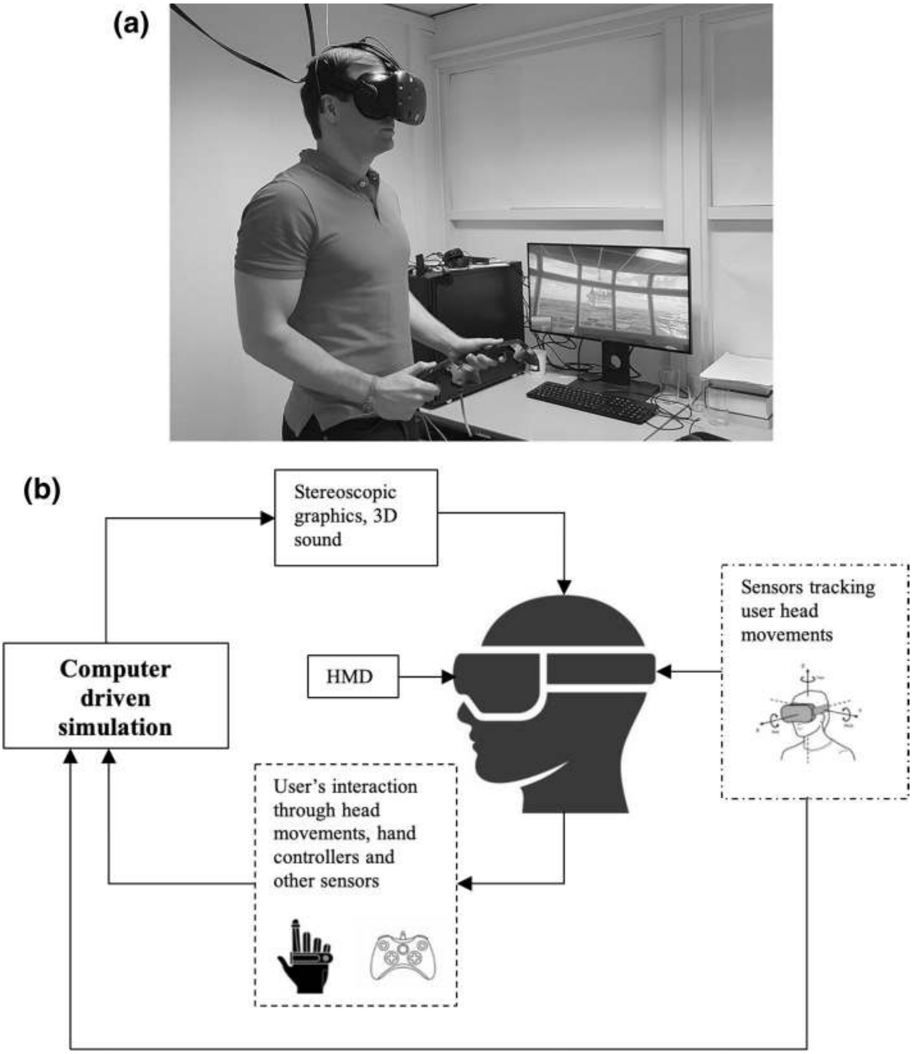

Fig. 1 **a** Sample VR HMD system, **b** VR HMD system explained

content in VR is personalized for each user according to their head position. There is also another immersive VR system called Cave Automatic Virtual Environments (CAVE), that consists of a room where all the walls and floor, are projection screens and the system contain motion tracking for tracking user movement. In CAVE systems users wear stereoscopic shutter glasses for the 3D view. Though immersive in nature, these systems are less popular due to the complexity of hardware and the relatively higher costs.

2 Background and Related Research

With the unique characteristics of VR, Dalgarno and Lee (2010) argue that it offers unique affordances for learning, such as representational fidelity, learner interaction and sense of presence (Dalgarno and Lee 2010). There is interest in VR technology for learning because of the assumption that with these affordances of VR, what has been learned in the virtual environment can be transferred to real conditions.

There are many studies and publications that report the benefits, limitations, effects, guidelines and challenges of using VR in education (Farra et al. 2015; Fowler 2015; Pantelidis 2009; Psotka 1995). The key added value of VR lies in the immersion offered by it (Jelfs and Whitelock 2000; Psotka 1995). "Immersion" or "Presence" felt by the users, is the sense of being present in the simulated virtual environment (Witmer and Singer 1998). Stevens and Kincaid (2015) claim that this "sense of being there" enables experiential learning through virtual environments that ultimately leads to positive transfer of knowledge. VR provides a controlled learning environment in which users can navigate, explore, manipulate and inspect the objects and their response in real-time. This explorative learning environment enables users to learn through experimentation. Thus, VR educational applications are best grounded on the constructivist theory of learning (Chen 2010). This constructivist, self-regulated, experiential learning through first-person non-symbolic experiences enabled by VR is the main reason for its value in applying it for education and training (Pantelidis 2009). Reid and Sykes (1999) went further and proposed VR as the ultimate education technology that will change the nature of how students learn. Three-dimensional virtual worlds and their educational uses have long been researched and discussed in the literature (Eschenbrenner et al. 2009; Ludlow 2015). Online virtual platforms, such as 'Second Life' are becoming increasingly prominent and finding interesting applications for learning and education (Minocha and Reeves 2010; Shen and Eder 2009). Considering these potential educational benefits of using VR and the recent advancements in affordable VR technology, the increased interest among educators and researchers to study the technology for educational applications is understandable. There are already a few comprehensive literature reviews that studied the state of the art of VR technology in education (Freina and Ott 2015) and a systematic mapping of educational application of VR HMDs (Jensen and Konradsen 2018). However, these reviews only considered the research that were published after the recent VR boom in 2013 and had a wider and general scope of educational applications of VR. There is currently a gap in the review of literature that focus on professional training applications of VR. Because classroom-based education provides valuable declarative knowledge to the students but practicing complex skills for proficiency is an important part of vocational and professional training. Professional learning settings are inherently different from the classroom based primary education. This type of training is typically delivered through on-the-job experience, simulations (roleplays and computer-based) and practical exercises. Thus, it is important to differentiate it from the rest of education in order to be more specific on the findings.

With VR growing in popularity, there are many efforts from academia and industry to utilize the technology in professional training (Grabowski and Jankowski 2015; Mantovani et al. 2003; Sacks et al. 2013). Hence there is a clear need to analyze how the effectiveness of VR in training has been studied and how results from such studies can inform the future training developments using VR as a training medium. In this review, we are interested to investigate the training applications (refers to the acquisition of skills such as cognitive or psychomotor skills) rather than the educational applications (refers to the acquisition of knowledge or information).

2.1 Goals

The aim of this paper is to make a systematic review of scientific studies on the training effectiveness of VR, to document the available evidence on VR applications and its effects on professional training outcomes. Implementing VR in training still requires development time and resources, so it is not only important to establish the effectiveness of VR in training, but also get inputs for efficient development and use of VR training applications in practice. Another aim of this study is to find if there are any methodological trends in VR application and skills that are more suitable for training using VR. We also aim to document the experimental methods used for testing the training effectiveness of VR that could be referred for input into future studies in this area.

3 Methods

This study has been undertaken as a Systematic Literature Review (SLR) based on the guideline from Kitchenham (Kitchenham 2004). A SLR is a method of identifying, evaluating and interpreting available research relevant to a particular research question or topic area (Kitchenham 2004). The main advantage of SLR compared to a normal research review is that it provides a higher degree of confidence about covering the relevant literature, and thus minimizes the subjectivity and bias through reproducible results (Kitchenham et al. 2010). Individual studies that contribute to a systematic review are called *primary studies*. A systematic review is a form of *secondary study*.

There are three main reasons for performing a systematic literature review (Kitchenham and Charters 2007).

- To gather and evaluate all existing evidence of a research topic in a rigorous and systematic way
- To identify gaps in current research in order to suggest areas for further improvement
- To summarize and provide background for performing new research activities

The following sub-sections detail the methodology of the SLR process implemented in this study, including the research questions, search strategy, inclusion/exclusion criteria, data extraction and synthesis of results.

3.1 Research Questions

The systematic review process consists of 3 stages: (1) Planning the review, (2) Conducting the review and (3) Reporting (Kitchenham 2004). The major differentiating factor of SLR over explorative reviews is the pre-defined protocol and research questions. Defining the scope of the review and answerable questions is an important first step of the SLR process. For defining the scope of the systematic search PICOC framework has been utilized (Booth et al. 2012). Table 1 details the elements defined for this study.

Based on the above-defined scope, the following research questions (RQs) were formulated:

RQ1: What are the benefits, effectiveness and limitations of VR in professional training settings?

Table 1 PICOC framework

PICOC Element	Definition
Population	Users, trainees in safety–critical areas and professional domains
Intervention	Utilizing HMD VR as a training tool or medium
Comparison	VR training vs. traditional training or no training
Outcomes	Training effectiveness, training transfer and performance indicators
Context	Professional training environment with VR HMDs

The aim of this question is to identify information and evidence of the training effectiveness of VR-based training. This question answers in what training area and/domains where VR has been applied.

RQ2: How VR is adopted in professional training setups?

The aim of this question is to identify how VR-based training is adopted in different professional training domains. The results obtained will be useful for developing frameworks for future training design using VR.

RQ3: What methodologies are used for assessing the training outcome/effectiveness for VR-based training?

This question aims to map out the methods for measuring training effectiveness in VR based training. The focus is on identifying methodologies and tools for measuring training effectiveness for future studies.

3.2 Search Process

Five interdisciplinary research databases were selected for the search (IEEE Xplore, Scopus (ScienceDirect is used for searching full texts), Web of Science, ACM digital library and ERIC). These databases were identified as relevant for education and training, technology applications in learning, psychology and social science. The literature search process was carried out in the month of June 2019.

We performed the search in the above databases using the following search string. The search term for this review combine the terms for virtual reality and training in conjunction with terms for possible outcomes, effectiveness and impacts of such training.

(“Virtual Reality” OR “Immersive VR” OR “Virtual Environment” OR VR)
AND
(Training OR Instruction OR “Training transfer” OR “Skill Acquisition”)
AND
(Impact* OR outcome* OR “skill development” OR affect OR effect*)

3.3 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria for selecting the primary studies were specified according to the SLR methodology. The primary criteria for inclusion were that the studies used immersive and interactive VR environments in three-dimensional (3D) graphics presented with a head-mounted display (HMD) for professional skills and safety training. Considering the research questions, in the general criteria, the time frame for study and relevant type of study were defined.

General Criteria:

- Peer-reviewed studies published between January 1st, 1988 and December 31st, 2018
- Studies that describe the applications and effectiveness of VR in professional training

Specific Criteria:

- Primary studies that compare VR-based training against traditional/typical methods of delivering training
- Primary studies that represent VR as state-of-the-art medium for training
- Studies that use VR HMDs for training professionals
- Secondary studies that quantify VR research in training effectiveness

The following exclusion criteria were defined for this review and studies meeting these criteria are excluded:

- Studies that are not published in English
- Studies that were published before 1988
- Grey literature, ex. white papers, project reports, technical reports
- Books, tutorials and poster publications
- Studies that not include VR HMDs in their testing
- Studies that are not related to/applied for professional training, safety training

3.4 Data Collection and Extraction

In the data collection and extraction phase of the review, the documents found in the searching phase were reduced to a final number of documents which were relevant for answering the three research questions. Inclusion and Exclusion criteria were utilized to screen the documents further.

The data extracted from each article are:

- Bibliographic information of the publication
- The application domain of the study
- The population of the study
- Type of training/intervention in the study
- The main research questions of the study and outcomes
- The method used for measuring the outcome
- The metrics used for measuring the outcome
- What are all the objectives/challenges addressed in the study

4 Results

This section presents the results of the review, answering the three research questions based on the extracted data from the 60 studies over a publication period of 30 years. Figure 2 presents the selection criteria processes based on the pre-established framework.

The initial high number of hits for the search string was due to the fact that the term Virtual Reality has been widely used for different applications and contexts. The search was further reduced to the application of HMD VR technology and in training contexts. Documents that describe just the concept or technology application without experiments, surgical simulators that use the term VR but highly purpose-built with surgical tools and other non-immersive VR applications were removed. After the application of inclusion, exclusion and quality criteria 60 studies were selected for the final data analysis.

In this study it was not possible to conduct an accurate meta-analysis as the training application domains, training methodology as well as the study design for assessing the effectiveness of VR with the data collection in those studies differed significantly. Overall, the results were synthesised by extracting the main themes under which the findings of this

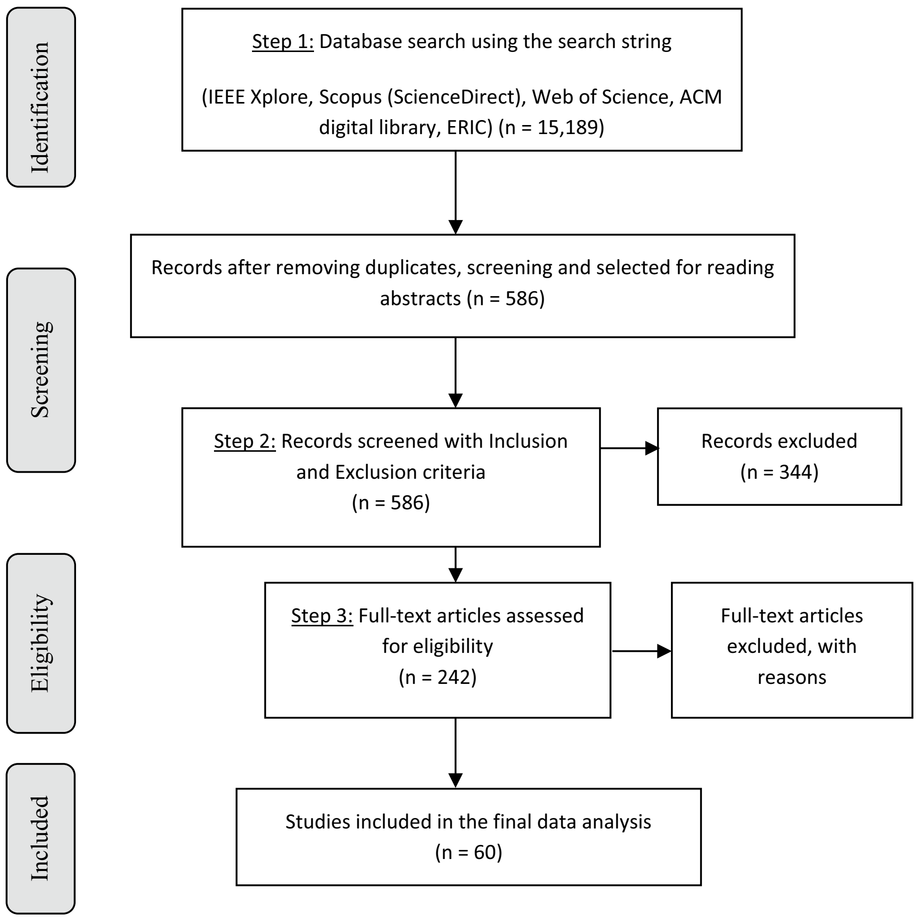

Fig. 2 Results from the search and selection process (PRISMA flow diagram)

review are identified and presented. The 60 studies included in the final data analysis were categorized and analyzed in the following sub-sections (see Table 2) based on the application domains and types of skills trained.

Although many of the skills trained overlaps between domains and many domains are interrelated (ex: firefighting, safety and emergency preparedness, etc.), these sub-categories help to organize the results.

4.1 Industrial Training

Industrial training is one of the major application domains for VR, as it allows to learn and perform simulated hands-on activities in a controlled, safe environment. Out of the 60 reviewed studies, 17 studies (28.3%) were on the industrial training applications (see Table 3). The review observed that industrial training applications for VR are mainly focused on procedural skills training for assembly (Boud et al. 1999; Carlson et al. 2015) or maintenance tasks (Bowling et al. 2008; Schroeder et al. 2017). Training has focused on the cognitive aspects of the trainees to recognize and remember parts assembly procedures (Carlson et al. 2015), the sequence of actions (Dwivedi et al. 2018) and orientation of components while carrying out the assembly and maintenance operations. Figure 3 shows the types of training areas for VR applications within the industrial domain. 12% of the reviewed studies in the industrial domain focused on visual inspection training. (Ragan et al. 2015) claimed field of view (FOV) and visual complexity significantly affected target detection during visual inspection training and found higher FOV led to better performance while higher visual complexity worsened performance. For procedure memorization tasks, enhanced spacial cues such as higher FOV and field of regard in VR HMDs significantly improved training performance (Ragan et al. 2010). In these studies, there is clear evidence that VR affordances such as high immersion benefits in training industrial tasks related to spatial memory skills. When it comes to training effectiveness and user acceptance of the training methodology, almost all reviewed studies reported positive effect of VR based training, except one. Kozak et al. (1993) claimed no transfer occurred from the VR to the real-world task for their selected pick and place task training. However, their finding was debated for the suitability of technology used for the selected criterion task in their study (Psotka 1995).

When it comes to the assessment methodology, among the 17 reviewed studies 5 were user studies where evaluations from the users were the metrics of assessment. The user evaluations generally had positive effects towards VR based training. Except for 2 studies, all other studies used students and volunteers from the universities as study participants. The type of industry ranged from manufacturing, energy, aircraft and automobile maintenance.

4.2 Firefighter Training

Effective training is a basis of good disaster preparedness. Among the emergency response occupation domains, firefighter face larger amount of varied environmental threats in their job and require unique skillset to carryout lifesaving tasks (Dunn 2015). VR enables the creation of large and complex training environments that facilitate the training of scenarios which are high resource intensive and difficult to carry out in real life. Due to this, there has been significant attention on VR based training solutions for firefighting (Hsu et al. 2013). 6 studies were identified in the review addressing the

Table 2 Field of application

Training domain	Description	No. of studies
Industrial	Training employees working in assembly lines, carry out maintenance and oversee safety–critical operations	17
Firefighting	Training firefighters for search and rescue operations	6
Safety and emergency preparedness	Training users for safe operations and emergency preparedness	15
Healthcare	All sorts of training associated with the healthcare industry from surgery training to general clinical competence for doctors, nurses	6
Aviation and Aerospace	Training astronauts for space missions	3
Defense	Training in defense sector including military, air force and naval officers training	6
Other	Sports and other training domains	7

Table 3 Summary of results from SLR in industrial training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Carlson et al. (2015)	Undergrad students (63)	Within and between-subject study	Physical, virtual (multi-color, wood color)	Assembly tasks training	Learning transfer (skill acquisition, learning curve, skill retention/decay)	Physical training outperformed VR training. People trained in VR had good skill retention after 2 weeks
Boud et al. (1999)	Students (25)	Between subject study	Conventional diagram, Desktop 2D, Desktop 3D, Immersive VR, AR	Assembly tasks training	Time taken to complete and accuracy	VR is found to be more suitable for assembly tasks training than AR
Ragan et al. (2015)	Students (51)	Between subject design	3 different levels of FOVs	Visual scanning training	Performance measure (target detection)	Field of view (FOV) and visual complexity significantly affected target detection during training. Higher FOV led to better performance but higher visual complexity worsened performance
Kozak et al. (1993)	University volunteers (21)	Between subject design	Real-world training, VR training, and a control group (no training)	Task training (Pick and place)	Performance measure (response time)	No transfer occurred from the VR to the real-world task (there is a learning curve in VR but that's only specific for that environment

Table 3 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Bowling et al. (2008)	Students (6)	Within-subjects design	Compares different inspection types	Aircraft maintenance inspection	Performance measures, process measures, subjective ratings (usability and presence questionnaires)	Participants perceived the virtual environment to adequately mimic a real environment. VR has the potential for use as an offline training tool for aircraft visual inspection tasks
Babu et al. (2018)	Convenience sampling from university (26)	Between subject design	2D interactive tablet view, Immersive VR	Two-wheeler maintenance training	Correct, wrong and confused recalls	Both 2D tablet and VR groups had similar performance right after the intervention but VR group performed better in the next day. Thus, VR group had less degree of recall decay compared to 2D tablet group

Table 3 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Caluya et al. (2018)	Students (16)	Within-subject study	VR, AR	Control room spatial memory training	Short term memory and memory transfer test	VR performs better in the immediate post-training tests, but AR performs better in memory transfer test so is better suitable for spatial memory training. VR remains a viable tool for spatial memory training because it is easier to train in VR than AR
Dwivedi et al. (2018)	Students (10)	Between subject study	Immersive with text-based instruction, Immersive with image-based instruction, Non-immersive with text cue, Non-immersive with image cue	Manufacturing manual assembly training	Assembly sequence (accuracy), time to complete	Only the immersive system with image cues had significantly better results than the non-immersive system with text cues Other pairwise comparison had no significant difference
Grabowski and Jankowski (2015a)	Miners (21)	Between subject user evaluation study	High immersive VR, moderate immersive VR	Mining skills training (Procedural)	Self-reported scores (presence, SUS and training questionnaire)	High user acceptance in training effectiveness using VR (immediate and after 3 months)

Table 3 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Murcia-Lopez and Steed (2018)	Students and staff (60)	Between subject study	Traditional training, VR training	Bimanual assembly training	Performance measures (success rates, immediate testing times and retention testing times)	Performance of virtually trained participants was promising (no significant difference was found between virtual training with animated instructions and best performing physical condition)
Vora et al. (2002)	Students (14)	Within-subject study	VR training, desktop-based training	Aircraft maintenance inspection training	Performance scores (search time and percentage defects detected) and subjective evaluation	VR system was viable and preferred to the desktop-based system as aircraft inspection training tool
Fast et al. (2004)	Non-welders, welding students and experienced welders (over 100)	User evaluation study		Industrial welding training	User evaluation (Questionnaire)	Virtual welding trainer provided a realistic experience of GMAW welding
Elbert et al. (2018)	Students (11)	Between subject design	VR training, training in real environment	Order picking training (logistics)	Transfer effect (picking times) and NASA-TLX to compare cognitive workload	Training effects achieved in VR can be applied to real-world order picking. order picking in virtual environments are perceived as less challenging compared to real order picking

Table 3 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Schroeder et al. (2017)	Students (75)	Between subject design	VR training, desktop-based computer simulations	Maintenance procedure training	Performance measures (procedural recall, effort), presence, Usability	Presence may not be the underlying cognitive mechanism by which simulation-based training is effective
Park et al. (2006)	Linemen (24)	User evaluation study	VR	Procedure training	User evaluation	VR based training system for live line COS replacement work has significantly enhanced the efficiency of the training
Brough et al. (2007)	Engineering students, graduates, engineers (30)	User evaluation study	Interactive mode, 3D animation, Video	Industrial assembly operations	Success rates in real assembly	VR training system can be successfully used to train operators to learn assembly operations
Ragan et al. (2010)	Students (41)	Between subject design	High and low FOV and FOR	Procedure training	Performance measures (time, errors)	Higher levels of immersion can produce a measurable improvement in the performance of an abstract mental activity

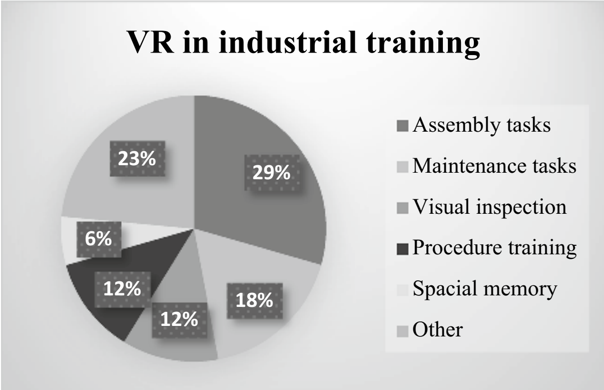

Fig. 3 VR training applications in industrial domain

training for firefighters using VR (see Table 4). Firefighters carry out complex spatial navigation tasks for fighting fires inside buildings and rescue operations as part of their jobs. The skills focused in the reviewed studies for training are mainly related to spatial navigation. For firefighting, VR based training is proposed as an alternative, where real-world training is impractical due to cost and personal safety of the trainees.

4.3 Safety and Emergency Preparedness Training

Safety and emergency preparedness training is another major application area for VR found in the literature. 25% of the studies reviewed covers this category of training (see Table 5). When it comes to safety and emergency preparedness training, VR application are seen as a realistic, safe and cost-effective alternative for traditional training methods. For example, VR simulation of emergency preparedness could provide more varied scenarios in a realistic manner and help attain and transfer the safety knowledge to the real-world situations. VR environments in which different disaster scenarios could be simulated provides valuable experiences and training to the personnel for preparing and responding to critical situations (Li et al. 2017a, b). This is because trainees are able to learn and practice the skill without risking their well-being and environments.

Because of the realism offered by VR emergency simulations, people show recognition of a dangerous situation in VR and readily produce adaptive responses, making the VR suitable for emergency simulations and for use as an effective training tool (Gamberini et al. 2003). VR- based training produced objectively better spacial knowledge in safety training. When full capability of VR utilized such as active navigation in VR produced better performance (Burigat and Chittaro 2016). Also, VR-based training improved the safety behavior in trainees promising to foster adequate self-evacuation during crisis situations in tunnels (Kinateder et al. 2013).

Almost all reviewed studies proposed VR based training as a novel alternative to traditional modes of training such as real-life drills and table-top exercises for safety & emergency preparedness. Also the studies reported high levels of engagement among participants in safety training (Buttussi and Chittaro 2017; Haller et al. 1999).

Table 4 Summary of results from SLR in firefighter training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Bliss et al. (1997)	Firefighters (30)	Between-groups, transfer of training design	Blueprints, VR, No training	Search and rescue training	Total time taken to execute the rescue, and the number of errors (wrong turns)	Both blueprint and VR training are equally effective and better than no training
Tate et al. (1997)	Navy firefighters (12)	Between subject study	VR training, traditional training	Shipboard navigation and firefighting training	Traversal time, Wrong turns	Mission rehearsal at real ship provides better performance than VR but it is not possible always
Clifford et al. (2018)	Convenience sample and firefighters (36)	Within-subject study	VR, high-definition TV, 270° projection display	Aerial based wildfire firefighting	Pre-Determined Analysis (PDA) and SAGAT for measuring Situational Awareness (SA)	Participants had greater ability to acquire SA inside the immersive displays. VR HMD provide the highest presence, also induced highest motion sickness
Mossel et al. (2017)	Fire brigade and paramedics (35)	User evaluation study	Mobile VR—treadmill, joystick	Emergency response training	Subjective feedback from users	The users found the VR system adequately suited for training
Waller et al. (1998)	Students (125)	Between subject study	Real-world, map, VE desktop, VE immersive, VE long immersive and no training	Spatial knowledge Acquisition	Knowledge transfer: mean time through maze, Representation differences	Short periods of VE training were no more effective than map training. With sufficient exposure to VR environment VE training surpassed real-world training

Table 4 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Clawson et al. (1998)	Unspecified (84)	Between subject design	3 degrees of VR control (passive, head movement only, active)	Spatial navigation training	Proportion correctness, traverse time, absolute angular error	Movement control in VR have greater effect on transfer effectiveness. VR navigation training was effective, both in requiring little training and in allowing effective transfer to real building

Table 5 Summary of results from SLR in Safety and emergency preparedness training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Kinateder et al. (2013)	Unspecified (43)	Between subject study	VR training, informed, no training	Tunnel safety training	Behavioral measures	Frequency and latency of self- evacuation, can be improved through VR training
Burigat and Chittaro (2016)	Undergrad students (54)	Between subject study	VR training, traditional training (printed maps)	Evacuation training	NASA-TLX, Kruskal–Wallis test for spatial knowledge acquisition and Usability measures	VR produced objectively better spacial knowledge. Active navigation in VR produced performance improvement. VR is perceived as more enjoyable, easier to comprehend and more effective than printed maps
Chittaro and Buttussi (2015)	Undergrad students (48)	Between subject study	VR serious game, safety card	Aviation safety training	Knowledge, Self-reported fear, Self-reported engagement, Physical arousal (EDA)	Immersive serious game produces knowledge gain that is maintained after one week. the immersive game was able to produce more engagement, negative emotion and physiological arousal than the control
Buttussi and Chittaro (2017)	Unspecified (96)	Between subject study	Desktop, narrow FOV HMD with 3 DOF, wide FOV HMD with 6 DOF	Aviation safety training	Knowledge (correct answers), self-efficacy (questionnaire), self-reported engagement and presence	The knowledge gained using the serious game was retained two weeks later regardless of display type. High fidelity VR display produce more engagement and presence

Table 5 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Chittaro et al. (2018)	Undergrad students (68)	Between subject study	Mobile VR, traditional training	Aviation safety training	Performance measure (time, errors), Engagement, instruction simplicity and efficacy	Participants who used the mobile VR tool were able to transfer the presented safety knowledge to the real world and don an aviation life preserver significantly faster and with fewer errors than participants who used the traditional briefing card. VR users also had higher engagement, self-efficacy
Zhang (2017)	Student trainees (10)	Within subject design	HMD VR, Desktop screen-based training system	Mining safety (drilling procedure training)	Subjective evaluation (questionnaire)	Participants felt high degree of immersion in HMD VR system. 9 out of 10 preferred HMD training experience over desktop training
Haller et al. (1999)	Missing	User evaluation study	HMD VR	Personnel safety training in process industry	Subjective evaluation	Efficiency in training delivery was increased, higher acceptance among users

Table 5 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Xu et al. (2018)	Crane operators (10)	User evaluation study	Immersive VR training, traditional training (onsite)	Safety knowledge training for rescue crane operators in railways	Subjective feedback from users	VR training system was considered intuitive, interactive, easy use, and learn than traditional training method. Comfort score was reported poor
Jung and Ahn (2018)	Students (64)	Between subject study	Traditional training, desktop, HMD & Joypad, HMD & wearable sensors	Lifeboat launching training (procedural and technical skills)	Recall rates for procedural skills and questionnaires for technical skills	HMD and wearable sensors group outperformed other groups in technical skills assessment. The desktop group showed the best performance in a procedural knowledge assessment
Tanaka et al. (2017)	Electrician and Instructors (70)	User evaluation study	Immersive VR	Electrical grid operation and emergency preparedness	Scale not provided	Immersive Virtual Substation provides a realistic environment, allowing electricians to practice maneuvers in a safely manner
Li et al. (2017a, b)	Undergrad students (96)	Between subject study	VR, Video, Manual, None	Safety training for earthquake emergency response	Performance measures (physical damage, visual attention), user feedbacks	VR training performed consistently better than other modes of training

Table 5 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Zhang et al. (2017)	Students. 90	Between subject study	VR, Desktop and textbook	Fire safety knowledge	Performance measures (Knowledge quiz and operational practice)	VR technology can better improve the effect of fire safety knowledge learning and skill training than the traditional methods
Stansfield et al. (2000)	First responders. (23)	Empirical study. Qualitative assessment	Immersive VR	Assessment procedures in first response	System assessment questionnaire	The study group was satisfied and accepted VR for first responder training. Many participants felt the scenario should be more in-depth and challenging
Gamberini et al. (2003)	Students (84)	Mixed methods	HMD VR	Fire emergency response training	Performance measures (time), behavioral measures	People show recognition of a dangerous situation in a VE and readily produce adaptive responses, making the VE suitable for emergency simulations and for use as an effective training tool

4.4 Healthcare Training

The application areas for VR in healthcare are immense and diverse (Ghanbarzadeh et al. 2014). Among the VR training application areas, medical domain has identified and adopted VR for surgical training to a greater success (Gallagher et al. 2005). This is because doctors and dentists are able to train for a variety of surgical scenarios repeatedly in VR without the pressure involved in live surgical procedures. Using simulations for the development and refinement of surgical skills is widely popular in the recent time. With many successful training applications, healthcare appears to be a more mature domain for VR simulation-based training. This is because a wide range of final applications have been studied in the domain. VR simulation applications are found to improve learning outcomes for a variety of surgical procedures (Ahlberg et al. 2007; Bharathan et al. 2013; Grantcharov et al. 2004). However, it is important to note that the VR systems used in surgical training are more sophisticated, have additional special equipment and haptic devices that replicate the feel and behavior of real surgical devices. Healthcare studies that utilized only HMDs are selected for this review (see Table 6) as other VR training systems such as MIST VR trainer are more sophisticated simulators for surgery that falls outside the scope of this review. Although a more mature domain for VR based training, HMD based VR applications aren't predominant in medicine. This could be because surgical procedures trained such as laparoscopic surgery involves camera manipulation, hand–eye coordination and bimanual maneuvering, which are accomplished by observing the monitor and the additional affordances of HMDs don't add extra value here (Li et al. 2017a, b). Huber et al. (2017) confirmed it in their study where combination of LapSim (from Surgical Science, Sweden) with HMD led to high levels of immersion, but there was no significant difference in the training effect. However, there are some use cases in healthcare training VR HMD's seem to add value, such clinical competence training for nurses (Dang et al. 2018) and operating room fire prevention and control training (Sankaranarayanan et al. 2018).

The skill trained in the health care domain range from cognitive skills such as surgical procedure (Yoganathan et al. 2018), safety procedure in operating room (Sankaranarayanan et al. 2018) and motor skills related to surgery (Anglin et al. 2017).

4.5 Aerospace and Aviation Training

Training in contexts that are impossible or very difficult to create or simulate is a reason for using VR in space training. Training for space operations has inherent challenges due to the very limited chance for on-the-job/hands-on training possibilities. There have been some successful use cases for VR based training systems in the space and aviation domain. One such use case is the Hubble scope maintenance mission training in VR. In the pebble repair mission, the astronauts had to operate a tele-robot in space using five different camera views on three monitor. VR-based training was utilised for enabling the astronauts to develop and maintain a dynamic 3D image in their head about the manipulator system to the Space Station, Shuttle and Payload (Logan 1998). For the space shuttle mission training, limited availability of personnel and training facilities made it challenging for training a large number of flight team members. The training facilities and simulations are prioritised for the crew and selected members of the primary flight team. Hence, the support and planning teams get very limited available time for training. An effective training was required for a 100-person team without the possibility of using the real telescope. VR was adopted for solving this challenge and to provide accurate knowledge of the geometry of

Table 6 Summary of results from SLR in healthcare training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Pulijala et al. (2018)	Dental residents (95)	Between-groups, randomized control trial	VR training vs conventional training (PowerPoint presentation)	Surgical training (corrective jaw surgery procedure)	Cognitive skills and self-assessment scores	Study group participants showed a significantly higher perceived self-confidence level. First year students (novices) showed highest confidence increase
Dang et al. (2018)	Nursing students (58)	Within and between-subject study	VR observation, active participation, TV observation	Clinical competence training for nurses	Immersive Tendencies and Presence questionnaires	VR observation mirrors active participation more closely than does TV observation
Huber et al. (2017)	Surgeons, surgical fellows, and Students (10)	Within-subject design	Immersive VR (IVR), regular laparoscopic simulation	Laparoscopic surgical procedure	Task performance measures and subjective feedback	Participants had high impression of presence in IVR session, but the performance scores were poor compared to regular laparoscopic simulations. There was no motion sickness registered in IVR sessions
Sankaranarayanan et al. (2018)	Resident surgeons (20)	Within and between-subject study	Immersive VR, conventional training (ppt and reading material)	OR fire prevention and control training	Identification of fuel, ignition, and oxidizer sources and correct sequence of operations	Immersive & interactive VR based hands-on training is effective way of teaching OR fire prevention and management scenarios

Table 6 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Anglin et al. (2017)	Unspecified (27)	Within and between subject study	VR, conventional training	Motor skills training	Skill measures	The rate of skilled motor learning occurs similarly in both Conventional training and HMD-VR. The training of a skilled motor task in HMD-VR does not fully transfer to a CT environment. In contrast, skilled motor learning in CT not only transfers but improves when transferred to HMD-VR
Yoganathan et al. (2018)	First year post grad doctors (40)	Between subject design	360-degree VR video, conventional 2D video	Basic Surgical skills training (knot tying)	Performance measure	360-degree VR video is found to be superior to conventional 2D video in the acquisition of knot tying skills

Hubble Telescope and procedural steps of the planned maintenance (Loftin and Kenney 1995). It was also noted that this VR-based training design was supported both by a task analysis method for training requirements and an intelligent tutoring system was utilised to define the learning scenarios.

VR was used for training both cognitive skills associated with task procedures and psychomotor skill associated with spatial orientation in the aerospace domain. Table 7 summarizes the results for these studies.

4.6 Defense Training

Military has long relied upon simulation-based training for preparing and keeping the soldiers battle ready. VR has been adopted in military for training due to its ability to allow defense personnel to try a range of simulations, without the associated costs, thus highly reducing training budgets while increasing safety. VR is applied in defense training programs, with simulators ranging from basic shooting systems into more immersive situations. VR enable the trainees to experience a particular situation within a controlled environment. For example, a battlefield scenario in which they can interact with events but without any personal danger to themselves. Soldiers can train in any number of different situations, environments and prepare them for combat situations or other dangerous settings. In the reviewed studies VR is mainly used in military training for providing situational experience such walking through the trainees in extreme situations such as parachute jump, navigating in the jungles, behind the enemy lines etc. For example, in the study investigating VR for topographical training, soldiers trained with high level VR showed better directional accuracy than other training modes (Singer et al. 1997). In another study on aerial door gunnery training, VR group outperformed LCD display group in gunner performance (Stevens and Kincaid 2015). Four of the reviewed studies were from the late 90 s that used previous generation VR technology (See Table 8) which could partially explain the interaction challenges by the participants in some of these studies from that period (Hall et al. 1998). Research related to defense usually takes longer period to declassify and normally not published in the research articles. This could be a reason why we haven't found many military VR training application in our search. The summary of the results from the VR applications for defense training is provided at Table 8.

4.7 Other Domains

Apart from the above-mentioned 6 major application domains, there have been attempts to utilize VR technology for training for sports, teacher training, calligraphy, etc. VR has been found to improve the awareness of the kindergarten caregivers to the toddlers' emotional experiences (Passig and Noyman 2001). VR assisted teacher training also found to significantly improved Classroom Management skills of Pre-service teachers (Lugrin et al. 2018). In the study focusing on oriental calligraphy, it was found that that training and transfer effects of VR were comparable and, in some situations, better than real training (Yang and Kim 2002). There are also increased interest in sport training applications for VR due to the realistic experiences' athletes might get from VR simulations. In the study investigated American football training using VR found two significant benefits of using VR for training: (1). VR provides trainees the ability to continue practicing their mental preparedness, (2) VR effectively and proactively reduces the injury possibilities of trainees by avoiding the physical impacts particularly to the player's heads (Huang et al. 2015a). The results from these domains are summarized in Table 9.

Table 7 Summary of results from SLR in aerospace training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Logan (1998)	Astronauts, mission controllers and support personnel	Observation study	VR, classroom lectures, Part-Task trainers, Shuttle Mission Simulations, Fully functional mockup	Ground-based training for space operations	Training transfer	Training in VR on Earth proves to be the best way to train for space
Loftin and Kenney (1995)	Space flight team members (105)	User evaluation study	VR training, traditional observation	Hardware knowledge and maintenance procedure training for Hubble telescope	User study. subjective feedback from Users	Virtual environment for training had a positive effect on job performance during the HST repair and maintenance mission. Visual and audio cues provided positive aid. Cybersickness didn't have a negative impact on training transfer
Aoki et al. (2008)	Students and researchers (36)	Between subject study	HMD VR, Desktop screen-based training system	Spatial orientation and navigation training for space station	Performance measures (Egress time, pointing angular error and response time for pointing task)	No differences in pointing angular-error or egress time among the groups. HMD VR was faster in pointing from destination to start location and from start to different destination (might be due to input device). Simpler desktop system may be useful for Astronaut 3D navigation training

Table 8 Summary of results from SLR in defense training

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Singer et al. (1997)	Students (48)	Between subject design	High level VR, restricted (low-level) VR configuration, standard map training	Topographical training for dismounted soldiers	Performance measure (Directional accuracy)	High level VR experience produces better spatial knowledge acquisition
Greunke and Sadagic (2016)	Landing signal officers (13)	User evaluation study	VR LSO trainer, 2H111 simulator	Landing signal officer training	Usability and feasibility	VR training system enables a paradigm shift in terms of the way LSOs train and provide greater opportunity to train anytime, anywhere
Stevens and Kincaid (2015)	Soldiers (76)	Between subject study	VR, LCD screen	Aerial door gunnery training	Performance, SSQ scores, Presence Questionnaire	VR group outperformed LCD display group in gunner performance. Simulator sickness was the same among groups. No connection between ITQ and performance or perceived presence
Pioch et al. (1997)	Unspecified (36)	Between subject design	VR stadium view, VR ROV centered view, no training	ROV Pilot training	Experimenter observation	VR Stadium view group outperformed the other groups in depth control and adherence to an expert path. There was positive transfer compared no training group

Table 8 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Hall et al. (1998)	Civilians and military personnel (10)	Between subject design	2D desktop view, Immersive VR	Procedure training (Air force)	Procedural test (correctly recalled sequence), Name test (recalled names of the devices)	VR group generally scored higher than 2D group on both procedure and name test. However, VR group spent more effort in interaction. Also, skill decay for the VR group was found to be generally greater than for the 2D group
Witmer et al. (1996)	Students (60)	Between subject design	VR, Actual building, verbal instructions and pictures (symbolic training)	Spatial navigation training	Performance measures (route traversal time, number of wrong turns, and total distance traveled), Questionnaires (PQ, SSQ)	Using VR, soldiers can use relatively safe virtual spaces for rehearsing missions that they will later perform in a perilous environment

Table 9 Summary of results from SLR for training in other domains

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Passig and Noyman (2001)	Kindergarten teachers (40)	Within-subject design	Pre, post VR exposure	Emotional awareness training	Experience questionnaire	VR experience improved the awareness of the caregivers to the toddlers' emotional experiences in the first days in kindergarten
Lugrin et al. (2018)	Pre-service teachers (54)	Between subject design	VR assisted; video-assisted	Teacher training for classroom management skills	Performance measures (instructor rating), self-report (efficacy)	No significant difference in instructor rating score between VR and video groups in pre-seminar test. VR assisted condition significantly improved Classroom Management skills compared to video-assisted condition
Pausch et al. (1997)	Undergraduate students (48)	Between subject design	VR, desktop	Visual scanning training	Performance measures [target detection, time (predicted, observed)], training transfer (positive and negative transfer)	VR users are more confident and faster in determining whether a target existed. There is positive transfer of training from VR to stationary displays and a negative transfer of training from stationary displays to VR

Table 9 (continued)

Study	Participants	Study design	Condition	Intervention	Metric for assessment	Outcomes
Yang and Kim (2002)	Unspecified (36)	Between subject design	VR, real environment	oriental calligraphy training (Motion and orientation skills)	Distance error metrics, learning and transfer effect, questionnaire	The training and transfer effects produced by VR training is as good as and, in certain situations, better than the real training
Rose et al. (2000)	University staff and students (250)	Between subject design	VR training, real training and no training	Sensorimotor skills training	Performance measures (errors in post-test trial)	Training on the virtual task was as effective in facilitating real task performance as training on the real task itself
Huang et al. (2015b)	Student athletes (17)	User evaluation study	VR training, no training	Football training (plan of action, strategy)	Assessment scores	Positive transfer, 30% overall improvement of knowledge
Chua et al. (2003)	Student (40)	Within-subject design	5 different VR layouts	Tai Chi training	Error analysis, self-reported difficulty	VR training did not have substantial effect on learning motor control tasks in Tai Chi

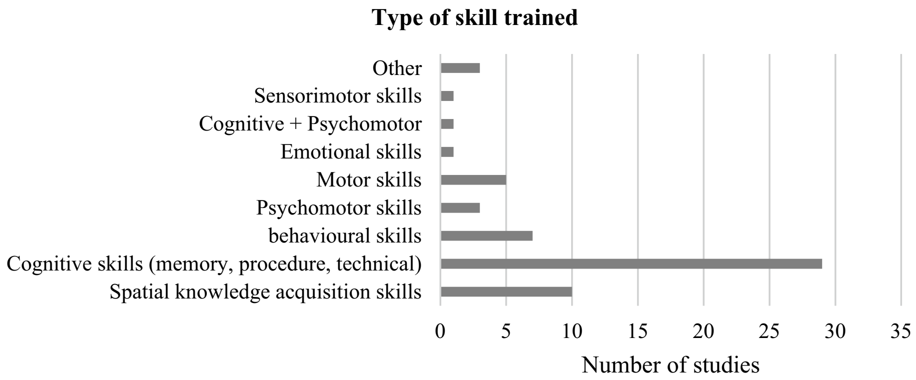

Fig. 4 Type of skill trained using VR

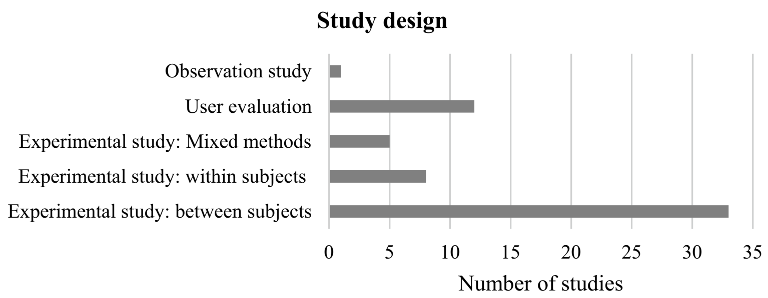

Fig. 5 Experimental method used in the studies

4.8 Summary of Types of Skills Trained

Figure 4 shows the breakdown of the types of skills trained in the review studies. Skills related to remembering and recalling procedures are most trained skills in the reviewed articles. This is in line with the high numbers of assembly, maintenance and procedure training applications. It is followed by spatial knowledge acquisition skills such as visual scanning, head movements and observation skills. VR has an advantage for training spatial skills due to head tracking (more natural interaction) and immersion. There are also studies that investigate VR's ability to train skills such as behavioral, emotional, motor and sensorimotor skills.

4.9 Training Evaluation Method

When it comes to the methodologies for assessing the effectiveness of VR based training, evaluating the task performance post training is the extensively used method. 33 studies used between subject design for their experiments, 8 studies used within subject design and 5 used mixed methods as their study design. The metric for assessment comes under 3 main categories: (1) Performance measures; (2) Self-reported measures and (3) Observations.

Performance measures evaluate the acquired skills and knowledge post exposure to the VR based training. The reviewed studies used performance measures such task completion rate, accuracy, sequence of steps done right, error rate, temporal, and behavioral measures etc. 12 of the reviewed studies were user evaluations. These are mainly self-reported measures such as questionnaires, rating scales and interviews that capture the user perceptions on the training methods. User perceptions included self-efficacy score, user satisfaction, usability, self-reported difficulty, immersion and presence scales, etc. Observations are the expert evaluations and researcher's survey about outcome of training. Figure 5 shows the breakdown of study designs among the review articles.

4.10 Types of Study Participant

The type and number of study participants add remarkable weight to the significance of conclusions and generalizability of each study results. University students and staff are the most commonly used participants in the review studies (See Fig. 6). Although the VR training applications were meant for professional training, only 19 of the reviewed studies used industry professionals and 6 studies used professional students as study participants. Rest of the studies appears to be utilizing convenience sampling since majority of the VR training applications developed and tested in university laboratories. This sampling bias raises the issue of how well the target populations are represented in these studies.

4.11 VR Proliferation

The publication years of the reviewed articles follow the technology trend of VR as discussed in the background section. As expected, there is a clear increase of research publication in the period after 2013. 52% of the reviewed article were published in the period between 2013 and 2018 (Fig. 7). This is in line with the proliferation and popularity of the technology post the arrival of HMDs that are both more efficient and affordable. Compared to the VR studies from the 90 s, VR technology has improved to an impressive degree. Especially improvements in computing power and display technology have solved many of the problems from the previous generation of VR in the 90 s, such as low resolution, high latency, heavier headsets, etc.

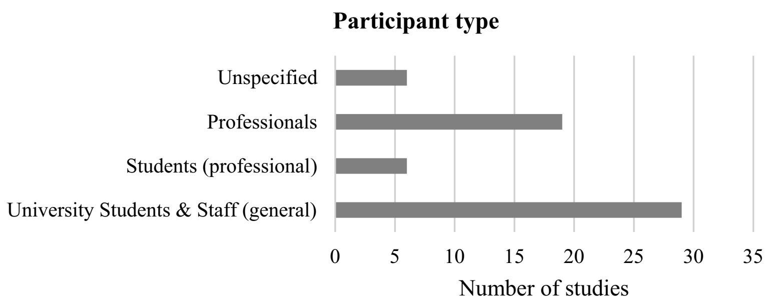

Fig. 6 Types of study participants

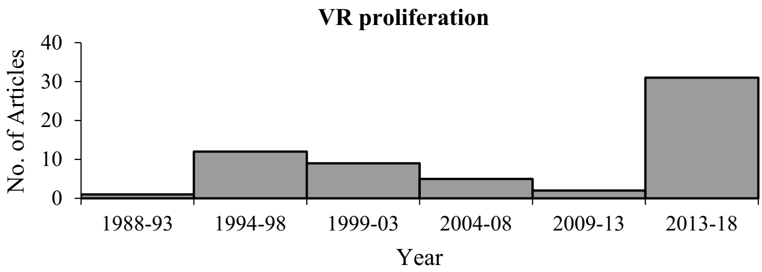

Fig. 7 VR proliferation in training research (temporal evolution of publications)

5 Discussion

This systematic literature review retrieved a range of VR applications that have been developed for training across various professional fields. Our search identified 6 major domains of VR applications in training in the literature to date, designed to train people in professional settings and for specific job-related competencies. In addition, few emerging application areas, such as sports training, teacher training etc. were identified in the review. VR applications are innovative tools that promises to have huge potential for education and training in general. The key benefits of VR mentioned in the reviewed studies are, VR allows trainees to understand the spatial relationships and concepts, and provides meaningful, contextual and situated learning experiences. In the applications listed in the review, VR helps to create realistic simulated experiences. Several of these VR applications were viewed and argued as a valid and reliable method for training. The studies that spanned over 30 years used different VR devices based on the state-of-the-art of that time. These devices ranged from very low resolution-high latency to high resolution-low latency, varying quality of tracking and locomotion mechanisms. Although technology limitations affected the user experiences, key features of VR such as high immersion and presences felt by the users have generally led to better performances in different learning situations. Studies carried out in space training concluded VR to be the most effective training medium for space operations (Loftin and Kenney 1995; Logan 1998). However, in this particular use case the VR training application was supported by a thorough job analysis and smart instructional design methods (Mellet-d'Huart 2009). Training in VR is shown to increase trainees' confidence (Pulijala et al. 2018), subjective attractiveness (Zhang 2017), enhancing skill retention (Babu et al. 2018; Carlson et al. 2015) and performance (Hall et al. 1998; Jung and Ahn 2018). Learner engagement and motivation is particularly important in safety training because more engaging and experiential safety training were found to be more effective than traditional training methods (Burke et al. 2006). The advantages of VR-based training are well-established by now. VR facilitates safe training environments, supports rehearsal of responses for emergency situations, enables skill acquisition through learning by doing, and provide training opportunities where training in real situation is not possible due to safety risk, cost and practicality. VR-based training could also be useful where real life or other training modalities are feasible due to the flexibility of VR for repetition, providing feedback and adaptive learning possibilities (Vaughan et al. 2016). Nevertheless, there are also experimental results that showed conflicting evidence on VR benefits (Kozak et al. 1993) or no benefits at all (Chua et al. 2003; Huber et al. 2017). In many of successful VR training instances, it is important to note that the simulation and its accuracy in connection to the training objective is more important than the VR technology itself. Surgical training is a good example for this where VR based training is successful still high immersive VR HMDs aren't generally preferred. In the following section, we discuss the identified challenges for VR-based training and come up with recommendation for VR adaptation for training in professional domains.

5.1 Challenges for VR in Training

There is a clear indication from the review for the increased interest in applying VR in professional training in recent years. Although VR was used for specific training situations for many decades, the technology is still fresh for most domains. To date, the education and training carried out through simulators is predominantly driven by technology and cost (Neubauer et al. 2017; Stedmon and Stone 2001). Simulator developers decide upon the specifications of consumer electronic technology based on their specific business model (e.g. technology level vs. cost), and ultimately what customers are willing to pay for. The details and sophistication of the simulators are directly connected to the cost of the simulator. The recent interest on the HMDs and their application into training were based on the fact that the hardware is now much more advanced, relatively cheaper and facilitate highly immersive simulations that were only possible in high-end expensive simulators previously, if at all. As the simulated environment in VR is fully digital, it is also believed to be much more flexible. However, there are a few important limitations that need to be paid attention to. The first main limitation is the simulation content for VR. Production of VR simulations is still very expensive, and time consuming. Most simulation applications tested in the reviewed studies were developed in laboratories for very specific contexts of use. How this translates to real-life training setting with varying training goals is still unclear. In addition, VR is still relatively a new type of Human Computer Interface (HCI) where the users are immersed and interact in 3D. Formal understanding and evaluation of interaction within VR is problematic because of the limited understanding of HCI in immersive 3D (Bowman et al. 1998). Due to the immaturity of interaction design techniques for VR simulations, the user experiences vary to a large degree between different simulation applications. User familiarity to the technology is an important challenge to address. In the review, it was identified that several studies reported cases of cybersickness and users struggling with the interaction in VR simulations.

The second main limitation lies in the VR hardware. Current consumer-grade VR HMDs are primarily designed for entertainment and media consumption. They were not designed keeping prolonged usage for educational and training settings in mind. VR device manufacturers themselves recommend frequent breaks while using VR HMDs to avoid discomfort. In traditional simulators, students could train for hours without break, but this is not possible yet with the current VR HMDs. The existing curricula for training might need to be modified for adopting VR HMDs.

In addition, there are also potential limitations, such as safety of the users and usability issues while adopting VR for training. Other personal factors such as disabilities, eye issues, etc. could also influence the utilisation of VR for training for a wider range of users. In an educational and training context, this is critical because the educational and training medium should be usable by most of the target population.

5.2 Recommendations for VR Adaptation in Training

Based on the review results on lessons learned and challenges for VR in training the following recommendations are proposed. Firstly, pedagogical and interaction aspects between the users and VR application should be carefully considered while adapting for training. In order to achieve a high degree of effectiveness, the design approach for VR based training should be supported by thorough analysis of the task and good instructional design methods. The training outcome and skill proficiency criteria should be well defined in order to assist trainees to develop skills through VR-based training.

When it comes to training applications for VR, the underlying learning theories are often overlooked or not paid enough attention. Most of the reviewed studies did not explicitly mention or explain the learning theories the VR applications were based on. Learning theories such as constructivism and experiential learning were briefly mentioned but how these theories are utilised in the development of their applications weren't explained. This makes it challenging for the generalisability of the findings from the studies. In other instances, especially the studies that had user evaluations as assessment methodology mainly focussed on the usability of the VR application rather than the actual learning outcome itself. This we suspect is mainly due to the novelty of the technology to the particular domain and researchers were merely playing with the technology and ideas of applications. So, the future VR training applications should have clear training objectives and goals training outcome. Also, the training outcome should be evaluated through robust assessment methodologies to objectively measure the trainee' increase of knowledge and skills in addition to measuring their training experiences.

Many of the technical challenges faced by the earlier studies, such as poor resolution, high latency and tracking issues are resolved in the latest generation of equipment. VR technology has been heavily updated in recent time and it renders many of the usability issues, quality of experience and cybersickness results from older results invalid or less likely to occur with the new technology. However, these human factor issues are non-negligible in training applications. Once incorporated, the technology will be used by people in various age groups, gender and technology familiarity. With the different stakeholders and multidimensional nature of learning process combined with the complexity of VR technology, simulator developers and researchers should focus on the usability. It is important to develop and validate methods to quantify the quality of experience in VR, so that the impact of VR training applications on the users could be measured and better training experiences created. It was also evident from the review that there are varying maturity levels of VR applications between domains, and still a lot to be done for the development of VR applications for training. Also developing and sharing best practices for VR training applications within and across domains might prove useful for avoiding common issues such as familiarization and usability challenges.

Finally, it could be safely said that VR has survived the initial phase in technology adaptation and has shown good potential as a training tool for many professional domains. However, before VR applications can be widely used as a training medium it must be demonstrated that it is an effective medium for learning skills and transferring them to real life settings. It is important to thoroughly investigate VR's applications and assess its true value and place within training before implementation.

5.3 Future Research

To better understand the barriers in VR based training and find ways to reduce them, the future research should move away from laboratory-style experiments and focus on the use of educational VR in realistic settings, as part of educational or training programme. As presented in the findings above, the actual context of use has a great influence on the learner experience. Majority of the reviewed studies focussed on very short-term use of VR-based training tools in experimental settings. However, we couldn't find many follow-up studies on the retention of skills acquired through these innovative training methods. Future research should also examine the effects of prolonged and repeated usage of the technology in skill acquisition as well as the user's motivation on using the technology.

Since VR training applications are heavily reliant on technology, educators and researchers have to rely on the technology developments from elsewhere. The development of VR technology is predominantly driven by industries outside education such as gaming and entertainment. The generalisation of VR technology for training is a key issue to address in the future research. Apart from few bespoke VR HMD's that are tailor made specific training needs, majority of training application would have to settle with off-the-shelf VR technology. The field could benefit highly with a guideline or blueprint to select the right VR technology for its application requirement.

The future studies should also be explicit on the theoretical foundations of their VR application and describe the development process of their training and course content.

One main reason for the renewed interest in VR technology is the cost and availability of the hardware. However, the cost-effectiveness of VR simulators for training compared to other training approaches is still largely unknown. Although the hardware cost has dramatically come down in recent years, it is still expensive and time-consuming to develop software for the VR systems. The cost–benefit of using VR-based training systems to train professional should be studied to quantify the financial benefits using VR in training. This is important for justifying the adaptation of VR in non-safety critical domains. It is also important to address the specific human factors issues associated with the VR technology prior to its application on educational and training settings. More research should be performed on the ergonomics, usability, quality of experience and effects of prolonged usage of VR on the users from the educational application perspective.

5.4 Limitations of the Review

The studies included in this review came from a wide range of training and educational contexts. Despite most studies had positive findings towards the use of VR HMDs in training, it is still hard to make a concluding statement on the effectiveness of VR HMDs in training. This is mainly due to the wide range of training applications and differing quality of research studies. Regarding the research quality, an important weakness in many studies was the measurement of learning outcomes without giving arguments for the validity of the evaluation instrument. Figure 5 summarized the type of experimental design used for studying the VR training applications. The majority of the studies utilized between-subject study design to compare VR training with other modes of training. Although case–control method was utilized in laboratory-based studies, most studies used convenience sampling. Though focused on professional training setups, majority of the studies used university students as participants. This concerns the representation of the sample to the actual end-users of the training systems. Furthermore, the review showed that many studies were in fact user evaluations (12 studies) of VR products that did not seek to uncover more general knowledge about learning in VR, and at the same time had an unavoidable bias towards a positive evaluation.

From the review point of view, due to omit/improper use of keywords, it is possible that relevant articles were not within the range of search of this study. Although additional articles deemed relevant were found through cross-referencing, this might be the reason for an incomplete overview of all VR training application described in the literature. Inclusion and exclusion criteria employed in the review might have some inherent limitations as well. Inclusion of grey literature such as PhD theses, technical reports, non-English research articles and whitepapers might have led to more exhaustive results, potentially with a larger representation from the industry.

6 Conclusion

In this article, we have reported the results from a systematic mapping study that reviewed the previous empirical studies focusing on the application of immersive VR for professional training. The review aimed to contribute to the knowledge of the scientific evidence on the effectiveness of VR for education and training. The findings of this review provide insights for educators and researchers into: (1) the different professional domains where VR technology was utilized for skill training (2) the types of research methods employed by previous VR studies in these domains for measuring the outcome, and (3) the types of skills trained using VR, and their related findings. The review identified a number of training situations where VR were highly valuable, such as industrial, aerospace, health care, defence, safety and emergency preparedness training. Overall, we found that majority of reviewed studies considered VR as a promising technology to enhance the learning process of trainees due to its ability to provide experiential learning, higher levels of interaction and encourage active learner participation. This combined with the availability of affordable VR headsets has led to increased interest in applying VR in educational and training settings. Still, this promise of effective training through immersive, simulation-based training should be supported by scientific evidence from testing VR training applications. As discussed in the limitations, it is still difficult to make a concluding statement on the effectiveness of VR HMDs in training. Differing quality and lack of robustness of studies point to the need for further and more rigorous research that examines the most promising uses of HMDs in authentic training contexts.

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