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A Systematic Review of Human–Computer Interaction (HCI) Research in Medical and Other Engineering Fields

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ABSTRACT

This article provides a systematic review of research related to Human–Computer Interaction techniques supporting training and learning in various domains including medicine, healthcare, and engineering. The focus is on HCI techniques involving Extended Reality (XR) technology which encompasses Virtual Reality, Augmented Reality, and Mixed Reality. HCI-based research is assuming more importance with the rapid adoption of XR tools and techniques in various training and learning contexts including education. There are many challenges in the adoption of HCI approaches, which results in a need to have a comprehensive and systematic review of such HCI methods in various domains. This article addresses this need by providing a systematic literature review of a cross-section of HCI approaches involving proposed so far. The PRISMA-guided search strategy identified 1156 articles for abstract review. Irrelevant abstracts were discarded. The whole body of each article was reviewed for the remaining articles, and those that were not linked to the scope of our specific issue were also eliminated. Following the application of inclusion/exclusion criteria, 69 publications were chosen for review. This article has been divided into the following sections: Introduction; Research methodology; Literature review; Threats of validity; Future research and Conclusion. Detailed classifications (pertaining to HCI criteria and concepts, such as affordance; training, and learning techniques) have also been included based on different parameters based on the analysis of research techniques adopted by various investigators. The article concludes with a discussion of the key challenges for this HCI area along with future research directions. A review of the research outcomes from these publications underscores the potential for greater success when such HCI-based approaches are adopted during such 3D-based training interactions. Such a higher degree of success may be due to the emphasis on the design of user-friendly (and user-centric) training environments, interactions, and processes that positively impact the cognitive abilities of users and their respective learning/training experiences. We discovered data validating XR-HCI as an ascending method that brings a new paradigm by enhancing skills and safety while reducing costs and learning time through replies to three exploratory study questions. We believe that the findings of this study will aid academics in developing new research avenues that will assist XR-HCI applications to mature and become more widely adopted.

1. Introduction

There are many complexities associated with Extended Reality for Human–Computer Interaction (XR-HCI). Several research initiatives have been undertaken in the field of XR-HCI focusing on a range of issues; in this article, we discuss these prior research efforts under the following categories: XR based Simulators for Training and learning; XR based Simulators in Orthopedic Surgical Training; Participatory Design; Information Modeling; Cognitive Load; Affordance; Assessment Method; Role of Avatars; Comparison; Absorption Stress, and Learning in 3D Immersive Virtual Training Environments; and Miscellaneous. The objective of this article is to provide a review of a cross-section of these articles from these various categories of research which can assist future research in meeting requirements to advance in it. Briefly, the contributions of this article are as follows:

- Providing an overview of existing challenges in a range of problem domains associated with healthcare that can be addressed using XR-HCI.
- Providing a systematic overview of the existing techniques for XR-HCI, and how these have been applied to the medical domain.
- Exploring the role of XR-HCI in future challenges for the medical domain.
- Exploring design and learning elements and the technology that is adapted to support XR-based learnings.
- Outlining the key areas where future research can improve by the use of XR-HCI techniques.

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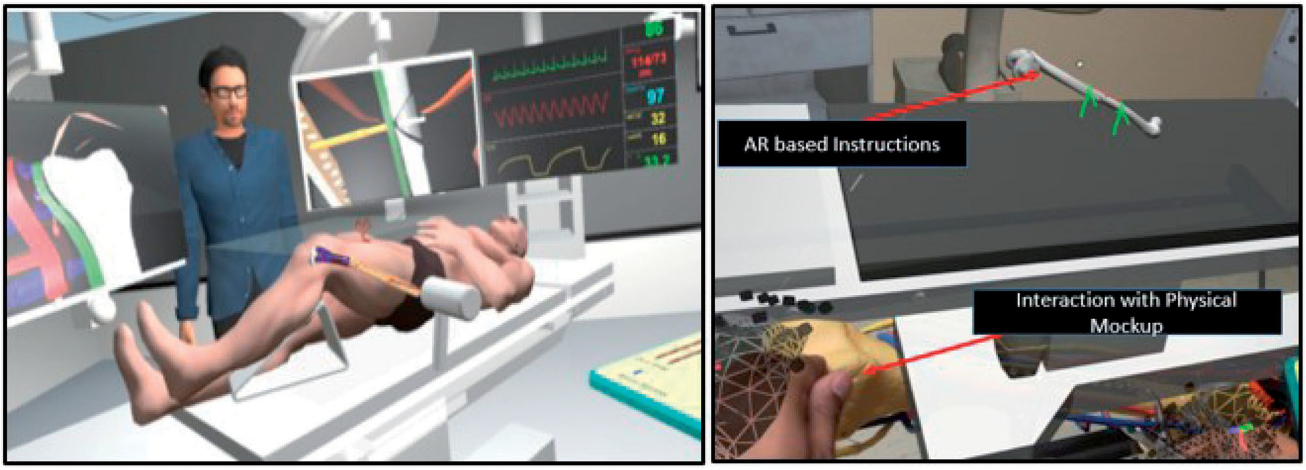

Figure 1. A view of the VR (left) and MR (right) based training environment for dynamic plate compression.

It is necessary to define and describe some of the key terms and concepts before a review of the literature. The rest of this article is structured as follows. The research methodology is provided in Section 2. In section 3, a discussion of the current research in XR-HCI for various domains is included along with categorization. Further, section 3 provides a presentation of the taxonomy and a comparison of selected mechanisms. Subsequently, section 4 maps out some validity threats. In section 5, an elaboration of the future research is included. Finally, the conclusion is presented in section 6.

1.1. Definitions

Extended reality tools and environments are being increasingly used to support learning and education (Cecil, 2021). The term Extended reality (XR) encompasses three categories: virtual reality (VR), augmented reality (AR), and mixed reality (MR). These technologies extend various levels of reality by blending real and virtual worlds to support effective immersive experiences (Cecil et al., 2019). By integrating XR into training, learners can be immersed in a multisensory environment that is more interactive, engaging, and effective. XRs can be used to support the design of Virtual Learning Environments (VLEs) which can be described as a special type of XR environments designed to support learning and training.

The ultimate display was conceived by Sutherland (1965) with three main features Immersion, interaction, and imagination which are nowadays accepted as VR (Sutherland, 1965). Presence in VR by using multiple sensory stimuli, such as visual, sound, and haptic is defined as the perception of the environment by the user in a realistic manner (Witmer & Singer, 1998). Biocca and Delaney (1995) defined VR as "the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment". Interaction and immersion are perceived to be VR's crucial features (Walsh & Pawlowski, 2002). Immersion refers to the illusion that the virtual sensory stimuli in the virtual environment replace the user's sensory stimuli (Slater & Wilbur, 1997), in other words, it is described as the involvement of a user in a virtual environment (VE) by disconnecting from the real world (Ott & Freina, 2015), interaction refers to the degree in which users could modify VLEs in real-time (Steuer, 1992) and how VR devices can automatically detect and respond to users' input signals. Interaction is the feature that makes VR different than conventional multimedia. VR typically involves the use of a headset, or head-mounted display (HMD) that occupies the user's entire visual field. In recent years, with growing research in computer graphics existing VR systems possess realistic visual feedback.

Another technology, Augmented Reality (AR), is a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects, in which a headset provides the user to observe simulated layers while they observe the real surroundings (Azuma, 1997). Demonstrating procedural information as real-time perceived ultra-reality in domains, such as medical, industry, and education has been investigated as an effective way of bringing additional information to user perception without blocking other visual fields. This can be achieved by sacrificing some extent of immersion in AR (Billinghurst, 2002).

MR utilizes both AR and VR to blend the physical and digital worlds, user situated in an interactive environment that could be either real with virtual assets, or virtual with physical objects (Hughes et al., 2005). The former approach is referred to as augmented reality and the latter is referred to as augmented virtuality. This type of XR uses advanced computer technology, graphics, and input systems that allow learners to co-exist and interact with physical and digital objects in real-time (Billinghurst & Kato, 1999). With mixed reality, Learners can complete realistic interactions with objects and people. Figure 1 (Gupta, 2022) (Images are used by authors' consent) shows the views of VR and MR-based training environments developed for dynamic plate compression. During the training, the users learn to complete a complex set of procedures including plate positioning, drilling, and screw insertion. The users can be seen interacting with the VR and MR-based training environments in Figure 2 (Gupta, 2022) (Images are used by authors consent).

Figure 2. Users interacting with the VR-based environment using Vive Pro headset (left) and MR-based environment using HoloLens 2 and physical mockup (right).

Haptic technology, also known as kinesthetic communication or 3D touch, refers to any technology that can create an experience of touch by applying forces, vibrations, or motions to the user. Haptic technology is gaining widespread acceptance as a key part of VR system, adding the sense of touch to previously visual-only interfaces. Haptic technology facilitates the investigation of how the human sense of touch works by allowing the creation of controlled haptic virtual objects. Haptic technology has enabled the development of telepresence surgery, allowing expert surgeons to operate on patients from a distance. To realize the full promise of VEs and teleoperation, further development of haptic interfaces is critical. Existing VR systems possess realistic visual and auditory feedbacks, haptic feedback is far from the user's perceptual expectations (Otaduy et al., 2013). To be able to interact with an environment, there must be feedback. In human–computer interaction (HCI), haptic feedback includes both tactile and force feedback. Tactile refers to the sensations felt by the skin and force refers to reproducing directional forces that result from solid boundaries. Haptic feedback is used for simulations that require direct contact between the user-driven avatar and the manipulated objects. It is also used to engage more of the user's senses to provide a deeper and more immersive experience.

Human–computer interaction (HCI) involves people participating and exploring with XR environments. Interactions, as mentioned above, offer various controls, such as involving users with a VE with enabling virtual object manipulation. This way it promotes the learning process for users. In other words, HCI investigates the interaction between people and computers to realize how and to what extent computers can enhance learning, and how it could be improved in terms of usefulness, engagement, effectiveness, and approachability. Visualization/interaction simulation is one of the focus points for researchers in recent years. There is a growing number of interaction-based research that involves how we think and behave and has a direct impression on human life. For a long time, text-based methods, such as books have been used as an effective way for maintaining the knowledge but also distributing it. With the high potential of VR for educational purposes thanks to realistic implementation and real-time interactions, it is a perfect alternative to conventional methods. The learning experience and skills depend on how well a subject is presented to the learners (Card, 2018).

With the ever-increasing adoption of such VR/MR-based simulators in medical and other application contexts, this article seeks to provide a review of existing VR/MR and other related methods to highlight capabilities, potential benefits, and drawbacks. Our literature review has focused on the role of such VR/MR and related approaches in the field of medicine and healthcare. They provide a safer, efficient, and healthy alternative to training using cadavers or training using small animals. One key outcome is that the assessments of such training-based interventions indicate residents and doctors can acquire more knowledge and skills after such VR/MR-based training experiences.

Furthermore, with the ongoing Covid-19 pandemic and concerns about the return of learners to institutions, there is an urgent need for technologies, such as virtual learning. Grasping current VR-HI limitations and advancements, VR could be a viable choice for healthcare and education domains.

1.2. Related works

Due to the growing scholarly scope of XR technologies, different types of research have been performed in the field of XR-HCI and general challenges include simulation for training, cognitive load, different types of affordances, etc. However, there is a lack of comprehensive research providing a categorization of the current research in XR-HCI. We found 23 potentially relevant articles, of which four were very relevant for our work, and reported the results of a systematic mapping study. Hence, we examine four review articles in total and introduce them shortly to illustrate the research gap we address with our systematic mapping study.

Radianti et al. (2020) conducted a systematic review of the educational domain, with three main points: the current domain structure in terms of the learning contents, the VR design elements, and the learning theories. They identified a gap which was the unexplored regions of VR for education. Further, they emphasized the need for more focus on the learning outcomes rather than the usability of the VR apps.

Yung and Khoo-Lattimore (2019) systemically reviewed 46 articles to answer five main defined questions about the usability of VR/AR in the tourism domain. They found an issue with terminology adapted from literature in the tourism domain. They also identified challenges around four domains: awareness of the technology, usability, time commitment for learning, and the willingness to replace corporeal experiences with virtual ones.

Kohli et al. (2022) reviewed Brain-Computer Interfaces (BCIs) and XR technologies and presented examples for the combination of these technologies. Then discussed the usage of these technologies in smart cities. They also presented ideas for future developments for the combination of BCI and XR technologies.

It is important to point out that none of these surveys present a pure systematic literature-based review of the existing VR-HCI techniques with a discussion on the way we categorized, future challenges, and the crucial role that VR has in different domains. In this article, we formalize three questions in the next section to select the most significant studies for review and then underline the importance of VR mechanisms, current challenges, and future trends in different domains by answering each of these questions. Our ultimate aim is to contribute to extending the XR knowledge on the current domains, especially medical, for current topics.

2. Research methodology

To advance our understanding of VR-HCI, this section has been carried out according to the guideline for systematic literature review (SLR) proposed by Kitchenham (2004) with a specific focus on research related to VR-HCI in different domains, such as medical, industry, and education. An SLR is a research method originating from the field of medicine (Kitchenham, 2004) that provides a repeatable research method and should supply sufficient detail to be replicated by other researchers (Kupiainen et al., 2015) In terms of leading to detailed answers within the necessity of VR-HCI in these domains, we developed three research questions to address the key concerns of VR-HCI in these domains. In the following section, we formalize these questions:

2.1. Question formalization

The goal of this section was to name the most relevant issues and challenges in XR-based research, including affordance, cognitive load, training, avatars, and possible XR solutions. This research effort will thus aim to address the following research questions:

RQ1: what is the importance of XR with usage growth of it? This question aims at the number of XR studies have been published over time, to underline the importance of XR along with increasing XR usage.

RQ2: How much are existing XR approaches meet the main domain metrics? The main purpose of this question is to evaluate existing XR approaches based on primary domain metrics.

RQ3: Which problems and solutions were identified with regard to XR for future trends? The objective of this question is to understand the role of XR, identifying its challenges and techniques used to ensure application of it.

A process as such can lead to detailed answers within the scope of this article. After identifying the need for research, research questions were formulated as a review protocol for our study. This protocol development has different stages, such as search query, selection of source and criteria, quality assessment criteria, data extraction, and data synthesis strategy.

2.2. Search query

Search strings were developed for academic databases and inclusion and exclusion criteria, by defining keywords. Search strings are defined by identifying synonyms and alternative spellings for each of the question components and associating them by utilizing the Boolean OR and Boolean AND. A search string has been defined by the selection of the most befitting keywords in terms of providing our subject. Hence, four keywords have been selected: "Virtual reality," "Mixed reality," "HCI," "HCC," and "Extended reality." After different steps and utilizing the outcomes of our initial analysis as a pilot to examine the coverage of the outcomes, the query was defined. Namely. To expand the scope as far as possible, the search string was applied to titles, abstract, and body of the studies. The search was conducted in December 2021, with a specified time range from 2017 to 2021.

2.3. Selection of sources

For our search query, we chose primary journal articles and conference papers. To obtain useful results, we categorized and examined these publishers. Our data sources were Google Scholar, Scopus, and Web of Science. As a result, the search procedure included articles from five of the most reputable technical and scientific peer-reviewed databases, including ACM Digital Library, IEEE Xplore, Springer Link, Science Direct, and Elsevier.

2.4. Selection criteria

A quality assessment checklist (QAC) based on Kitchenham et al. (2009) is being developed to assess only individual articles from peer-reviewed journals published between 2017 and 2021 to be qualified for inclusion in this review. Kitchenham's checklist (Kitchenham et al., 2009) contains the following questions: (a) Does the research article clearly specify the research methodology? (b) Is the research methodology appropriate for the problem under consideration?

Table 1. Summary of the inclusion-exclusion criteria for review protocol.

Criterion	Rational
Inclusion1: A study that clearly described how the mentioned HCI technique(s) could be applied and assisted in XR environment were selected.	We want to identify how HCI elements affect interactions in the XR, thus, we need articles that directly proposed HCI in the XR or indirectly proposed them from a service provisioning perspective.
Inclusion2: A study that is developed by either of academics or practitioners.	Both academic and industrial solutions are relevant to this study.
Inclusion3: A study that is published in XR field.	XR is our reference field.
Inclusion4: A study that is peer-reviewed.	A peer-reviewed article guarantees a certain level of quality and contains a reasonable amount of content.
Inclusion5: A study that is written in English.	For feasibility reasons articles written in other languages rather than English are excluded.
Exclusion1: A study that includes journal and conference papers only.	Masters and doctoral dissertations, textbooks, editorial notes, unpublished working articles and manuscripts or conference abstracts on not completed trials were excluded, as academics and practitioners alike most often use journals and conferences to acquire information and disseminate new findings.
Exclusion 2: A study that does not focus on HCI elements in the field of XR environments.	The focus of this article is only on studies that present HCI elements specifically in the XR.

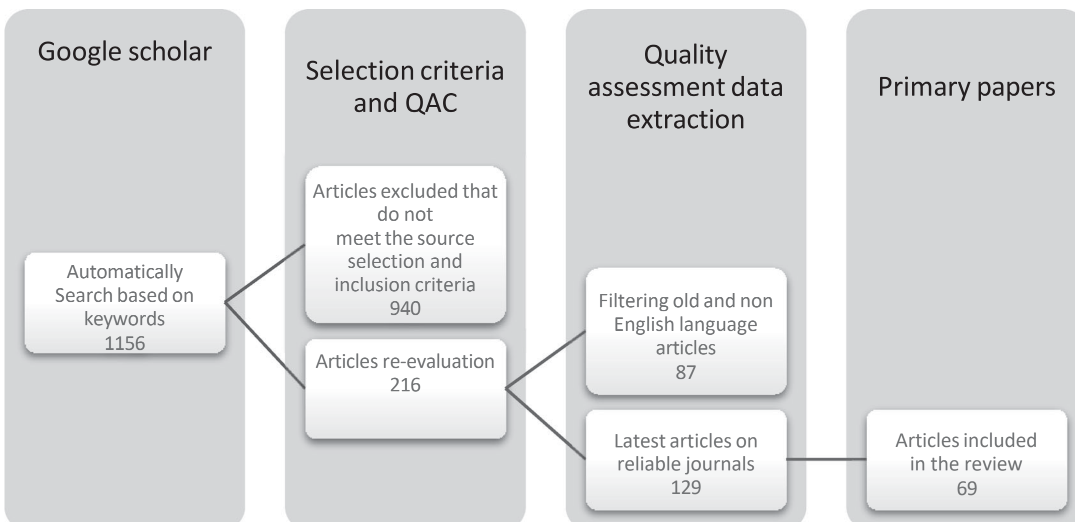

Figure 3. An overview of the utilized article identification process.

(c) Is the analysis of the study properly done? The study is filled with "yes" if it meets the assessment criteria. The inclusion–exclusion criteria for our review methodology are summarized in Table 1.

2.5. Quality assessment and data extraction

To optimal direction of literature review flow, the recommended reporting items for systematic reviews and meta-analyses PRISMA (Page et al., 2021) technique was employed. It should be noted, that PRISMA focuses on the procedures that authors might employ to guarantee that systematic reviews are transparent and thorough. The data extraction phase summarizes the data from the chosen research in preparation for future analysis. A total of 1156 studies were found. We mostly scan abstracts and look for keywords and themes that indicate the article's contribution. Insufficient abstracts were thus discarded. The whole body of each article was then reviewed for the remaining articles, and those that were not linked to the application of our specific issue were also deleted. Regarding the authors contribution to the search process, all search results were independently checked by two reviewers for title and abstract, then the full text was screened thoroughly by two reviewers, and probable discrepancies were addressed by a fifth reviewer. Following the application of inclusion/exclusion criteria and QAC to this research, 69 publications were chosen as primary studies for review. Figure 3 depicts an overview of the process used to identify the publications in this investigation.

The distribution of the selected primary articles across time is depicted in Figure 4. As can be observed, the number of articles published on the topic of XR-HCI increased significantly from 2017 to 2021; also, the majority of the selected articles were published in 2021. Our first formalization question (RQ1) clearly underlines the relevance of XR and the need for new and improved HCI methods, as well as the growing use of XR simulation in medical and educational settings.

3. Literature review

In this chapter, an exhaustive review of the current literature is presented (Table 2). In section 3.1, the review of XR-based simulators in surgical training is provided followed by the review of XR-based simulators in orthopedic surgical

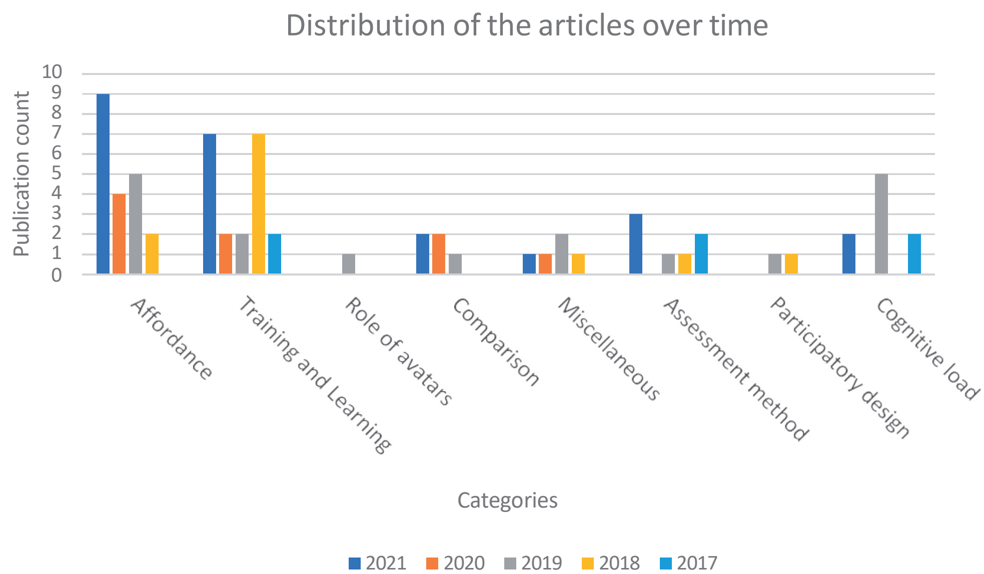

Figure 4. Number of primarily selected studies per year.

training in section 3.2. The review of the participatory design approach is presented in section 3.3. In section 3.4, the related work pertaining to information modeling is included. The current work in the HCI domain is discussed in section 3.5. A review of assessment methods is provided in section 3.6. In section 3.7, a review of assessment approaches in the XR domain is included. In section 3.8, the role of avatars is presented. Section 3.9 is comparison approach used in the XR simulations. In section 3.10, Absorption Stress, and Learning in 3D Immersive Virtual Training Environments are discussed. Articles that couldn't be categorized in prior above sections, will be reviewed in section 3.11.

3.1. XR-based simulators for training and learning

Jefferson (2019) presented the initial outcomes of using an immersive VR-based preoperative planning tool for laparoscopic donor nephrectomy. The author stated that it was challenging to understand more than 2500 CT images hence they developed 3D models using a 3D slicer which allowed an interactive and comprehensive anatomy when viewed through an immersive headset. The CT images of seven patients were used for a study in which two surgeons assessed the preoperative understanding using CT alone and CT on the immersive headset. The results from the study indicated that immersive models enhanced the surgeons' understanding of the patient's arterial and venous anatomy. Moreover, the surgeons' overall confidence regarding the operation improved while interacting with the 3D image on the immersive headset.

A mixed-reality simulator for training in Nasal Endoscopy is presented was presented by Barber et al. (2018). The mixed reality-based approach used HTC Vive, 3D printed model, and Vive trackers. Vive trackers were placed on the 3D printed skull and the endoscope through which the virtual skull and virtual endoscope were synced. Using this approach, the users could interact with the virtual object in the Vive-based 3D environment and at the same time could feel a haptic sensation from the real object as well.

Huber et al. (2017) have compared a non-immersive laparoscopic simulator with a fully immersive Vive laparoscopic simulator. Ten members of the surgical department participated in the comparison task. The participants performed three tasks which were peg transfer, fine dissection, and cholecystectomy. The results show that participants show a high level of exhilaration when using the Vive simulator due to the high level of immersion.

Wijewickrema (2017) has discussed the design of a haptic Cochlear implant surgery training module. They have also evaluated the module through pre and post-test. The evaluation revealed that the participants found concurrent verbal and visual cues helpful.

3.2. XR-based simulators in orthopedic surgical training

A Mixed Reality-based surgical navigation system for orthopedic surgical navigation has been discussed by Wu et al. (2018). The MR-based navigation system consists of HoloLens display, a magnetic launcher, a passenger sensor, and a processer. The MR-based system is useful in providing real-time 3D visualization. Using the MR-based system, the 3D reconstructed virtual model generated using a CT scan or MRI can be integrated with the body of the patient which can be helpful in guiding the operating procedure. Such a system provides additional visual information related to the internal organ of the patient which is not visible to the naked eye. The MR-based navigation system has several advantages over the conventional image-guided surgical system, such as intuitive and detailed imaging information, less time spent and mental load, and low risk of errors among others.

Shi et al. (2018) discussed the role of a visuo-haptic training simulator in the education and training of residents. The simulator was developed for a widely practiced surgery in

Table 2. Reviewed articles including categories and domains.

Title	Author	Year	Category	Domain
IoT avatars: Mixed reality hybrid objects for CoRe ambient intelligent environments	Yiyi Shao	2019	3	General
Human−computer interaction based joint attention cues: Implications on functional and physiological measures for children with autism spectrum disorder	Vishav Jyoti	2020	1	Medical
Patient-specific virtual and mixed reality for immersive, experiential anatomy education and for surgical planning in temporal bone surgery	Ayame Yamazaki	2021	4	Medical
Application of virtual reality for crew mental health in extended duration space missions	Nick Salamon	2018	5	Space and Medical
A multi-user virtual reality experience for space missions	A. Del Mastro	2021	5	Space (multi-user)
Interaction design for multi-user virtual reality systems: An automotive case study	Iang Gong	2020	4	Industry (multi-user)
Brain training with the body in mind: Towards gamified approach-avoidance training using virtual reality	Naomi Kakoschke	2021	2	Medical
VR with older adults: Participatory design of a virtual ATM training simulation	Wiesław Kopec	2019	6 and 7	General
Digital restoration of fragmentary human skeletal remains: Testing the feasibility of virtual reality	Mikolas Jurda	2019	4	Medical
Virtual reality simulation facilitates resident training in total hip arthroplasty: A randomized controlled trial	Jessica Hooper	2019	2	Medical
Undergraduate nursing student experiences in using immersive virtual reality to manage a patient with a foreign object in the right lung	Benjamin Stephanus Botha,	2021	6	Medical
Harvis: An interactive virtual reality tool for hemodynamic modification and simulation	Harvey Shi	2020	4	Medical
A comparative study on inter-brain synchrony in real and virtual environments using hyperscanning	Ihshan Gumilar	2021	6	Medical
Healthcare training application: 3D first aid virtual reality	Narmeen, N, Al-Hiyari	2021	2	Medical
Parkinson's disease simulation in virtual reality for empathy training in medical education	Yi (Joy) Li	2021	6	Medical
Novel virtual reality-based training system for fine motor skills: Towards developing a robotic surgery training system	Madhan Kumar Vasudevan	2020	2	Medical
Virtual reality training system for surgical anatomy	Xin Wang	2018	2	Medical
Virtual reality for user-centered design and evaluation of touch-free interaction techniques for navigating medical images in the operating room	Anke Verena Reinschluessel	2017	6	Medical
Toward interprofessional team training for surgeons and anesthesiologists using virtual reality	Vuthea Chheang	2020	2	Medical
Virtual reality facial emotion recognition in social environments: An eye-tracking study	C.N.W. Geraets	2021	1	Medical
Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation	Misha Sra	2019	1	Medical
Effects of virtual reality simulation program regarding high-risk neonatal infection control on nursing students	Mi Yu	2021	8	Medical
Effect of the haptic 3D virtual reality dental training simulator on assessment of tooth preparation	Akitaka Hattori	2021	8	Medical
Navigation modes, operation methods, observation scales and background options in UI design for high learning performance in VR-based architectural applications	Chengyu Sun	2019	8	Architectural
Effects of immersive virtual reality exposure in preparing pediatric oncology patients for radiation therapy	Michelle Tennant	2021	2	Medical
Prompting in-depth learning in immersive virtual reality: Impact of an elaboration prompt on developing a mental model	Andrea Vogt	2021	2	General
The human source memory system struggles to distinguish virtual reality and reality	Marius Rubo	2021	2	Medical
Effect of cognitive training based on virtual reality on the children with autism spectrum disorder	Jun-Qiang Zhao	2021	2	Medical
Introducing VR technology for increasing the digitalization of SMEs	Vasiliki Liagkou	2019	5	Industry
VR training model for exploiting security in LPWAN	Vasiliki Liagkou	2019	5	Network
Evaluating the user experience of omnidirectional VR walking simulators	Kyle Hooks	2020	5	General
Development and application of VR course resources based on embedded system in open education	Kenan Li	2021	4	Education
Immersive virtual reality (IVR) renal models as an educational and preoperative planning tool for laparoscopic donor nephrectomy: Initial experience	Jefferson, F.	2019	2	Medical
Virtual functional endoscopic sinus surgery simulation with 3D-printed models for mixed-reality nasal endoscopy	Barber	2018	2	Medical
New dimensions in surgical training: immersive virtual reality laparoscopic simulation exhilarates surgical staff	Huber, T	2017	2	Medical
Design and evaluation of a virtual reality simulation module for training advanced temporal bone surgery	Wijewickrema, S.	2017	2 and 6	Medical
Mixed reality technology−Assisted orthopedics surgery navigation	Wu, X.	2018	2	Medical
Role of visuohaptic surgical training simulator in resident education of orthopedic surgery	Shi, J.	2018	2	Medical

(continued)

Table 2. Continued.

Title	Author	Year	Category*	Domain
A virtual hip replacement surgery simulator with realistic haptic feedback	Kaluschke, M.	2018	2	Medical
A Microsoft HoloLens mixed reality surgical simulator for patient-specific hip arthroplasty training	Turini, G.	2018	2	Medical
Augmented reality visualization for orthopaedic surgical guidance with pre-and intra-operative multimodal image data fusion	El-Hariri, H.	2018	2	Medical
Development of a simulator with HTC Vive using gamification to improve the learning experience in medical students	Gonzalez, D. C.	2018	2	Medical
Effectiveness of virtual reality in participatory urban planning: A case study	van Leeuwen, J. P.,	2018	7	General
Eyemotion: Classifying facial expressions in VR using eye-tracking cameras	Hickson, S.	2019	8	General
Confusion prediction from eye-tracking data: Experiments with machine learning	Salminen, J.	2019	8	General
Cognitive load measurement in a virtual reality-based driving system for autism intervention	Zhang, L.	2017	8	Medical
3D travel techniques for virtual reality cyberlearning systems	Lai, C.	2019	8	General
Towards an objective measure of presence: Examining startle reflexes in a commercial virtual reality game	Schirm, J.	2019	1	General
Affordances as a measure of perceptual fidelity in augmented reality	Pointon, G.	2018	1	General
Danger from the deep: A gap affordance study in augmented reality	Wu, H.	2019	1	General
Estimating distances in action space in augmented reality	Gagnon, H. C.	2021	1	General
Investigating educational affordances of virtual reality for simulation based teaching training with graduate teaching assistants	Ke, F.	2020	1	Educational
Effects of affordance on the visual perception of smart washing machine user interface design	Li, H.	2021	1	General
Exploring the educational affordances of augmented reality for pupils with moderate learning difficulties	Koutromanos, G.	2020	1	Educational
Exploring the affordances of computer-based assessment in measuring three-dimensional science learning	Thompson, C. J.	2021	1	Educational
Comparing touch-based and head-tracking navigation techniques in a virtual reality biopsy simulator	Ricca, A.	2021	1	Medical
The impact of virtual reality and viewpoints in body motion based drone teleoperation	Macchini, M.	2021	1	General
The effect of feedback on estimates of reaching ability in virtual reality	Gagnon, H. C.	2021	1	General
It's in your hands: How variable perception affects grasping estimates in virtual reality	Readman, M. R.	2021	1	General
Affordance analysis of virtual and augmented reality mediated communication	Keshavarzi, M.	2019	1	General
Affordance compatibility effect for word learning in virtual reality	Gordon, C. L.	2019	1	Educational
Perceived educational usefulness of a virtual-reality work situation depends on the spatial human-environment relation	Dobricki, M.	2021	1	Educational
Revisiting affordance perception in contemporary virtual reality	Bhargava, A.	2020	1	General
Affordances of virtual and physical laboratory projects for instructional design: Impacts on student engagement	Nolen, S. B.	2018	1	General
Development and evaluation of a trauma decision-making simulator in oculus virtual reality	Harrington, C. M.	2018	6	Medical
Comparing middle school students' science explanations during physical and virtual laboratories	Dana Gnesdilow	2021	2	Education
Examine the effect of different web-based media on human brain waves	Jozsef Katona	2017	8	Medical
Electroencephalogram-based brain-computer interface for internet of robotic things	Jozsef Katona	2019	8	Medical

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the field of spine surgery known as pedicle screw placement. In spine surgery, it is crucial to position the screw correctly as neural structures are close to the bony pedicle. A study was conducted to assess the role of such a simulator in the training of the medical residents. In the study, the residents (no. ¼ 5) first trained on the VR simulator. Subsequently, they perform the same steps on a human cadaveric spine specimen. Finally, the positions of the pedicle screws were evaluated and compared to a control group (no. ¼ 5) which did not interact with the simulator and only learned the steps through the traditional teaching method. The results show a significant difference in screw penetration rates, screw placement accuracy, acceptable rates of screws, and average screw penetration distance between the training and control group. This study shows that the VR simulator can be a useful method to train medical residents before surgery.

A VR-based hip replacement surgery simulator is discussed by Kaluschke (2018). Milling is an important aspect of this surgery. However, the surgeon cannot see where or how he/she mills, but only feels the force of the reamer. To construct a realistic simulator, high forces are required to mimic the milling forces. The authors for this purpose have used an industrial robotic arm for force feedback. The robotic arm was not built for haptic feedback hence novel control and haptic rendering algorithm were implemented on it. The haptic rendering algorithm computes collisions of the reamer with the hip and generates forces and torques, including an appropriate friction model. The haptic control mechanism controls the robot. It receives the forces and torques from the haptic rendering algorithm and transfers them into a stable configuration of the industrial robotic arm.

A Mixed Reality Surgical Simulator for Hip Arthroplasty training is presented (Turini, 2018). The overall system, main phases of design, and development of the HoloLens-based simulator are discussed. The system combines patient-specific replicas, AR features, and audio technology. The CT scan of the required bones was used for the creation of virtual models and 3D printed physical content. The Arthroplasty Virtual simulator provides two configurations (1) visualization of bones, pelvis, and preoperative planning and (2) complete virtual content with hidden muscle. Students were asked to assess the simulator using a Likert Questionnaire form. Positive feedback was provided for Head Tracking, Gesture, voice interaction, and spatial sound. However, a neutral opinion was expressed about the ease of aligning surgical instruments with an AR view finder.

El-Hariri (2018) presented a method to create 3D volume to align pre-operative data to intra-operative information from optically tracked ultrasound and CT images. The AR-enhanced scene can be visualized using Microsoft's HoloLens. A study to demonstrate the capability of the method has been conducted using a foam pelvis phantom by comparing the location of fiducial markers in the real and virtual spaces. The RMS errors for the x, y, and z axes were 3.22, 22.46, and 28.30 mm, respectively.

Gamification as a learning strategy is used by Gonzalez and Garnique (2018) to enhance medical students' skills in knee cruciate ligament surgery. The simulator is developed for the HTC Vive platform. The simulator first shows a tutorial related to the steps to be followed. Subsequently, the users train using the simulator. A total of 30 users completed the learning with and without the tutorial. The results were taken for criteria, such as score, time, precision, error, and sequence. Out of 950 points, 20 students received a score of 720, and 10 received a score of 700. The results show that the knee surgery simulator not only helped train in the surgical procedure but also motivated them to improve their medical skills.

Approach Avoidance Training (AAT) presented by Kakoschke et al. (2021) to modify the link between unhealthy foods and automatic appetitive responses. They designed and tested this approach using VR by moving a range of 3D healthy and unhealthy foods toward and away from users using hand controllers that track movements and gestures. Participants, using a Vive controller, picked up food items and put them at a floating target (push action) or ate them by closing the items to their mouth (pull action). They found VR effective for their approach.

Hooper et al. (2019) utilized VR simulation for teaching orthopedic surgery residents to see it is beneficial for their performance in cadaver Total Hip Arthroplasty (THA) surgical skills. They compared the improvement in cadaver THA performance, specific aspects of surgical skills, and knowledge and perception of surgical anatomy and indications. Participants first completed a written pretest and a single THA for establishing their baseline knowledge, then half of them randomly interacted with VR simulation. They utilized OramaVR software platform and Oculus Rift CV1 headset for their simulation. Their results showed that VR improves surgical and technical skills but has no effect on medical knowledge.

Al-Hiyari and Jusoh (2021) proposed two teaching modules for their prototype 3D first Aid VR. A teaching module that described the cause and symptoms of seizure and a training module was utilized to train first aid instructions in a VR simulation. Wang and Wang (2018) proposed a VR simulation for the entire chest anatomy to perform the anatomical operation with experimental steps. They divided the process into three modules: scene construction, result determination, and UI interface.

Vasudevan et al. (2020) presented a Microscopic Selection Task (MST) with varying degrees of difficulty for robot-assisted surgery using VR. They devised a visual magnifier in VE to nullify the vertiginous effect on the users to use the zooming feature of simulation to see microscopic objects in it. They also adapted Fitts's Law to quantify psychomotor performance. For studying the impact of simulation on training performance they conducted Vibrotactile Feedback (VTFB). Their result showed improved performance metrics.

To train and improve intraoperative communication between anesthesiologists and surgeons during laparoscopic procedures (Chheang et al., 2020) proposed An anesthesia simulation software and laparoscopic simulation software are combined within a multi-user VE. The anesthesia simulation software LLEAP was utilized for vital sign monitoring during VR simulation. Two training scenarios were used: undetected bleeding and insufficient muscle relaxant medication. Their result showed the usefulness of simulation for training in VR.

By showing the treatment process to patients through virtual reality, Patients can have a comprehensive understanding of the treatment process through virtual reality, to reduce patients' anxiety. Tennant et al. (2021) recruited a group of patients and their families who needed treatment. The patients ranged in age from six to eighteen. Before the participants underwent surgical treatment, the research team showed them the simulation of two treatment stages using virtual reality technology. After that, the research team tracked and investigated, and recorded their performance in anxiety and health.

Vogt et al. (2021) studied the psychological model of a virtual reality learning environment, and compares the learning results of participants, to evaluate the learning effect of various psychological models. They tested 64 experimenters. The author obtains the data and further analyzes the data by asking participants to conduct in-depth semantic processing of the learning content. During the experiment, participants can choose additional prompts for learning content, and researchers can further analyze the mental model through the prompts selected by participants. Their results showed that learning content should be explained to the learners in detail before allowing the participants to enter the virtual reality world for learning, which will have a positive impact on the learning effect.

Rubo et al. (2021) put forward a hypothesis that human source memory is difficult to distinguish virtual reality from reality and if this hypothesis can be confirmed, virtual reality may have a certain therapeutic effect on mental diseases of specific people. In addition, if this hypothesis can be confirmed, people should also study the potential risks of using virtual reality. In the process of this experiment, the researchers first invited the participants to the laboratory alone. Then filled in the informed book of the experiment according to relevant laws and regulations. After that, the participants performed a memory task, and the researchers informed the participants to remember the patterns of each model they see. After the test, the researchers informed participants to attribute each model to the correct category. The memory task of this experiment was divided into six consecutive memory test tasks. Participants will test the physical models of 15 random animals in reality. Participants tested the three-dimensional models of 15 random animals in virtual reality. In this experiment, the author found that compared with traditional displays, human memory confusion between virtual reality and reality is more frequent. This showed that in the human memory system, the classification of virtual reality is very close to reality. In the virtual world, users with virtual bodies can deepen their impression of the virtual reality world however, this may cause more memory confusion.

Medical personnel can use virtual reality technology to carry out early intervention and treatment for children with autism spectrum disorders. In Zhao et al. (2021), a total of 120 children with autism spectrum disorders participated. Their study divided the children into two groups, one group participated in the simulation experience of virtual reality, and the other group was the control group. The results show that children patients participating in the simulation experience of virtual reality completed more training designed by the researchers, and the time required to complete the training.

Authors in Gnesdilow and Puntambekar (2022) developed a design-based unit to teach science ideas, such as force, friction, etc. to middle school students. They asked children to conduct a written explanation for each experiment to see how they can make the connection between concepts and their use of evidence. They compared students learning processes from two different perspectives. They asked one group of students to conduct a virtual lab Virtual-then-Physical (V-t-P) and vice versa for the second group. They also used an inclined planes test to evaluate students' physics knowledge at the start and end of the unit. Their results show that students those students perform better when they only conducted the virtual lab. They also concluded that in performing both labs, students who do a physical lab before the virtual lab may benefit more than other groups.

3.3. Participatory design

Participatory Design is a method to involve the people who are going to be affected to have their input during the design process (Ehn, 1996; Harrison, 1996). It is a democratic design process for the design of social and technological systems based on the argument that users should be involved in the design and all stakeholders should have input during the design process (Muller & Kuhn, 1993). The participatory design method was first used in Scandinavia (Jensen, 1997).

A study has been presented involving civic participation in the design of a public park using VR in Van Leeuwen (2018). The results of the study indicate that 3D visualization helped both designers and untrained citizens to be more creative. The results also indicate that the participants using immersive VR headsets experienced a higher level of engagement during the design process compared to participants using non-immersive VR systems.

A study was conducted by Kope,c et al. (2019) involving a group of older adults who engaged in creating a VR-based ATM training simulation by using a participatory design approach. The results from the study demonstrate that VR is an effective way to directly gain valuable insights related to the design from the participants.

3.4. Information modeling

Information modeling supports the interdisciplinary approach in which experts from respective fields come together for the design of complex systems, such as XR-based simulators (Cecil, 2009). In the information modeling approach, the emphasis is on the data/information exchanges that occur between the interdisciplinary team members along with the availability of tools and resources as well as information inputs and constraints that influence the design and development of a target system (Cecil & Pirela-Cruz, 2013). Information modeling has been used in the design and development of complex systems in domains, such as manufacturing (Cecil, 2009; Lu & Cecil, 2015), and surgery training (Cecil & Pirela-Cruz, 2013, 2016).

Model-Based Systems Engineering (MBSE) approaches utilize such models to help define, design, and document a system that is under development. These models play an important role in providing an efficient way to explore and communicate the system aspects to the customers and stakeholders.

3.5. Cognitive load

Learning systems should be designed in a way that provides appropriate levels of cognitive load to their users. Cognitive load theory categorizes cognitive load into three broad types: The intrinsic load of the learning task (inherent to the complexity of the task), the extraneous load of the learning situation (a result of superfluous processes that do not directly contribute to learning), and the germane load of the learning process (mental schema formation for the actual learning) (Sweller, 1988). Intrinsic load refers to the load imposed by the nature of the topic to be learned. Extraneous load refers to the load imposed by the manner in which the information or instructions are provided to the users. Also, distractions in the immersive environment add extraneous cognitive load (Cecil et al., 2017). This increases intrinsic and extraneous loads during training in immersive VR. There are different types of methods used to assess the cognitive load on a user during the interaction with a simulator. They are broadly divided into (1) Subjective and (2) Objective Assessments.

Researchers have developed and utilized several subjective methods to measure cognitive load. Some of the methods are the NASA TLX test (Hart & Staveland, 1988), PAAS Scale (Lox et al., 2000), among others. The PAAS Scale measures the mental load of a person during a task; it consists of a Likert chart ranging from 1 (very, very low mental effort) to 9 (very, very high mental effort). The NASA TLX test measures the mental, physical, temporal demand, effort, and frustration using a 21-point Likert scale.

The objective assessment of the cognitive load can be categorized into:

(a) Task-based assessment

The cognitive load can be measured objectively by using a test called Dual-Task Measures. In this test, it is assumed that when the learning task becomes overloading, the level of performance in the secondary task decreases. The secondary tasks can be tasks, such as pressing a button when the user hears a buzzing sound and identifying letters that are displayed on the screen, among others.

In Britt et al. (2015), the cognitive load study during traditional cadaveric dissection training and VR simulation training was conducted using secondary task analysis; reaction to a sound stimulus was chosen as the secondary task. The results indicate that VR training leads to a lower cognitive load compared to traditional dissection. Secondary task analysis has also been used to measure cognitive load during VR-based temporal bone surgery and mastoidectomy training (Andersen et al., 2020).

Yu et al. (2021) focused on the teaching experience brought by virtual reality simulation programs to students and the improvement of students' clinical knowledge.

The author divided senior nursing students from nursing college into two groups: nursing students, and senior nursing students. The two groups of senior nursing students practiced in virtual reality simulation and routine neonatal intensive care unit, respectively. The internship projects included various nursing care for newborns and the prevention of neonatal diseases. Through data statistics, they find that students who have experienced virtual reality learning are more satisfied with the learning plan. Virtual reality technology can also be conveniently used for repeated learning.

Hattori et al. (2022) studied the characteristics of this new dental training simulator and the traditional manikin simulator, and to evaluate the training effects of these two devices. They made a full evaluation between tactile simulators and traditional simulators. In the traditional simulator, students were asked to cut the denture attached to the simulation head. They evaluated the results through visual inspection. A total of 30 students participated in this study. All of them were from the sixth grade of the Dental College. Each student used traditional and new simulators to prepare abutment teeth of fully cast crowns. Then the author invited three professionals to evaluate the students' final products. In addition, the scores of the two simulators were counted and analyzed. Their results indicated that tutorial design should be according to the characteristics of different simulators, rather than blindly implant tutorials into simulators.

Sun et al. (2019) studied the user interface design to improve students' learning effect. They focused on the description and design of the four key elements of the user interface. These four elements are navigation mode, operation method, observation scale, and background options. The author found 120 students to participate in their study and conducted a group experiment. They used HTC Vive for the simulation and found that the background environment is not an important factor in the design of the user interface. The closer the design of virtual reality is to the real effect, the better. In addition, the user interface can affect the learning effect of students to a great extent.

(b) Assessment using physiological indices

Cognitive State or mental state can be measured using different modalities, such as external physiological indices (pupil dilation, eye movement, gaze, facial expression, etc.), central physiological indices (related to the central nervous system, such as brain activity), and peripheral physiological indices (related to the peripheral nervous system, such as muscle activity, heart rate, among others).

Some researchers have measured various eye-related data to recognize facial expressions, confusion, and emotional arousal among others (Hickson, 2019; Salminen, 2019; Zhang et al., 2017). In Hickson (2019), users wearing HMD were asked to pose with various facial expressions; the images of their eyes were photographed using the eye-tracking camera which was later used to classify facial expressions using a machine learning algorithm. Eye fixation data coupled with a random forest machine-learning algorithm was used to classify confusion in Salminen (2019).

In Zhang et al. (2017), multimodal physiological indices along with performance data were used to measure cognitive load in individuals with Autism Spectrum Disorder (ASD) when interacting with a driving simulator. Physiological data included pupil dilation recorded using eye trackers, brain activity recorded using EEG, and other peripheral physiological data, such as muscle activity using electromyography (EMG), and heart rate using electrocardiography (ECG) were recorded. The performance was recorded in terms of driving behavior, use of brake, and accelerator during the interaction with the simulator. The results show that multimodal information can be used to measure cognitive load with increased accuracy.

Li (2020) studied the level of presence in a VR-based operating room developed for laparoscopy training. Thirty-seven surgeons and surgical trainees interacted with the simulator and were asked to complete the survey based on the Presence questionnaire. The results indicated that participants, especially the young trainees were excited to interact with the simulator. 25 out of the 37 participants indicated that the talk and the sounds in the environment enhanced the presence.

Gardner et al. (2017) studied the feasibility of the Situation Awareness Global Assessment Technique (SAGAT) tool to assess situational awareness in the surgical trainee. 43 third-year medical students interacted with two scenarios developed for advanced cardiac life support as part of ten-team training sessions. SAGAT method involves freezing the simulation and probing the trainees with questions. The results show that it is feasible to measure situational awareness using the SAGAT tool in a simulated team setting.

To monitor the changes ongoing in the brainwave values of the test subjects in real-time, and also record and evaluate statistically the monitored values during browsing different mass media content (texts, pictures, videos) web pages (Katona, 2017) employed electroencephalography (EEG) headset and utilized the MindSet Development Tools (MDT) package, offered by NeuroSky to apply Brian Computer Interfaces (BCI). In three phases, 15 healthy individuals used PCs to browse the internet to assess the developed environment. A text-content webpage was investigated in the first testing session. The static picture contents predominated in the second phase. The test subjects watched the same videos in the third phase. They came to the conclusion that different media content causes changes in brainwave strength.

Katona (2019) investigated the design opportunity of supervisory achieved by moving a mobile robot using IoT technology *via* brain–computer interface, which can utilize some cognitive human skills and features by a BCI system designed for human–computer-based control of IoT-based robot (IoRT) unit using a headset and a self-built mobile robot. The EEG headset was then used to assess the users' brain activity, human intervention performance, and latency owing to the BCI system. Their findings revealed that the IoRT and BCI may be employed effectively in education and in a variety of learning environments.

Previous work on cognitive load mostly focused on assessing the load on the users using various subjective and objective assessment techniques. Researchers have not focused on developing scenarios within the VR environments which would affect the load on the users. Few researchers have used dual-task measures depending on basic tasks, such as buzzing sound and identifying letters, among others. However, such tasks are completely unrelated to the process being performed in the VR environment.

3.6. Affordance

The word affordance was first coined in Gibson and Carmichael (1966) by psychologist James J. Gibson who defined it as what the environment offers to the individual. In the context of Human–Computer Interaction, the term affordance was defined by Norman as action possibilities that are perceivable readily by an actor (Norman, 1988). Gaver delineated affordances as the properties of the world which are defined with respect to how people interact with them. Gaver provided an analysis of the relationship between affordance and perceptual information about the information which led to four possible combinations *viz.* perceptible affordance, false affordance, hidden affordance, and correct rejection. In perceptible affordance, there is perceptual information available for affordance. In the case of false affordance, perceptual information is not available for affordance. When perceptual information is available, but affordance is not, it is known as a hidden affordance. When both perceptual information and affordance in unavailable, it is called correct rejection (Gaver, 1991). Despite the growing interest in VR, questions regarding what and how VR affords users, how users feel about VR services, what they experience in learning contexts, and which aspects could promote affordance remain unanswered. It is critical to examine how users perceive qualities, how these qualities elicit motivational affordances, and what cognitive experiences are held.

During the design and development of XR-based applications, designers focus on spatial, manipulation, and feedback affordances (Elliott, 2015). Head-mounted XR-based displays provide natural movement of the head and body which enables users to sense the depth of images in an intuitive manner creating a sense of presence. Spatial affordance refers to a person's understanding of the space and the environment around him/her and in what ways he/she can interact with it. Spatial affordance becomes imperative in XR as a person is constantly surrounded by space/environment. Manipulation of virtual objects is a key activity a user performs in any XR-based environment. Manipulation affordance is the affordance offered by manipulating or interacting with the virtual object in an XR environment. Affordance can also be achieved by providing feedback to the user without any latency. The user should be able to see the result of the action (such as picking up an object) instantaneously on the XR display.

Schirm (2019) measured presence in a VR environment where the users had to locate seven items in a VR environment. Two events were designed to measure the presence which were (i) the swing of a chandelier and (ii) a ghost appearing. Head movement distance was calculated when the chandelier swung and head movement speed was measured when the ghost appeared. Head movement speeds of a startle response produced the most distinct results in our study, especially in conjunction with bounding box dimensions of the head movement trajectory. Participants whose reaction was classified as strong had more experience (mainly with VR), felt more present and were more impressed with their VR game.

Pointon (2018) developed a test for objective assessment of judgment and action-based measures to measure perceptual fidelity in AR using HoloLens. Observers were asked whether they pass through a holographic aperture presented at different widths and distances using virtual poles and then to judge the distance to the aperture. Distance between poles varied from 60 to 30 cm and changed every 7 s by 5 cm. A crossover point was set which was the largest aperture width at which participants stated they could no longer pass through for at least two consecutive trials. The ratio between the crossover point and the participant's shoulder width was noted. If the ratio >1, participants overestimated the size of the aperture needed to pass through, and if the ratio <1, participants estimated that they could pass through an aperture that was smaller than their ability. Passing through estimates were relatively accurate, but somewhat larger than actual shoulder width (Mean ratio ¼ 1.18). This is consistent with classic findings in the real world on affordances for passing through.

Wu (2019) conducted a similar study in which gaps of varying widths and depths were placed in AR using HoloLens and users were asked if they will be able to step across the gaps. As predicted, the results revealed a significant effect of pit depth on users' judgment. Planned contrasts with the deep pit as the reference showed that participants underestimated their capability to step over the gap when presented with the deep pit relative to the shallow pit. There was no difference between judgments for the medium and the deep pits.

Gagnon et al. (2021) conducted an experiment to test the egocentric distance perception in AR. Two real-world settings; a large open room and a hallway were used for this experiment. A 1.8 m AR avatar was placed at 10, 15, 20, 25, 30, and 35 m, and the users were asked to estimate the distance of the avatar. The results of the experiment showcase that the participants underestimate the distance to AR avatars.

Ke et al. (2020) investigated the affordances and constraints of a VR-based learning environment for the teaching training targeted toward graduate teaching assistants in relation to the task, goal-based scenarios, and learning support design. A total of seventeen participants interacted with the OpenSimulator-supported teaching program. The results of the study show that a VR-based learning environment fostered participants' performance. The VR-based environment helped them notice and attend to students' actions and reactions.

Li and Chen (2021) conducted an experiment to understand the difference between people's cognition of operation and the form of product presentation. They explored the gender-based visual perception for the interface design of smart washing machines. The results demonstrated that gender differences significantly affect the sensitivity to perceiving smart technology products.

Koutromanos (2020) examined the potential educational affordances of Augmented Reality (AR) for pupils with Moderate Learning Difficulties (MLD). Three open questions were asked to 25 teachers who specialized in AR. The responses revealed 10 affordances viz. in situ contextual information, individualized guidance, feedback, gamified experiences, learning object visualization, interaction reinforcement, and ability to obtain first-person view including three new affordances *viz.* attention capturing, skill development efficiency, and repeatability.

Thompson and Hite (2021) explored the affordances in computer-based assessment through the development of 3D science learning. Task-based interviews were performed to compare the 3D environment to multiple-choice questions. The results show that the 3D items are more or equally effective with MCQs.

Ricca et al. (2021) compared touch-based and head-tracking navigation technologies for aVR-based biopsy simulator. The study compared two viewpoint-changing techniques with two levels of interaction fidelity in which 21 novice users participated. An objective test (time, precision, and error) and subjective survey (5-point Likert scale) was conducted, and the results show that touch-based viewpoint movement improved the task completion performance.

Macchini (2021) compared different viewpoints and users of VR on the operation of a fixed-wing drone. 30 volunteers participated in the study in which the body motion analysis was performed, and a presence questionnaire was provided. The results showed that VR correlates with a higher sense of spatial presence and spontaneous body motion patterns were affected by VR.

Gagnon (2021) studied the effect of feedback on action capabilities for two reaching behaviors (reaching out and reaching up). The results show that reach was initially overestimated. However, the estimations became more accurate over the feedback blocks.

Readman et al. (2021) investigated the influence of perceptual-motor variability on perceived grasp ability in Virtual Reality. Participants estimated grasp ability after an experience with four types of grasps; constricted, normal, extended, and variable. Two experiments were conducted; in the first experiment, the participants experienced all three grasps 33% of the time and in the second experiment, they experienced constricted and normal grasps 25% of the time and extended grasp 50% of the time. The results show that if the feedback is inconsistent, the perceptual system disregards the experience with different action capabilities.

Keshavarzi (2019) explored non-verbal communication features for VR and AR-mediated communication settings. Four interaction methods were chosen for the study; face-to-face interview, zoom call, Virtual reality-based Avatars, and AR-based Holograms. The results showed that over 75% of participants ranked 2D video as their first choice. Participants narrowly preferred holograms over VR. The acceptance rate of holograms and VR increased in less emotionally engaged conversation tasks.

Gordon et al. (2019) had done three experiments to understand the learning affordances for word learning in VR. The results of the first experiment showed that direct manipulation induces affordances for word learning. The results of the second experiment underscored that virtual hands interacting with the objects affect affordances. The results of the third experiment showcased that affordance was affected mostly by the compatible hand and not by the spatial location.

Dobricki et al. (2021) conducted a study to study the utility of VR for teachers in which 10 horticulture teachers interacted with VR environments to study the planning of the garden. The results of the study showed that VR was rated higher in educational usefulness and the teachers felt more present in VR.

Bhargava et al. (2020) compared possibility judgments in the virtual environment and real world. Participants were asked to judge if they could pass through a sliding doorway that was adjustable while wearing an HTC Vive headset. They were also allowed to walk if they were not sure of their judgments. The results show that participants can judge possibility effectively both in VR and real-world. However, the participants made more movements in VR to acquire the possibility of information.

Nolen and Koretsky (2018) compared students' engagement and interest in engineering between virtual and physical laboratory projects, designed to be realistic and replicate engineering practice. 118 students' interest and engagement in two physical laboratory projects and one of two virtual laboratory projects in a senior-year capstone course were investigated. Students reported greater engagement, perceptions of contribution to their group's learning, opportunities to transfer prior learning from coursework, and end-of-course interest in engineering problem-solving in the virtual laboratory project rather than the physical laboratory projects.

Jyoti and Lahiri (2020) designed a VR-HCI-based Joint Attention (JA) task for children with Autism Spectrum Disorder (ASD). Their JA-based cueing utilized two approaches: namely avatar-mediated and environment-triggered. Avatar-mediated cues consisted of gaze-based cueing, a combination of head turn and gaze-based cueing, and pointing a finger toward the objects. Their environment-triggered cueing involved sparkling of the targeted objects, in addition to head turn, gaze, and pointing gesture-based cueing. However, they had limitations for the sample size and limited exposure to the system. Although their results are promising the transferability of the learned JA skills to the real world remained to unsettle.

Because the avatar's face can be dynamic in virtual reality, it can practice interactively with the training object. In the traditional emotion recognition task, the picture cannot be easily manipulated. In addition, most traditional training only shows an isolated face or upper body. Geraets et al. (2021) studied the role of virtual reality in social networks. Emotion recognition in video and photo tasks is compared with virtual reality. Through the covariates of recognition and memory, the visual attention and virtual reality emotion recognition tasks in virtual reality were studied and tested.

Sra (2019) utilized a wearable device to enhance the virtual reality experience through vestibular electrical stimulation. The research on the vestibular system has lasted for a long time. Vestibular electrical stimulation is a special method to stimulate vestibular reflex. In addition to this wearable device, the research team also used methods, such as connecting heart rate and skin electrical activity to collect data in this study. The research team's system supported many types of virtual devices, including virtual different kinds of sports.

3.7. Assessment method

3.7.1. Knowledge assessment

Few researchers have studied the impact of using XR simulators for medical training by conducting pre and post-tests with participants (Watterson et al., 2002; Wijewickrema, 2017). A pre and post-test-based method were utilized to measure the subjective experiences of the trainees for VR-based endoscopy surgical training in Wijewickrema (2017). A low-cost VR simulator to train residents to increase surgical oncology capacity and capability was discussed in Watterson et al. (2002).

3.7.2. Skills assessment

Researchers have also adopted skills-based assessments to better understand the impact of using VR-based training simulators. They have focused on conducting assessments within the simulator to assess the skills of the users (Harrington et al., 2018; Park et al., 2011). An in-simulator assessment environment to test the decision-making skills pertaining to blunt thoracic trauma was proposed by Harrington et al. (2018).

Ausburn and Ausburn (2008) compared the effectiveness of VR with traditional still color images presenting an operation theatre in terms of six aspects *viz.* (a) accuracy, (b) recall, (c) perceived confidence, (d) perceived difficulty, (e) time on learning, and (f) time of scene orientation. 31 surgical technology students with high (HV) and low levels (LV) of perception skills participated. The results demonstrated that HVs were more confident with VR and LVs were more confident with still images. HVs found tasks easier in VR whereas LVs found it more difficult. LVs performed better in one complex task with still images and HVs performed better in VR.

Botha et al. (2021) proposed a VR simulation for a South African undergraduate nursing institution. Students were asked to manage a patient suffering from a foreign object in the airway with all available diagnostic tools and patient management tools in the simulation using an Oculus Rift. Participants had the theoretical knowledge to partake in this simulation. Students completed a questionnaire that contained the System Usability Scale (SUS). The overall feedback of students was positive for their simulation.

Gumilar et al. (2021) presented a VR simulation that employs hyperscanning, a technique that simultaneously records the neural activities of participants in the real world. In their simulation, two subjects could see each other as virtual avatars. The virtual avatars imitate the subject's hand motions and the subjects conducted finger pointing and finger tracking tasks for research. Their neural activities were recorded by electroencephalography (EEG) hardware. They find out simulated hyperscanning in VR enhances inter-brain synchrony in collaborative tasks that are carried out in a VE.

To engage medical students in the daily life of Parkinson's disease and enhance their empathy level (Li et al., 2021) proposed a VR gaming application. They designed this simulation to present students with a better understanding of the symptoms and challenges patients encounter in their daily life. One of the main characteristics of their simulation is simulating the hand tremors of patients and students were asked to do various tasks ranging from turning the alarm clock, showering, tooth brushing to making breakfast.

To develop interaction methods for the operating room (Reinschluessel, 2017) presented an Interactive Virtual Operating Room(IVOR) tool. They also developed two touch-free interaction techniques, for browsing medical images inside the OR integrated into IVOR, all to minimalize the learning process. To provide a room-scale VR with hand tracking capabilities, they used HTC Vive and Leap Motion. The results showed positive feedback from surgeons who had no prior experience with VR.

Knowledge assessment does not assess the skill level of the users and skills-based assessments do not evaluate the knowledge gained by the users after learning interactions with a simulator. There is a lack of an integrated assessment approach involving the assessment of comprehension, skills, and knowledge as well as the cognitive load imposed on the users.

3.8. Role of avatars

Shao et al. (2019) proposed an MR IoT-enabled Avatar system architecture consisting of four components; a Unity3D-based avatar system, a CoRe network server with a web-of-things-inspired communication framework, one or more IoT-enabled objects, and sensors, radios, or other custom display elements. Their IoT Avatar is inspired by video game characters and HUD concepts. It is a virtual object which is representative of an actual physical object to provide interactions with that. As an early design, they formed an MR representation Avatar for a plant and claimed that the more detailed of their proposed IoT avatar concept remains an avenue for future research.

3.9. Comparison

To perform safe and accurate operations comprehension of anatomy is crucial for any surgeon. However, 3d-printed physical models are expensive, and considering that vital structures are embedded in the interior structures of the bone it is challenging to elicit. Yamazaki et al. (2021) built visualized temporal bone models on an MR headset by using a 3D slicer which allows users to convert tomography images to VR and MR images. This way surgeon's viewport could be changed to see the bone from various angles and have access to the inside of the organ. They compared their approach to conventional navigation. However, in terms of accuracy, current MR and VR models cannot compete with conventional navigation.

Gong et al. (2020) studied interaction design strategies for a multi-user VR manufacturing context (automotive case study) and utilized two types of data sources: CAD models designed by CATIA and optimized by PIXYZ, and used 3D scan laser technology for collecting point cloud data of factory environment. They conducted two tests: one from Gothenburg in Sweden with a verified stable connection and real-time synchronization for both objects and audio. The second test is in the case company's facility in Gothenburg. Their results indicated that a multi-user VR system can complement and improve the existing manufacturing engineering (ME) processes.

VR is gradually adapted by experts in forensic anthropology to examine components of the human body. Jurda et al. (2019) designed a VR reassembly for three cases of fragmentary remains and twenty participants using Vive combined with an in-house application Augmented Reconstruction Toolset (A.R.T) reassembled the parts. Then, they used CloudCompare software in conjunction with a desktop application to compare the result with the VR method. The results demonstrated that the VR approach has a better response time and lower error rate.

For performing vascular simulation in VR (Shi et al., 2020) developed a software platform with a flexible GUI capable of virtual vascular modification and flow visualization. They also presented a generalizable design architecture for simulated workflow. They conducted a user study interaction to compare the result for vascular modeling on 2D and VR displays (semi and fully-immersive displays). Their results showed a faster execution time for 2d desktops; however, their results demonstrated some degree of intuition inherent to VR.

Li and Wang (2021) integrated VR into students' learning environment and expand the traditional two-dimensional computer graphics into a three-dimensional real-time simulation program. They made a comparison between virtual reality classrooms and non-virtual reality classrooms. After experiencing the virtual interactive world, students' memory of learning affairs is significantly improved. However, the authors also acknowledged that virtual reality technology is limited by equipment and other conditions, so it is difficult to widely promote it in classrooms all over the world at this stage.

3.10. Absorption stress, and learning in 3D immersive virtual training environments

A major focus of research within the area of Human–Computer Interaction (HCI) is the design of 3D Virtual Reality (VR) environments. VR-based immersive training environments are becoming more widely used in many occupational settings [e.g., medicine (Mao et al., 2021)]. To further improve the quality of virtual training environments, it is important to consider how differences in how users experience immersive media and whether these individual differences affect one's ability to learn from these environments. A growing number of studies have examined the role of individual differences in performance using VR environments (Buttussi & Chittaro, 2018; Makransky et al., 2019; Persky et al., 2009; Ratcliffe & Tokarchuk, 2020) with mixed results. In the present study, we aimed to investigate further whether individual differences in absorption, a personality trait related to how readily users adapt to the VR environment predict users' stress levels while using an immersive training environment as well as comprehension of information encountered during training.

Absorption is defined as an individual's disposition to become completely attended to a real or imagined experience event (Tellegen & Atkinson, 1974). This results in an "altered sense of self" wherein individuals engage in intense perspective taking while remaining impervious to distractors outside the attended stimulus (Tellegen & Atkinson, 1974). Sacau (2005) demonstrated that absorption involves an element of fascination with media and that it should be considered in research on virtual environments. Findings from this study suggest that absorption is a strong predictor of spatial presence, which refers to one's feeling of being physically present in a simulated experience (Slater & Wilbur, 1997). Absorption has also been found to be a strong predictor of this "feeling" of presence in VR (Kober & Neuper, 2013). Despite absorption's strong relationship with presence, there has been little research on absorption's relationship with learning outcomes in VR.

Previous studies on learning outcomes in immersive learning environments have focused on the relationship between presence and learning, but this body of research has yielded inconsistent results (Buttussi & Chittaro, 2018; Makransky et al., 2019; Persky et al., 2009). Even with more recent findings that support the idea that presence contributes to learning gain (Ratcliffe & Tokarchuk, 2020), researchers still struggle to understand what mechanisms underlie this relationship. This gap in understanding also exists in findings where presence has been associated with negative learning outcomes (Makransky et al., 2019). A better understanding of individuals' emotional experiences while using virtual reality may help us understand how immersive environments can be better implemented.

3.11. Miscellaneous

While the vast majority of the research focus for VR focused on treatment for aliments, such as pain or various disorders, there are a few research concentrated on the prevention of disorders. In Salamon et al. (2018), they presented approaches to use VR to run or ride a bike on the International Space Station (ISS). Because astronauts are required to exercise for at least 2 hr a day to prevent the degrading effects of being in space.

In Mastro et al. (2021), they presented a VR reconstruction of Mars and Moon to develop an immersive simulation of the MARS CITY station, within the framework of the Mars City research project. This would allow users to experience a multi-user simulation living on Mars to study crowd behavior. Their suggested simulation will consist of movement at different levels of gravity in single or team configurations, manipulation of objects during exploration of the space utilizing a VR treadmill, and integrating of real-time data and their visualization during exploration.

Liagkou and Stylios (2019) introduced two main virtual reality platforms in this research, which were used to realize the virtual environment suitable for training users' Low power wide area networks (LPWAN) operation in the industrial 4.0 working environment. They focused on three issues: Virtual Reality technology in SMEs, Virtual Reality platforms, and Evaluation of the two Virtual Reality training environments. They compared the main technologies of unity and Opensim VR platforms. Through the comparison of different scenarios created on the two platforms, they found that Opensim can better and faster complete a multi-user shared environment. If the enterprise does not need a multi-user scenario, unity will be a better choice.

Low power wide area networks (LPWAN) are a major module in the Internet of things. However, due to the problems of overall architecture and protocol layer design, LPWANs have some security risks. In Liagkou et al. (2019), the authors studied a virtual reality training scenario to help users investigate the security problems in LPWANs, also a set of virtual reality models to try to help users solve the hidden dangers of data security. They designed and produced three related application scenarios. These three related application scenarios will help users understand the privacy problems in low-range Wan and operate IoT devices in such LPWAN networks.

Location movement of users in the real world has always been a major challenge in the field of virtual reality. Most of the current methods still have a lot of room to improve in terms of price, practicability, and user experience. Hooks et al. (2020) evaluated two new treadmills: flat treadmill and bowl omnidirectional treadmill. They collected data from 54 participants. The author's conclusion in this article is that the bowl treadmill is more popular than the flat treadmill. Compared with the flat treadmill, users generally reflect that the bowl treadmill is easier to use, more comfortable, and faster to respond to users' actions.

4. Threats of validity

In this article, we attempted to conduct a rigorous systematic review. There is less risk of introducing bias into a systematic review by adhering to PRIMA guidelines to inform our search. However, the methodological quality of the studies examined was not assessed in this systematic review, which could be a source of bias. Therefore, it might have endured several validity threats. Therefore, future research which will interpret or directly use the conclusions in this systematic review should account for these limitations.

1. Articles that aimed at particular topics which were more likely to have addressed other issues rather than our pre-defined categories are omitted. Only English and peer-reviewed articles and conference papers are included. Popular databases described in previous sections were used for finding peer-reviewed articles and there is a possibility that some quality articles and articles were missed.
2. The defined questions for the purpose of this article may not cover the whole area of VR-HCI, completely. Future relevant research could consider this and define questions that cover more for this area.
3. Major reliable electronic databases were selected and relied on previous review experiences. In point of fact, the statistics indicate that these databases would have to offer the most relevant and credible studies. However, the selection of all applicable primary studies could not be guaranteed. There is a possibility that some applicable studies were overlooked throughout the processes mentioned in the previous section. There could be various reasons, ranging from the search string to the data extraction. As accurately as possible, we attempted to prevent this by complying with the references in primary studies.

5. Future research

This article provides a comprehensive review of defined categories of topics and provides an overview of major techniques in the area of XR in various application contexts. There is an increasing number of articles highlighting the emergence of VR in education (between 2017 and 2021) that address training and HCI measures (such as affordance). Future research thrusts in this important area of HCI for designing XR approaches and environments are summarized below:

1. While XR-based training is becoming more widely adopted in medical education, there needs to be a more critical study of its impact on surgeons or residents trained using such new approaches and their ability to perform various surgeries after they become full-fledged surgeons working in hospitals or clinics. Such benchmarking of improved skills and successful surgical outcomes is necessary for the public and the healthcare educational community to gain more confidence in the proven outcomes of adopting such innovative approaches to learning and training in healthcare and medicine. Beyond surgery, there is a need to explore various other specialties within medicine and design user-centric learning environments and approaches that help residents and budding doctors improve their various diagnoses, knowledge, and medical skills. XR allows medical trainees (physicians, surgeons, nurses, technicians, and others) to interact with realistic 3Denvironments (involving patients, medical instruments, examination/consulting rooms, etc.) and learn/understand the various steps in a diagnostic or caregiving process in a safe space and then interact in such realistic scenarios. This subsequently enables them to obtain real-time performance feedback which can be used as a foundational basis to address problem areas through repeated training sessions; this, in turn, enables them to improve their healthcare skills while also increasing their confidence in their own knowledge and skills. Further, such a simulation of a target procedure planned for a patient can be shared with the patient before the procedure if the patient is interested. This 3D scenario of a complex process may enable some patients to have a better idea of their injury or problem area and how the medical team is planning on completing a surgery or some other medical procedure. This will improve the overall patient user experience and possibly reduce their stress during the caregiving period.
2. Future research needs to emphasize certain elements of data collection. Only a few articles focused on gender diversity and balanced samples. Future research efforts in this area need to adopt a more robust and balanced sampling of user data to reflect the gender, ethnic, and age diversity of populations.
3. Measuring user experience satisfaction is also one of the key factors that should be considered for future research. This will help to create user-friendly and effective XR applications leading to improved user performance. Utilizing emerging technologies can help in providing a better sense of immersiveness and user satisfaction to most users. However, very few studies have focused on the role of experience and age in trainees' attitudes toward XR simulator-based training experiences which rely on cutting-edge digital technologies and cyber-intensive approaches. While anecdotal evidence seems to highlight the younger residents and nurses being more receptive to XR and haptic technology (than their older and more experienced counterparts), there need to be more studies throwing light on the attitudes and receptiveness of the more experienced residents, doctors, nurses and other healthcare professionals who may have a less enthusiastic response to digital technologies.
4. Most of the research articles reviewed to deal with VR-based training; there is a need for a greater emphasis on designing and assessing the impact of MR-based

approaches and environments. In general, MR has a great potential for providing a more rich and complete training experience than VR alone. Future research can investigate the design of such complex MR environments for individuals as well as for collaborative training involving multiple individuals interacting through next-generation computer networking techniques.

5. Learning Analytics (LA) is defined as "the use of static and dynamic information about learners and learning environments, assessing, eliciting and analyzing it, for real-time modeling, prediction and optimization of learning processes, learning environments, as well as educational decision-making" (Ifenthaler, 2015). Since different individuals have various learning preferences, the ability of such XR simulators to modify each user's learning experiences is one vital area of future research. Another future thrust is exploring and adopting artificial intelligence (AI) principles in future XR research to provide a human-AI combination platform. AI could assist in the creation of real-time environments which can be beneficial to users' learning progression and provide better solutions for safety issues existing in surgical and educational domains. AI-based approaches can help 3D environments to learn from each individual user's learning patterns and make changes to the type of user interactions as well as identify/implement changes to the learning content to adapt to the learning style of individual users. A related area is designing Intelligent Autonomous Agents (IAA) which can be integrated into various decision-making simulation systems and help assist budding doctors and health care professionals in such 3D-based training systems. The design of such systems is in its infancy and has significant potential in playing a key role in medical training and diagnosis.

Some of these thrusts are summarized below:

- Recording students' interactions during normal classrooms for various activities and identifying patterns of learning for individual students as well as highlighting any consistent topics where the majority of students seem to have difficult grasping certain concepts during the virtual learning and training interactions
- Exploring analytics-based approaches to determine behaviors and skills that underlie successful individual and collaborative problem-solving which can improve the effectiveness of learning and training approaches.
- Adopting machine learning approaches that learn how to respond to individual students learning patterns s and make dynamic changes to the 3D environment to enhance and enrich the learning content and process.

6. Conclusion

This study presented a systematic review of XR-HCI techniques and approaches. Similarly, we reviewed several state-of-the-art XR-HCI, clarifying and discussing open issues via an in-depth analysis of over 69 primary studies among the basic 1156 articles from our search query. Through answers provoked by three exploratory research questions, we found evidence confirming XR-HCI as an ascending approach that introduces a new paradigm by increasing skills and safety and reducing costs and learning period. Based on the available literature, we decided to classify the field into seven subdomains; Affordance; Training and HCI; Role of avatars; Comparison; General; Assessment; Cognitive load, and Participatory Design. The majority of the articles reviewed focus on training elements involving HCI principles. The research outcomes from these publications underscore the potential for greater success when such HCI-based approaches are adopted during such 3D-based training interactions. Such a higher degree of success may be due to the emphasis on the design of user-friendly (and user-centric) training environments, interactions, and processes that positively impact the cognitive abilities of users and their respective learning/training experiences.

The overall discussion of the various research approaches as well as the highlighted outcomes based on this study provides a comprehensive and systematic state-of-the-art review in the XR-HCI area encompassing the benefits of adopting HCI-based XR approaches, an overview of some of these approaches, a summary of current challenges related to such XR applications. This review article will enable researchers to become familiar with existing principles and technologies in this rapidly developing field, which can then be used as a basis or foundation to develop new research approaches and technologies that can further contribute to the maturity and adoption of such XR-HCI applications.

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