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Metaverse in education: Opportunities and challenges

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Metaverse in education: Opportunities and challenges

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Editorial: Metaverse in education: opportunities and challenges

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metaverse, augmented reality, mixed reality, virtual reality, immersive 3D

Editorial on the Research Topic
Metaverse in education: opportunities and challenges

The emergence of the Metaverse marks a transformative era in the field of education where learning transcends traditional classroom boundaries and enters immersive virtual environments. This digital transformation of learning and teaching pedagogies offers unparalleled opportunities for engaging, interactive and personalized educational experiences that enable learners to explore complex and practical concepts in visually stimulating ways. However, there remain significant challenges in terms of accessibility, equity, scalability, and technical advancement. With the Metaverse reshaping education, the academic community needs to address its challenges to unlock its full potential for enhanced learning. As part of this Research Topic, the following is a summary of the contributions made by fellow academics to highlight the applications, potential and associated challenges toward a fully functional educational metaverse.

Mirault et al. introduced an innovative study leveraging Virtual Reality (VR) to assess reading fluency in primary school children. The study utilized a VR adaptation of the lexical decision task to intricately record children's eye movements. It then assessed the external validity of VR metrics, including lexical decision reaction time and accuracy, gaze durations, and refixation probabilities, by comparing them with the traditional gold standard for reading fluency, the One-Minute Reading test. Findings revealed strong correlations between VR assessments and traditional fluency metrics, suggesting that VR-based assessment serves as a valid child-friendly alternative for assessing children's reading behavior.

Li J. T. S. et al. evaluated the use of augmented reality (AR) to teach post-stroke and COPD management to third-year pharmacy students in Hong Kong. Despite the use of AR modules for immersive learning, feedback from 54 students showed no improvement in knowledge or counseling confidence, with technical issues (e.g., setup complexity, network dependency, and battery drain) detracting from the experience. The authors suggest that the significant time and expense involved in creating AR content requires careful topic selection to ensure its cost-effectiveness, particularly when traditional methods could be just as effective.

Tang et al. proposed a design for immersive VR to train biomedical science undergraduates in animal handling. The authors developed a virtual animal handling simulator (ViSi) and reported that students participating in ViSi positively assessed their involvement in the virtual environment and their concentration on the assigned task. The authors noted that the impact of immersive VR technology integrated into skills training is promising, although there are a few technical problems to be resolved.

In their study of 360° Desktop Virtual Reality (DVR), Albus and Seufert found that using signals to highlight key information significantly increased recall and comprehension while reducing extraneous cognitive load, or unnecessary mental effort, among learners. However, they observed no difference in germane cognitive load, which is the effort related to the learning process itself, between the signaled and non-signaled groups. This indicates that signaling in DVR environments may enhance learning efficiency by improving memory performance and minimizing cognitive overload.

In this review article by Reyes et al., the authors explored the relationship between the Metaverse and complex thinking through a systematic review of the literature by analyzing 234 publications. Their study reveals that the extensive exploration of the Metaverse began in 2022, the timeline that aligns well with the advancements in the design of algorithms and virtual reality technology. This massive interest from the academic community underscores the importance of the Metaverse in fostering pedagogies centered around complex thinking that encompasses scientific, critical, systemic and innovative thinking. The research highlights how the Metaverse, when viewed through this lens, opens new horizons of research avenues to harness the Metaverse's full potential for the future academic landscape.

This review article by Mikhailenko et al. delved into the use of eye-tracking in immersive virtual reality for education, suggesting a transformative approach to educational methodologies. The review not only talks about the technicalities of eye-tracking but also covers its multifaceted applications across disciplines. The narrative is built around the integration of eye-tracking with virtual reality, with the potential to revolutionize the educational landscape through personalized and engaging learning strategies. The merging of eye-tracking and virtual reality can enable innovative learning and assessment approaches through a better understanding of student engagement and cognitive processes. The authors advocate for further research to maximize the benefits of eye-tracking in the virtual reality environment, which could unlock new dimensions of personalized learning experiences.

Li Z. et al. performed a comprehensive bibliometric analysis of virtual reality in anatomy education. The review, which covered publications from 1999 to 2022, revealed a substantial increase in research on the use of virtual reality in anatomy education, indicating a growing interest within the academic community. Learning human anatomy is challenging for medical students due to the lack of specimens for experimental teaching and the unclear observation of fine specimen structures. However, virtual reality can overcome such challenges by providing active learning environments and improving observational clarity. The article advocates for collaborative efforts across countries to further advance virtual reality-based anatomy education while highlighting the challenges associated with the technology costs and training requirements.

Myburgh reflected on the creation of virtual reality experiences for biology students. He highlighted how, during COVID-19, while academics around the globe tried to keep educational processes going, it was challenging to provide adequate learning support for subjects like biology that rely heavily on practical laboratory training. The author, therefore, emphasized the need for virtual laboratories with immersive learning environments to overcome such challenges in the context of remote teaching. The article presents an overview of the available resources that can be used by faculty for remote teaching; however, the creation of a set of free and open-source virtual laboratories is proposed to address the global demand for a more accessible, hands-on biology education.

The study by Mukasheva et al. evaluated a virtual reality (VR)–based workshop to support deeper learning of sorting algorithms. The concepts of bubble sorting and selection sorting were integrated into a VR sorting application developed by the authors. The authors concluded that the level of visualization and student interaction in the VR environment had a significant positive impact on students' understanding of the abstract concepts and processes required to develop the sorting algorithms.

Sahin et al. studied the impacts of an intervention with a teenager with autism spectrum disorder (ASD) facilitated by a smart glasses-based social communication module. The module used sensors in the smart glasses to monitor the social interactions of the adolescents and to prompt the child to use socially accepted behaviors when interacting with others. The intervention was conducted over two weeks in addition to regularly scheduled interventions provided by two professionals. At the end of the 2 weeks, the teen's parents and two teachers reported a global-scale improvement, as measured by the Social Responsiveness Scale 2 (SRS-2) School-age Form, as well as on several of the subscales, which demonstrated the promise of augmented reality interventions with autistic children.

A comprehensive literature review of immersive virtual reality (VR) headsets in post-secondary education was conducted by Concannon et al.. The authors identified three types of student engagement in the VR environment. They concluded that educating educators would spur the adoption of VR as a pedagogical method that has been shown to have multiple benefits compared to traditional instruction. The authors noted that concerns about the cost and accessibility of head-mounted displays may be reduced with the availability of mobile phone-based headsets. The authors identified an additional concern, the adaptability of learning in a VR environment to the real world.

LaDisa and Larkee described an immersive virtual environment for research, teaching, collaboration and outreach at Marquette University. The authors outlined processes used during the design phase to identify potential users. The system favored by potential users was a CAVE Automatic Virtual Environment as it enabled collaboration through a shared visualization experience. Modifications to address lag time, eye fatigue, and simulation sickness were noted. Examples of CAVE immersive visualization system projects in Engineering, Arts and Sciences, Health Sciences and Nursing were highlighted.

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Case Study of a Digital Augmented Reality Intervention for Autism in School Classrooms: Associated With Improved Social Communication, Cognition, and Motivation via Educator and Parent Assessment

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Background: Impairment in social communication is the primary deficit in school-aged children with autism spectrum disorder (ASD). Research has shown that there are efficacious interventions to address social communication deficits, yet their delivery is hampered by the lack of human and time resources. Emerging assistive technologies, such as smartglasses, may be able to help augment the social communication interventions currently provided by human educators and therapists. While emerging research suggests assistive socio-emotional coaching smartglasses can be effective and usable in research settings, they have yet to be studied amidst the complex social, physical, and time-constrained environment of the school classroom. This structured case study reports on the feasibility and efficacy of 16 intervention sessions of the Empowered Brain *Face2Face* module, a smartglasses-based social communication intervention.

Methods: A 13-year-old fully-verbal adolescent male student with a diagnosis of ASD received a total of 16 smartglasses-aided intervention sessions over a 2-week period. Interventions occurred twice-daily during school days and were facilitated by school professionals in a middle school in Massachusetts, USA. Outcomes were measured using the Social Responsiveness Scale 2 (SRS-2), a commonly used validated measure of social communication in children with ASD, by the participant's parent, paraprofessional, and two teachers. Difficulties in usability during the study were recorded through observation notes.

Results: The participant completed the 3-week study [one pre-intervention week (baseline) and two intervention weeks] without any observations of adverse effects or usability concerns. The parent and three educators completed the SRS-2 for the baseline and intervention weeks, and results demonstrated significant improvement in social communication after the intervention relative to baseline. The parent, special education teacher, and general education teacher noted marked reductions in SRS-2 total T score, with improvement in SRS-2 social communication, social motivation, social cognition, and restricted interests and repetitive behavior subscales.

Conclusion: Smartglasses are a novel assistive technology that can help facilitate social communication and behavioral coaching for students with ASD. The use of the *Face2Face* module by educators over a 2-week period was associated with improvements in social communication.This study supports the use of this novel technology to deliver assistive social communication and behavioral coaching in schools.

Keywords: autism, assistive technology, digital health, augmented reality, artificial intelligence, mental health, social communication, special education

INTRODUCTION

Autism Spectrum Disorder (ASD) is a childhood onset developmental condition with a rapidly increasing prevalence, and is present in 1 in 59 school-aged children (Baio et al., 2018). Impairment in social communication is the hallmark feature of ASD, encompassing perseverative deficits in verbal and non-verbal communication (American Psychiatric Association, 2013).

Evidence suggests that social communication can be improved through a range of interventions for children with ASD (Locke et al., 2013; Watkins et al., 2017). While these efficacious interventions have been studied in the school environment, their implementation has been somewhat thwarted by a lack of educational resources as schools attempt to provide specialized educational needs to a growing number of children with ASD. The magnitude of the demand for specialized educational resources is considerable, with the US school system providing half a million children with ASD federally-mandated special education under the Individuals with Disabilities Education Act (IDEA) (Snyder et al., 2016). The mismatch between supply and demand of such educational interventions has not only led to limited support for students with ASD, but also to parental dissatisfaction (White, 2014) and burnout among school professionals (Corona et al., 2017).

Children are spending more time in school, with the length of the school day increased to ∼7 h over the last few decades (Kolbe et al., 2012). With almost a third of their day being spent at school, schools have become a central part of children's lives. Schools are not only educational establishments, but highly social environments, with many interpersonal relationships and interactions between students, teachers, and other educational professionals.

Schools are fertile ground for social interventions that have been found to be broadly effective (Locke et al., 2013; Watkins et al., 2017), increase both peer and teacher interactions, and may help improve non-targeted skills such as language and inappropriate behavior (Rogers, 2000) in children with ASD. Within schools, there has been a move toward incorporating students with ASD in inclusive classrooms where they learn alongside their neurotypical peers. However, this has not resolved many of the social functioning limitations seen in students with ASD, many of whom struggle with feelings of isolation and loneliness during school time (Bauminger and Kasari, 2000). Teachers have identified many barriers to implementing successful inclusion programs, with lack of training, time, and administrative support being key factors (Werts et al., 1996).

Prompt detection of ASD and early intervention are thought to be critical to long term outcomes (Dawson et al., 2010). Interventions for social communication, especially those delivered around school-settings, are also important for long term success. As children with ASD mature, they gain greater insight into their social communication deficits. This realization has a series of consequences, including increased stress when interacting with unfamiliar peers (Lopata et al., 2008; Corbett et al., 2010), and greater anxiety in social situations where they have repeatedly been unsuccessful (Bellini, 2006; Corbett et al., 2014). While there is concern that without intervention, impairment in social functioning may be lifelong, role-play exercises and interactive games between humans can significantly increase social skills (Corbett et al., 2014).

While individuals with ASD express a desire to have a job (Hendricks, 2010), persisting social skill deficits may pose a key challenge (Hurlbutt and Chalmers, 2004). People with ASD experience high rates of unemployment/underemployment that exceed other groups with disabilities (Shattuck et al., 2012). People with ASD also often have unflattering work histories, with short-lived periods of work interspersed with long periods of unemployment (Ohl et al., 2000). While there are many barriers to people with ASD obtaining employment, it has been found that the social demands that accompany jobs are a key challenge. Social skills such as small talk (Holmes and Fillary, 2010), eye contact (Amalfitano and Kalt, 1977), emotion recognition (Kee et al., 2003), and conveyance of emotions (Zapf, 2002), have all been found to be important for jobs and job interviews. Technology-aided social skills interventions have become increasingly studied, and may provide long term benefits to people with ASD who are seeking employment (Wainer and Ingersoll, 2011; Walsh et al., 2016), however the majority target job-specific skills such as cleaning tasks (Van Laarhoven et al., 2012) or shirt folding (Bennett et al., 2013). There is an immense

Abbreviations: AI, Artificial Intelligence; AR, Augmented Reality; ASD, Autism Spectrum Disorder; IEP, Individualized Education Program; SRS-2, Social Responsiveness Scale 2.

need to develop social skills focused interventions that aid more generalized workplace interactions (Fast, 2004).

Novel assistive technology may potentially address this disconnect between demand and availability, with the promise of improved quality of education, reduced burden on teachers, and potentially reduced costs for school districts. Socially focused interventions may be especially suitable to digitization given that they can be particularly useful for children with ASD (Locke et al., 2013), but are hampered by limited training of human providers alongside lack of physical resources (Dingfelder and Mandell, 2011; Locke et al., 2015). A range of assistive technologies have proven to be effective interventions in ASD (Bauminger-Zviely et al., 2013; Grynszpan et al., 2014), and assistive technology provides one of the most common teacher-led strategies for helping students with ASD in both general and special education classrooms (Hess et al., 2008). While technologies such as the iPad have undergone considerable research (McMurray and Pierson, 2016), newer technologies such as smartglasses have also attracted interest (Liu et al., 2017).

The Empowered Brain Technology Platform

The Empowered Brain is a tool that provides socio-emotional coaching to children and adults with ASD (Keshav et al., 2017; Liu et al., 2017). The Empowered Brain consists of a smartglasses platform in combination with a series of software modules that focus on key coaching areas, such as improving attention to social cues, helping coach facial emotion recognition, and aiding in transitioning between different environments. In this study, the Empowered Brain *Face2Face* module was tested on Google Glass smartglasses hardware.

Smartglasses, like Google Glass, are head-worn computerized glasses that can transmit visual and auditory information to users through a small clear optical display(s) and bone conduction/audio speaker, respectively. Smartglasses, like smartphones, typically contain a wide variety of sensors that can collect data regarding the user's body movements and interactions with the environment. These sensors include a camera, a microphone, an accelerometer, a gyroscope, and Wi-Fi/Bluetooth.

Face2Face Module

The human face is one of the most powerful tools in social communication (Jack and Schyns, 2015), and is of fundamental importance in interpersonal interactions (Pavlova et al., 2017). Faces display information regarding traits, stable features such as gender and identity, and more dynamic facial data that helps with understanding of emotion, intention, attention, and understanding speech (Lee et al., 1998; Pascalis et al., 2011).

Impairment in social cognition (Baron-Cohen, 1991; Baron-Cohen et al., 1995) and social motivation (Chevallier et al., 2012) have both been described as being relevant to the facial perception, processing, and recognition difficulties of people with ASD (Kirchner et al., 2011; Tang et al., 2015; Tanaka and Sung, 2016), including how much attention they pay to socially salient features, such as the eyes of others (Klin et al., 2002; Jones et al., 2008; Kirchner et al., 2011). Gaze indifference and gaze aversion are two proposed hypotheses that may help to explain the altered eye gaze behavior seen in ASD. In gaze indifference, the eyes of others are not seen as an important or engaging stimulus (Moriuchi et al., 2017), while in gaze aversion, eye contact is avoided as it is seen as threatening (Tottenham et al., 2014) or results in sensory overstimulation (Corden et al., 2008). These altered patterns of attention to faces and eyes may be especially pronounced during non-passive circumstances, such as interactive social situations (von dem Hagen and Bright, 2017). Certainly, given the heterogeneity of ASD in both neurobiological underpinnings and behavioral presentation, it is unlikely that one unified theory alone will explain the multitude of altered facial processing abilities or eye gaze patterns that have been described.

It is in this context that the Empowered Brain *Face2Face* module aims to provide a social communication intervention that improves social motivation and cognition, while simultaneously addressing the underlying challenges described by both gaze indifference and gaze aversion hypotheses. *Face2Face* achieves this, in part, by utilizing game-like augmented reality (AR) to increase the social motivation of the user to engage with the face of another person (**Figure 1**). *Face2Face* also provides an intervention that is graduated in intensity, difficulty, and is highly customizable through both human and artificially intelligent machine input. *Face2Face* relies on utilizing the relatively preserved visual skills in ASD when delivering its cues, and uses audio alerts that are considerate of the sound hypersensitivity experienced by many with ASD. The approach of Face2Face is reflective of its origins as an updated and enhanced version of *Face Game*, a previously described smartglasses research app that has been studied in ASD (Keshav et al., 2017; Liu et al., 2017).

To play *Face2Face*, the user wears the smartglasses system while the Face2Face module is running, and interacts with another person who will be positioned in front of the user. This interactive facilitation recognizes that "real-world" situations allow for the challenges of social communication to be most apparent (von dem Hagen and Bright, 2017), and reduce barriers to generalizability of learned skills (Shindorf, 2016). The Face2Face module requires two people to be present: the user and the facilitator (another person who will help facilitate the Empowered Brain-augmented interaction).

The Empowered Brain can detect the presence of a human face, determine where a user is looking relative to that face, and help guide user's gaze toward the face in real-time. Guidance to the user is provided through visual directional prompts and auditory tones that vary depending on the positioning of the user's gaze and the positioning of the detected face. The Empowered Brain modules use developmentally and contextually appropriate game-like elements to make the experience engaging and fun for both child, adolescent, and adult users. For example, a cartoon-like character is optically superimposed over the face that they are being guided toward.

This cartoon-like character gradually fades as the user moves his gaze toward the target face, eventually disappearing completely. At this point the user obtains points for successful task completion. The module has a series of levels and

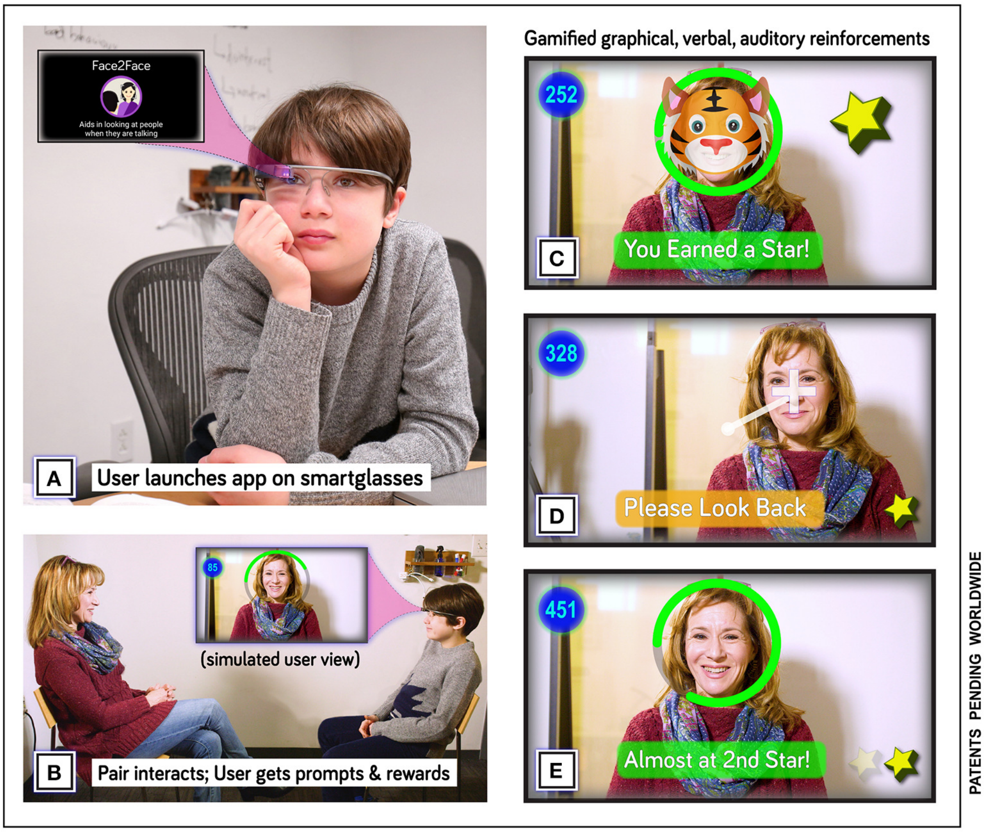

FIGURE 1 | Intervention aimed to increase face-directed gaze via an augmented-reality game on smartglasses. **(A)** User can start the game (Face2Face) by voice command or tapping the side trackpad of the glasses (Google Glass Explorer Edition). He sees and hears feedback via the screen and bone-conduction speaker. **(B)** User has a social interaction (e.g., a conversation, in the case of a verbal participant), and the game gives feedback in realtime while the pair maintain interaction. **(C)** Representation of on-screen feedback: the user has maintained gaze with the partner for a predefined period and earns a star and temporary face mask as reward. **(D)** When mutual gaze is lost, the user receives graphical, verbal, and auditory coaching to resume. **(E)** As the game progresses, it takes longer periods of gaze maintenance to earn further stars and masks.

difficulty settings. Specific game data elements are recorded and transmitted to a secure central artificial intelligence (AI) powered processing center where they are available for viewing through a web-based dashboard. User performance is measured through graphs of rewards, events, and attention data. The socio-emotional coaching apps of the Empowered Brain have been previously found to be well-tolerated (Keshav et al., 2017), feasible to use (Liu et al., 2017), free from adverse effects in people with ASD (Sahin et al., 2018), and associated with improvements in the symptoms of ASD (Liu et al., 2017) and attention deficit hyperactivity disorder (Vahabzadeh et al., 2018). These studies were, however, conducted in controlled research settings, utilizing the caregivers of participants with ASD, and were based on a single intervention session.

The Empowered Brain features key innovations in physical design, AI, and data analytics, and is supported by software, engineering, and data partnerships with a number of technology companies including X (formerly Google X, Mountain View, CA), Affectiva (a leading Emotion AI company, Boston, MA), and Amazon (use of an experimental AI technology).

Educator-Facilitated and Classroom-Based

The real-world school setting has proven itself to be a more difficult environment to provide a social communication intervention than a controlled research setting (Lawton and Kasari, 2012). Teachers and their paraprofessional colleagues may be ideal personnel to help deliver school-based communication interventions in students with ASD (Lawton and Kasari, 2012). Their intimate knowledge of a student's strengths, weaknesses, and style of learning, combined with their established position in delivering guidance, places them in a unique position. Students' perception of teacher support and teacher-led promotion of interaction and respect have been linked to increased student motivation and engagement (Ryan and Patrick, 2001).

This report outlines the efficacy, usability, and safety of the Empowered Brain *Face2Face* module intervention twice during every school day over a 2-week time period. In this report, the facilitators were several of the school professionals who were familiar with the research participant (education paraprofessional, special education teacher, general education teacher). Additionally, the intervention was used during the school day, and within an inclusive classroom setting. Outcomes were measured with the Social Responsiveness Scale 2 (SRS-2) School-age Form. The SRS-2 is a validated social communication measure used in ASD populations (Constantino and Gruber, 2012), and consists of 65 items, resulting in a total score, and five subscale scores (social awareness, social cognition, social communication, social motivation, and restricted interested and repetitive behaviors). The SRS-2 can be completed by teachers (Dickson et al., 2017) and parents (Ashman et al., 2017), with recent research noting that parental ratings may be higher than that of teachers (Nelson et al., 2016).

This case study attempted to use some elements of a single-subject design, although did not include repeated measures during individual phases of the study, an important element of single-subject studies. The focus on incorporating some elements of single-subject design was deemed to be important as single-subject research can be used as a means to testing and understanding the use of novel technology in educational settings, and has been identified as an important contributor to evidence-based practice in special education (Horner et al., 2005). Single-subject research has already helped to identify computer-assisted guidance for students with ASD as an evidence-based practice (Barton et al., 2017). The lack of repeated measures during individual phases is however a key limitation.

METHODS

A 3-week structured case study of the Empowered Brain *Face2Face* module was conducted in a 13-year-old male student with ASD ("the participant"), in a middle school in Massachusetts.

A Case Study Incorporating Elements of a Single-Case Design

This case study utilized some components of single-case experimental design. Single-case experimental approaches have been shown to be methodologically sound (Horner et al., 2005; Kratochwill and Levin, 2010; Smith, 2012), capable of demonstrating effectiveness of interventions, and is especially suitable for the assessment of outcomes of psychological/behavioral interventions (Robey et al., 1999; Borckardt et al., 2008; Smith, 2012).

Our case study incorporated the four of key features of a high-quality single-case design as far as it was possible to do so (McMillan, 2004). One of these features is using ratings or measures that are reliable and consistent. Our study uses a validated and reliable 65-item scale that is viewed as a gold standard measure for measuring social communication in people with ASD. Three other important features that have been identified, and are included in our methodology, are: (1) having a detailed description of the measurement and treatment conditions (the school classroom); (2) having at least one baseline and treatment phase; and (3) changing only one variable between phases (use of the Empowered Brain smartglasses).

The fifth and final feature of single-case design is the ability to repeat the measurement as often as necessary. In our study, the key behavioral measure was repeated three times, at the end of the baseline week, and at the end of each of the two intervention weeks. While having repeated measures within each study week would offer more data, and would more robustly fulfill this fifth feature on paper, there were a number of factors that made this impractical. Firstly, the educators in our sample had limited time to provide more regular rating assessments as they were not only the facilitators of the intervention, but also continued in their full-time teaching role throughout the study. Secondly, the use of the SRS-2 as a daily measure of social communication has not been studied, and the authors believe that other simpler behavioral measures may be more appropriate if more regular measurements were needed. Thirdly, a reasonable amount of data was collected during our study. The SRS-2 is a robust assessment of social communication, with 65 different scored items, and was performed by four different individuals on three different occasions, providing a total of 780 rated items regarding the participant. However, the lack of daily/near daily data are noted by the authors as a limitation in this study, and makes the study design most consistent with a case study.

The study commenced with a baseline week (Week 1), during which the participant received no intervention, and had his regular school and home schedule. At the end of the week, school educators and his mother completed the SRS-2 based on the interactions and behaviors they witnessed during the baseline week. The SRS-2 was completed by three school educators: the participant's special education teacher, general education teacher, and assigned paraprofessional. The use of cross-informant (educator and parental) ratings is the gold standard in child behavioral assessments (Dickson et al., 2017). The participant's baseline week was the control for this report.

The study then proceeded to the first intervention week (Week 2) where the participant received twice-daily *Face2Face* interventions. The intervention was facilitated by one of his school educators, during which time the participant continued to be in the classroom alongside his peers. The intervention was 10 min long and was delivered at approximately the same times each day. At the end of Week 2, following eight intervention sessions, the participant's educators and parent each completed an SRS-2 based on the behavior seen during that week. The second intervention week (Week 3) was a duplicate of the first intervention week, and a repeat SRS-2 was completed at the end of the week.

The participant completed the intervention during two class periods, one general education class and one special education class. The structure of both classes allowed for the teacher to facilitate the intervention for 10 min during the class period, within his classroom, while another education professional was in the room.

The Intervention

During the intervention weeks, the participant received the intervention twice every school day during the same school periods (**Figure 2**). The intervention was provided by his general education teacher in the morning, and his special education teacher in the afternoon. One of the 16 interventions was

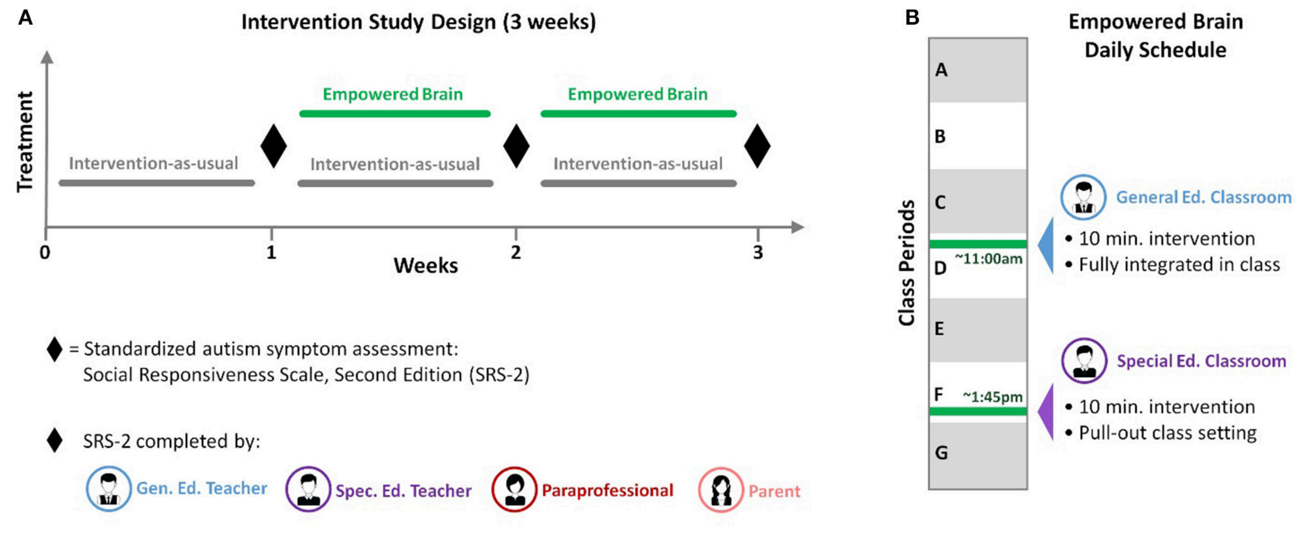

FIGURE 2 | Study design. **(A)** Overall design of the 3-week study. A baseline week was followed by 2 weeks where Empowered Brain intervention was added to the interventions the school otherwise proveded. At the end of the baseline week and each Empowered Brain week, the participant was rated according to the gold-standard autism rating scale, the Social Responsiveness Scale-2nd Edition (SRS-2) (See **Figure 4**). SRS–2 ratings were conducted in all cases by the participant's general education teacher, the special education teacher, paraprofessional, and the parent. **(B)** Design of each day of the study during the intervention period. Two 10-min intervention sessions were run daily, with a late morning session in the participant's regularly scheduled general-education class (See **Figure 3**), and an afternoon session in his regularly scheduled special-education pullout class.

provided by the paraprofessional during a class when the special education teacher was unexpectedly unavailable. The intervention ran concurrently to the class the participant was attending. The educator identifies a peripheral location in the classroom where the intervention was performed, with the student and educator sat facing each other (**Figure 3**).

Each intervention session was split into three segments, during which time the teacher was encouraged to engage in a natural conversation with the participant about relevant academic topics, for example a student's current project, homework assignments, or academic activities of the day. Each intervention lasted 10-min. The three phases were as follows:

1) "Pre-*Face2Face*," in which the participant and facilitator conversed without the Empowered Brain for 1 min;
2) "*Face2Face*," in which the participant and facilitator conversed while the participant wore Empowered Brain running the *Face2Face* module for 8 min; and
3) "Post-*Face2Face,*" in which the participant and facilitator conversed without the Empowered Brain for 1 min.

During the *Face2Face* phase (Phase 2), the participant would wear the Empowered Brain and would experience the feedback coaching of the *Face2Face* module as he conversed with the educator. During the conversation, the *Face2Face* module monitored the level of attention the participant was directing to the educator's face. The participant could gain game-like points and AR rewards when he looked toward the educator during the conversation. If the participant looked away from the educator, he would get visual and auditory guidance to help him redirect his attention back to the educator.

The Participant

The participant was a white Caucasian male aged 13 years and 11 months. He was diagnosed with ASD by his pediatrician at the age of 2. He receives special education services with an Individualized Education Program (IEP) at a mainstream public school in Massachusetts.

The participant previously had ASD-related interventions including applied behavioral analysis, occupational therapy, and speech and language therapy. He has previous experience with smartphone and tablet devices. He has no concurrent psychiatric disorders and was not receiving any psychotropic medication at the time of the study. Additionally, he has no history of epilepsy or seizures.

The Classroom Setting

This study was performed in a public middle school in Massachusetts, USA. The intervention was delivered twice-daily during school days. The first session was delivered by the student's general education teacher during the morning general education class. This classroom setting consisted of 2 educators, the general educator teacher and a paraprofessional, looking after a class of 23 students. The second daily session was delivered by the student's special education teacher during an afternoon special education class. The special education teacher was aided by a paraprofessional in looking after the 11 students in this class.

Consent and IRB Statement

The use of the Empowered Brain running on multiple head-worn computing devices by children and adults with ASD was approved by Asentral, Inc., Institutional Review Board, an

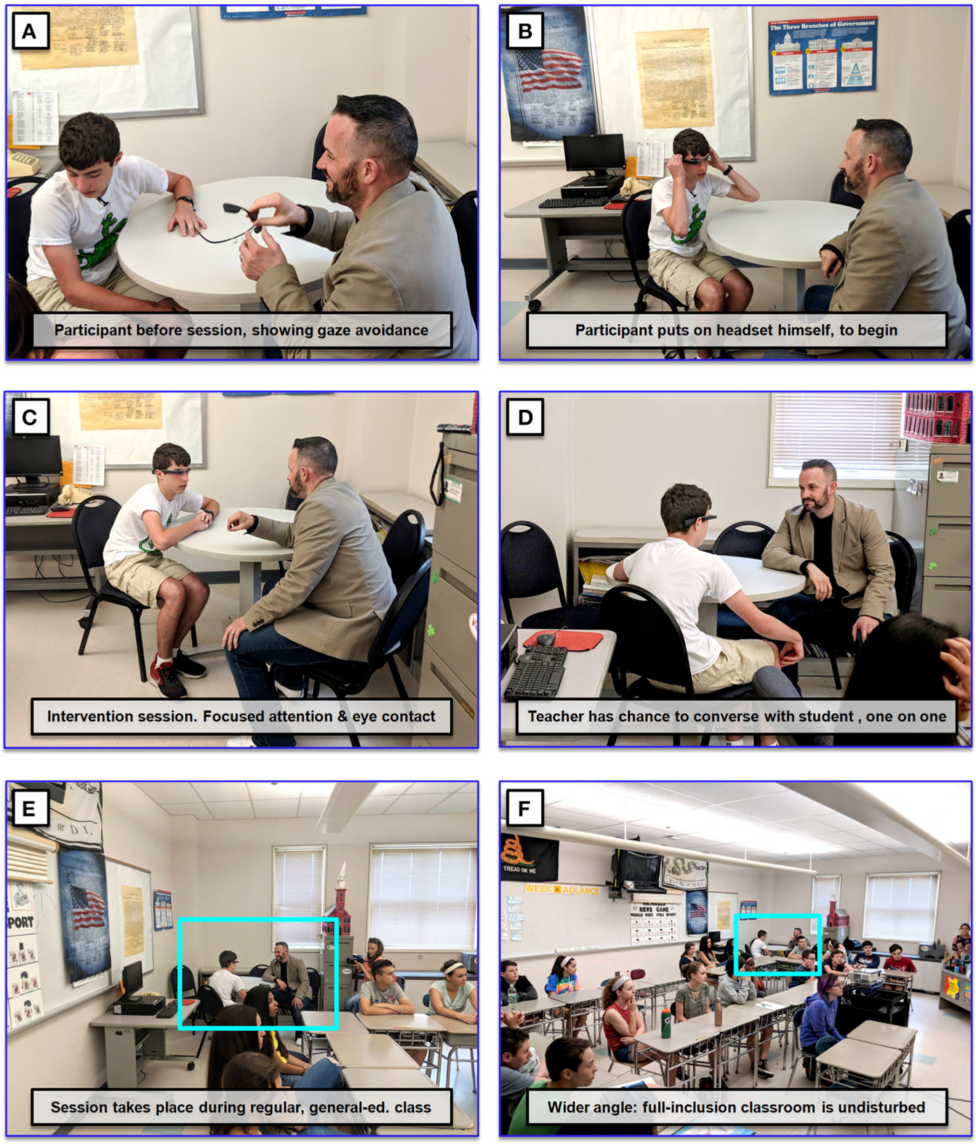

FIGURE 3 | Intervention in the context of an inclusive, general-education classroom. **(A)** Teacher and study participant before onset of an intervention session. **(B)** Intervention session begins when participant puts on the smartglasses running the Face2Face software. **(C,D)** Teacher and learner have one-on-one time, and discuss mostly academic topics while the AR smartglasses provide rewards for mutual gaze. **(E)** Half the intervention sessions in this study were conducted within a general-education classroom. **(F)** The teacher succeeded in conducting the one-on-one session in the back of the classroom, while simultaneously managing the rest of the classroom. In this example other students were delivering presentations of their class projects. Consent was obtained to publish this photograph in a publicly accessible research journal.

affiliate of the Commonwealth of Massachusetts Department of Public Health. The study was performed in accordance with relevant guidelines and regulations, and in accordance with the Helsinki Declaration. Written informed consent was obtained from all parents/legal guardians of all minors involved in this study. Consent to conduct this research was also obtained from all educators involved in the study. Written informed consent was obtained from the participant's parent for the publication of their identifiable information.

RESULTS

The baseline school week concluded with no concerns by the participant's teachers or parent (mother). All three school educators and parent completed the baseline SRS-2 at the end of the initial week.

The intervention was delivered to the participant on a total of 16 occasions over the 2-week intervention period, twice-daily during the 4 days of school in each week. School educators and

TABLE 1 | Special education teacher.

SRS-2 Measure	Week 1 (Baseline)		Week 2		Week 3	
	Raw score	*T*-score	Raw score	*T*-score	Raw score	*T*-score
Total score	82	66	70	62	55	57
Social awareness	7	53	6	51	7	53
Social cognition	17	69	15	65	13	62
Social communication	31	67	27	64	21	58
Social motivation	12	60	10	57	8	53
Restricted interests and repetitive behavior	15	68	12	63	6	52

TABLE 2 | General education teacher.

SRS-2 Measure	Week 1 (Baseline)		Week 2		Week 3	
	Raw score	*T*-score	Raw score	*T*-score	Raw score	*T*-score
Total score	99	72	41	52	34	50
Social awareness	6	51	10	62	7	53
Social cognition	16	67	6	49	5	48
Social communication	36	72	12	50	9	47
Social motivation	26	85	8	53	8	53
Restricted interests and repetitive behavior	15	68	5	51	5	51

TABLE 3 | Parent (mother).

SRS-2 Measure	Week 1 (Baseline)		Week 2		Week 3	
	Raw score	*T*-score	Raw score	*T*-score	Raw score	*T*-score
Total score	109	80	61	61	50	57
Social awareness	12	70	7	54	10	48
Social cognition	19	74	11	59	10	57
Social communication	36	78	19	59	15	55
Social motivation	16	71	9	56	10	58
Restricted interests and repetitive behavior	26	87	15	68	10	59

TABLE 4 | Paraprofessional educator.

SRS-2 Measure	Week 1 (Baseline)		Week 2		Week 3	
	Raw score	*T*-score	Raw score	*T*-score	Raw score	*T*-score
Total score	92	70	85	67	90	69
Social awareness	9	59	9	59	11	64
Social cognition	18	70	19	72	17	69
Social communication	27	64	23	60	30	66
Social motivation	18	71	12	60	12	60
Restricted interests and repetitive behavior	20	77	22	80	20	77

the parent noted no usability or adverse effects that resulted in an intervention session being terminated early or being postponed. All three school educators and the participant's parent completed an SRS-2 at the end of Week 2 and Week 3, following eight total intervention sessions and 16 total intervention sessions, respectively. The results of the SRS-2 ratings are outlined in **Tables 1–4** (and in graphic format in **Figure 4**).

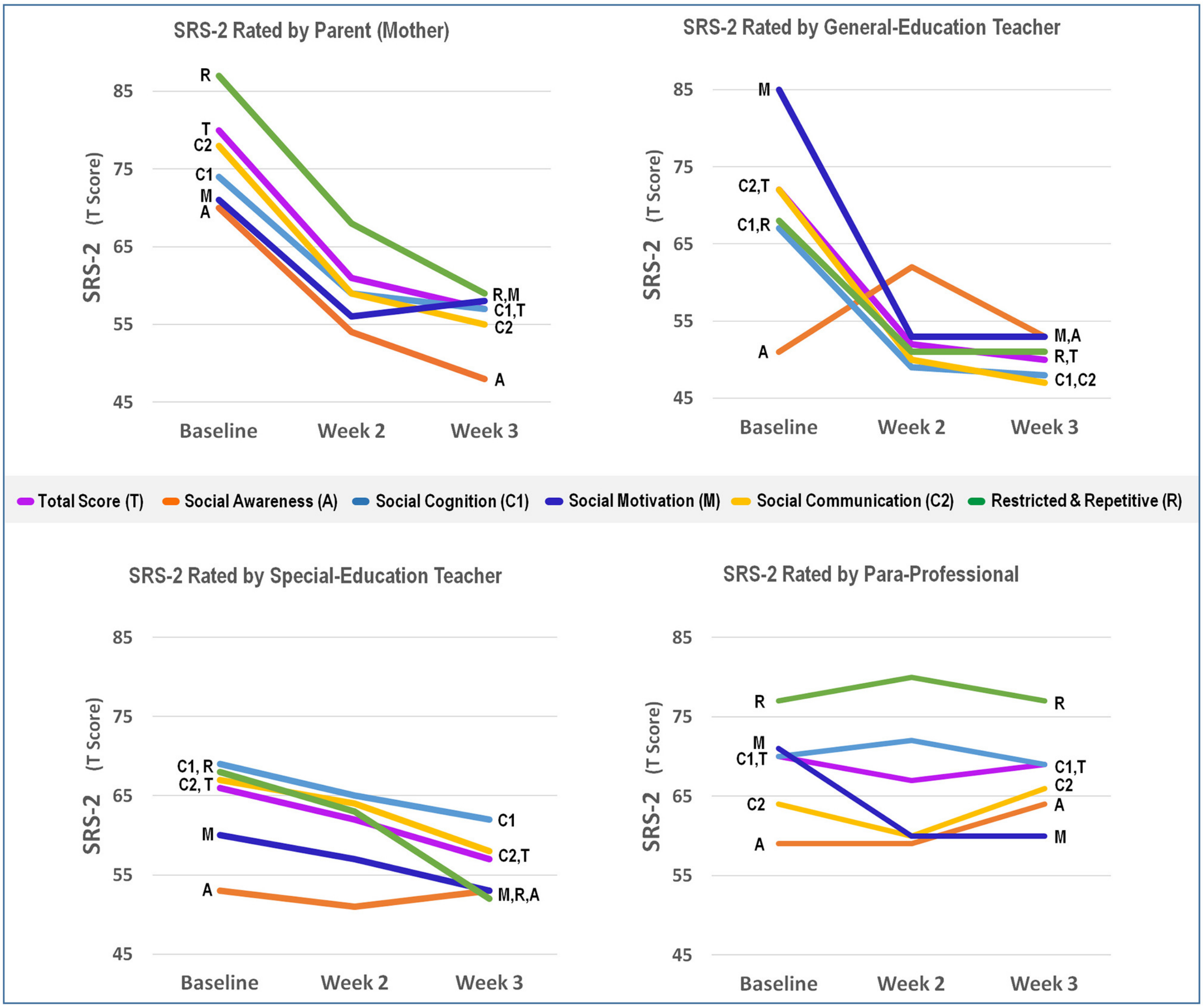

FIGURE 4 | Total and subscale Social Responsiveness Scale 2nd Edition (SRS-2) T scores for educators and parent at baseline and at the end of the intervention weeks.

DISCUSSION

Emerging assistive technologies may help to augment the delivery of social communication interventions in educational settings. There is great demand for such technologies given the growing ASD student population and current lack of access to specialized resources. However, it is important to study several aspects of these technologies, including their usability, reliability, efficacy, but also the ability for users to use and benefit from the technologies in real-world settings. This is especially important when technologies are created for use in schools given the challenges in integrating assistive digital tools in the busy schedule and environment of a classroom.

The findings of our case study demonstrate preliminary evidence that this particular autism-focused intervention, the Empowered Brain, is associated with improvements in social communication. This improvement was observed through the use of the SRS-2, a gold standard and validated social communication scale. The student's parent (mother), special educator teacher, and general education teacher, reported an improvement in the SRS-2 global scale in addition to improvement in social communication, social cognition, social motivation, and restricted interests and repetitive behavior subscales. The paraprofessional, who only provided a single intervention, did not note any substantial change in the SRS-2 total score.

Our findings have a number of implications and limitations, adding to the current literature in several important ways. Firstly, it was evident that a wide variety of school educators were able to use this smartglasses intervention with the student, despite this being their first experience with smartglasses. The school educators were keen to support the student's social communication needs through technology. Secondly, the educators were able to use this technology in the school setting, and specifically within the same classroom that the child would otherwise be attending. Compared to a research setting, this dynamic classroom/school environment poses considerably more sensory, social, physical, and organizational challenges. Finally, the successful and timely completion of all 16 intervention sessions of *Face2Face* demonstrates that this is a practical and usable technology in this setting. At no time were any issues of usability or negative effects with the use of *Face2Face* noted, and lack of adverse effects have been previously reported in a larger population (Sahin et al., 2018).

The potential adoption of this technology may have broad implications on the educational system. Anecdotal feedback from educators involved in the study suggested that they found the 10 min intervention sessions to be an important time period for assessment and relationship building. This has implications for the larger context of education, as it provides the teacher with additional tools (data and trust/social capital) to increase personal agency and effectiveness. The findings may also indicate a role for this intervention to address the socio-communicative challenges that often interfere with student engagement and teacher effectiveness in schools. Classrooms endeavoring to deliver an inclusive learning experience must balance administering differentiated content-based instruction that engages the unique abilities and needs of a neurodiverse student population while simultaneously identifying individual-specific disruptions in the learning process and implementing targeted interventions informed by data derived from observation and assessment (**Table 5**). Smartglasses, worn by student, can potentially serve as a non-invasive mechanism (or platform) to administer and monitor differentiated learning content as well as user-specific targeted interventions. Smart glasses, worn by the teacher, can potentially help to facilitate the collection of observational data in real-time and provide immediate feedback for action as well as long term goal setting and strategy developed during the IEP process (this has not yet been tested). Smart glasses and augmented reality as platforms for differentiated instruction and targeted intervention in schools (as described above) can theoretically be applied to every student in the classroom (based on their specific needs) and can fundamentally change the way academic content and curriculum is delivered as well as impacting the way educators are trained and evaluated. Software development for the device that can effectively address many of the pain points and lingering challenges educators and parents face is necessary to fully realize the potential of the platform.

Consideration must be given to a number of limitations of the study, both in regards to methodology and the findings. Firstly, this report is a case study, and there are limitations to the generalizability of our findings to the broader ASD student population. We have also noted that we had a limited number of data points in our study. While research on smartglasses in ASD has been quite limited, cohort studies following multiple learners would help to improve our understanding of the efficacy of such interventions across the spectrum. Further testing of this technology requires continuous measures to supplement the pre- and post-measures that have been obtained in this study. Additionally, it is important to replicate these results in order to understand causality.

TABLE 5 | Advantages for the educational system.

The advantages for schools and teachers include:

- A new tool for precise implementation of differentiated instruction and data driven strategy development
- A quantitative method (to work alongside qualitative methods) of data collection and analysis
- Interventions can be conducted in-class with little maintenance from teachers
- An increase in student ability to attend which should also translate into an increase in quality time-on-task for both teacher and student

The advantages for parents include:

- Increased awareness of school-related challenges and interventions
- Increased engagement in school-based content and intervention strategies
- Improvement of real world skills observable and verifiable in the home

TABLE 6 | Potential challenges for broader adoption.

The challenges to broader adoption include:

- Educator reluctance to change practice
- Educator reluctance to adopt new technology
- Inherent difficulty in successfully changing well-worn practice
- Cost of device for cash-strapped schools and districts
- Lack of proliferation of smart glasses in main stream society
- New technology still in development

Additionally, we have designed this intervention for use in the educational system of the United States. There is considerable variance in the curriculum, use of assistive technology, and availability of special education resources in educational systems across the world. While some systems would share many similarities with the United States, there may be a need to make cultural and country-specific adjustments to the technology. The authors note that the base hardware of the Empowered Brain, Google Glass, was never available for purchase in many countries across the world. Importantly, there are a number of additional challenges to the adoption of this technology by the educational system, including educator attitudes and cost-implications (**Table 6**).

As with any intervention, there is always a possibility of a placebo effect. The smartglasses provide a game-like experience that augments a person's normal perceptual experience. It is possible that such a novel experience is particularly prone to a placebo effect on the student, as well as the raters. On the other hand, people with ASD struggle with new experiences, and may also demonstrate extreme reactions to experiences that are difficult to their normal schedule, or that incorporate novel sensory stimuli (American Psychiatric Association, 2013). It was therefore reassuring that over 16 sessions, this digital perceptual experience did not result in these well-documented ASD-related adverse behaviors such as tantrums and/or meltdowns.

In future studies, we intend to broaden the scope of our target population to include students with other cognitive-based learning disabilities. While measuring the effectiveness of particular apps, we will also monitor the impact on overall quality of time-on-task for teachers and students. Social and behavioral issues often interfere with both a teacher's ability to convey content and skill, and the students' ability to receive and absorb that content and skill. If our intervention can increase attending and reduce behavioral distractions, it should also have a positive impact on the quantity and quality of time spent "on task" for both teachers and students. If this proves to be the case, we can begin to predict and plan for how much time "on task" will be required to move toward proficiency and mastery for each child in the classroom.

AVAILABILITY OF DATA AND MATERIAL

Collected data (SRS-2) is included in this paper.

AUTHOR CONTRIBUTIONS

NS, JS, RL, RA-S, NK, and AV designed and undertook the intervention. The writing of this technology report was led by AV, and all authors contributed.

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Head-Mounted Display Virtual Reality in Post-secondary Education and Skill Training

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Background: This review focused on how immersive head-mounted display virtual reality (VR) was used in post-secondary level education and skill training, with the aim to better understand its state of the art as found from the literature. While numerous studies describe the use of immersive VR within a specific educational setting, they are often standalone events not fully detailed regarding their curricular integration. This review aims to analyse these events, with a focus on immersive VR's incorporation into post-secondary education.

Objectives: (O1) Review the existing literature on the use of immersive VR in post-secondary settings, determining where and how it has been used within each educational discipline. This criterion focused on literature featuring the use of immersive VR, due to its influence on a user's perceived levels of presence and imagination. (O2) Identify favorable outcomes from the use of immersive VR when it is compared to other learning methods. (O3) Determine the conceptual rationale (purpose) for each implementation of immersive VR as found throughout the literature. (O4) Identify learning theories and recommendations for the utilization of immersive VR in post-secondary education.

Methods: A literature review was undertaken with searches of Education Research Complete, ERIC, MEDLINE, EMBASE, IEEE Xplore, Scopus, and Web of Science: Core Collection to locate reports on the use of immersive VR in post-secondary curricula.

Results: One hundred and nineteen articles were identified, featuring disciplines across Arts and Humanities, Health Sciences, Military and Aerospace, Science and Technology. Thirty five out of 38 experiments reported to have found a positive outcome for immersive VR, after being compared with a non-immersive platform. Each simulation's purpose included one or more of the following designations: skill training, convenience, engagement, safety, highlighting, interactivity, team building, and suggestion. Recommendations for immersive VR in post-secondary education emphasize experiential learning and social constructivist approaches, including student-created virtual environments that are mainly led by the students themselves under team collaboration.

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Conclusion: Immersive VR brings convenient, engaging, and interactive alternatives to traditional classroom settings as well as offers additional capability over traditional methods. There is a diverse assortment of educational disciplines that have each attempted to harness the power of this technological medium.

Keywords: virtual reality (VR), head-mounted display (HMD), immersive technology, educational technology, education, training, simulation

INTRODUCTION

In the year 2012, Palmer Luckey initiated a Kickstarter campaign to fund the Oculus Rift: an affordable head-mounted display (HMD) virtual reality (VR) system that would allow tech-savvy enthusiasts to begin building and experiencing their own virtual environments. Prior to this time, HMD VR technology had often contained head-tracking issues, resulting in inaccurate and poor representations within the virtual world (Robinett and Rolland, 1992). Despite using the most sophisticated HMD graphics processors that were available in the early and late 1990s, realistic image processing of virtual environments would often overburden the system's computation ability, causing the user to experience tracking and latency issues. In other words, the actions of the user from the real world would often fail to translate accurately into the virtual world. Latency issues were brought to acceptable standards in the early 2010s when computer engineers were able to identify and correct the delays associated between a user's actions and the hardware's capability. Since the mid-2010s, an "unprecedented" uptake of HMD VR has been seen in both academic and industry contexts (Elbamby et al., 2018). VR has steadily been adopted into post-secondary educational systems with relative success, because of its ability to retain student learning and interest while saving resources and improving experimental efficiency (Liang and Xiaoming, 2013).

This review focused on immersive VR in post-secondary level education and skill training to gain a better understanding of its potential ability to train users under higher-order thinking conditions, which typically requires advanced judgment skills such as critical thinking and problem solving. Immersive VR is also capable of training users for advanced conditions that simulate hazardous environments or undesirable social situations that may be less appropriate for users below post-secondary educational levels. Although the literature regarding the use of immersive VR within post-secondary educational settings is quite diverse, these events are often standalone and seldom provide details on how immersive VR is adopted into associated curriculums. This review aims to analyse these events, focusing on how immersive VR can be incorporated into post-secondary education.

Rationale

The International Data Corporation (IDC) expects compound annual growth rates of VR to increase by 78.3% for the next 5 years, rising from $16.8 billion in 2019 to $160 billion by 2023 (Nagel, 2019). The fields for this growth are expected to include the education sector, with VR for lab and field work in higher education settings having a 5-year compound annual growth rate of 183.4% (Nagel, 2019). With the increased availability of consumer-level HMD VR hardware on the market, such as the Oculus Rift, HTC Vive, Playstation VR, and mobile phone technology, this newfound accessibility has led to an upshift in immersive VR adoption into academic settings. There has also been an increase in available software that runs on HMD VR, yet research on what is utilized in academic settings is ever changing and upgrading. An update to understand the "how and for what" aspects of virtual technology, affecting performance in academia, has been recommended (Jensen and Konradsen, 2018). This state-of-the-art review observes the disciplines, methods and theories in post-secondary practice that features the use of immersive VR.

Virtual Reality (VR)—Definition and Features

VR is broadly defined as an environment where users can accept and respond to artificial stimuli in a natural way (Zhang, 2014). Other definitions of VR include the human-machine interface that allows users to "project" themselves into a computer generated world, where specific objectives can be achieved (Zhang, 2014). VR is sometimes known as "Ling-jing" technology (Hui-Zhen and Zong-Fa, 2013; Hu and Wang, 2015). Depending on the setup of the human-machine interface, the components of the hardware and the amount of real-world images that are placed into the virtual world; a user's experience will vary between the differing types of mixed reality including augmented reality (AR), augmented virtuality (AV), mirror reality (MR), and virtual reality (VR) (Cochrane, 2016; Tacgin and Arslan, 2017). See **Table 1** for a glossary of terms. Note that the proper usage of these terms has not caught up with the rate in which virtual reality concepts have grown (Cochrane, 2016; Tacgin and Arslan, 2017). There are often misconceptions between VR concepts and types. For example, some scientific literature will refer to AR applications as VR and vice versa (Tacgin and Arslan, 2017).

Immersion

One feature of VR is its physical level of immersion, defined by the degree a user associates being within a virtual environment (Rebelo et al., 2012; Parsons, 2015). Immersion is reduced when a user is able to perceive aspects of the real world while experiencing the virtual world. For example, users who can perceive the frame of a projection screen, depicting a virtual environment that simulates being in outer space, may compromise the users' level of immersion. When classifying the level of immersion, based on the human-machine interface, there

TABLE 1 | Glossary of common terms describing Virtual Reality.

Term	Definition	Examples
Immersive VR	The user is entirely surrounded by the virtual environment, encompassing optimal field-of-view (Rebelo et al., 2012).	HMD VR. CAVE.
Non-immersive VR	The user is not entirely surrounded by the virtual environment, allowing images of the virtual world and real world to both be seen simultaneously (Rebelo et al., 2012).	AR. AV. Desktop computer experience.
Augmented Reality (AR)	Also known as stacked VR, computer images are superimposed onto a glass or lens display, simultaneously showing both real world and computer generated images. The view is mainly the real world, supplemented with computer generated graphics.	A marker overlay is projected onto a pair of glasses (Smart Glasses) so the user can see both the real world and virtual overlay at the same time.
Augmented Virtuality (AV)	A real-world image is projected into a virtual world, allowing the integrated real-world image to interact with the virtual world in real-time. A view that is mainly the virtual world, supplemented with captured real-world images.	A camera places a real-world image of the user into a computer generated soccer field, allowing the user to see him or herself move and kick a virtual ball. (Immersive Rehabilitation Exercise (IREX) systems).
Avatar	Derived from the Sanskrit word that refers to the God Vishnu's manifestation on earth (Milgram et al., 1995; Trepte et al., 2010), this is a projected image and representation of a user or artificially intelligent character within a virtual world.	User acts as a firefighter in a fire-safety virtual environment. World of Warcraft character.
Cave Automatic Virtual Environment (CAVE)	Images are projected onto the walls, ceilings and floors of a room-sized cube, which change based on a user's actions while he or she is inside the room. The movements of the user are often detected by tracking technology.	A user sits in a fixed wheelchair, placed in the middle of a room. The projected images on the floors, ceilings, and walls create the effect that the user is moving along a path, within a garden, as the chair's wheels are spun.
Distributed Reality	A web-based virtual environment, where multiple users control their avatars to interact with each other in the virtual world, despite the users being physically located in different geographical locations.	Second life. World of Warcraft.
Engine	A framework of coding used to script and animate computer programs such that they become virtual worlds.	Unity. Unreal Engine 4.
Latency	The delay between a user's action (head rotation) and corresponding change in the virtual environment to represent the user's new field of view.	Lag. Sensor sampling delay. Image Processing delay. Network delay.
Mirror Reality	A virtual environment that aims to recreate a copy of the real world.	The digital viewfinder of a camera shows a pixel image of the real world.
Mixed Reality	Also known as hybrid reality, real-world images are combined with a virtual world. The amount of real-world images that are used in the virtual world determines the mixed reality's abilities as defined by the reality-virtuality continuum (Milgram et al., 1995).	AR. AV.
Smart Glasses	Mobile computers that combine HMD with sensors to display computer graphics in the real world.	Google Glass. Microsoft HoloLens.
Stereoscopy	Also known as stereoscopics or stereo imaging. The perception of three-dimensional (3D) images that are often created by presenting two offset images, separately shown to the left and right eye.	Anaglyph 3D films, viewed with red and blue filter glasses. Most modern HMD units feature stereoscopic 3D.
Tracking Technology	Sensors that detect movement, position, and angle of an object or user while in a virtual space. The sensors relay numeric coordinates to the computer or base station for processing.	A user's hands are represented in the virtual space with the use of controllers. Infrared sensors or gyroscopes on the controllers provide positional data to a base station for processing.
Virtual Reality (VR)	A computer system that creates an artificial environment where users can project themselves and respond to artificial stimuli in a natural way or complete specific objectives (Zhang, 2014).	A user enters a virtual world, seeing and interacting with the virtual environment, with the use of a HMD and gloves, respectively.

are three types: full immersion is achievable when the user utilizes a HMD (goggles, VR helmet or headset); semi-immersion is achievable when the user utilizes large projection or liquid crystal display (LCD) screens; and non-immersion is achievable when utilizing typical desktop computer setups with keyboards and mice (Gutiérrez Alonso et al., 2008; Rebelo et al., 2012; Parsons, 2015). Note that the main difference between these levels of immersion is due to the user's field of vision (FOV), where an optimal FOV of 180 degrees horizontal and 60 or more degrees vertical is achievable with the HMD hardware (Rebelo et al., 2012). Reduced perception (seeing, hearing, touching) of the real world tends to result in greater levels of VR immersion (Gutiérrez Alonso et al., 2008; Rebelo et al., 2012).

Interactivity

The second feature of VR is its level of interactivity, defined as the degree of accuracy and responsiveness a user's actions represent when using the input hardware (Rebelo et al., 2012; Parsons, 2015). For example, with the use of physical hardware such as motion-sensing gloves, VR systems will allow users to interact with objects that are located within the virtual environment. Using input hardware to interact with a virtual environment is analogous to using a mouse and keyboard to give commands to a desktop computer. Common VR input devices include motion-sensing gloves, remotes, controllers, Lycra suits, Leap Motion (for barehanded gestures) or photo sensors to transfer the user's real-world actions into the virtual world. The position and motion of the user's hands can be updated in real-time with the use of sensors that allow for up to six degrees of freedom. Some input devices are equipped with features to provide kinaesthetic communication to the user, such as force or haptic feedback response. An example of this force feedback occurs in skill training when an operator's surgical tools become resistant to movement, after colliding with visceral tissues in a virtual patient, during simulated laparoscopic surgery.

Imagination

The third feature of VR is grounded with the user's imagination, defined as the extent of belief a user feels is within a virtual environment, despite knowing he or she is physically situated in another environment (Burdea and Coiffet, 2003; Rebelo et al., 2012). Note that interactivity and immersion have a direct effect on a user's level of imagination, which is dependent on the VR's input devices, graphics, and objectives (Rebelo et al., 2012). These features of immersion, interaction and imagination form the "VR Triangle (Burdea and Coiffet, 2003)." Note that not all VR setups attempt to emphasize all three features (immersion, interaction and imagination) in a virtual environment. For example, a surgical simulator, designed for skill training, requiring force, and haptic feedback controls would place interactivity above immersion and imagination.

Presence is a subjective concept that defines the psychological degree a user understands where it is possible to act within the virtual environment (Rebelo et al., 2012). A user feels present in a virtual environment when he or she feels the experience is derived from the virtual environment, rather than the real world (Rebelo et al., 2012). Deep presence occurs when a user feels both immersion and involvement in the virtual environment (Rebelo et al., 2012). Involvement has been formally defined as the user's attention and effort being placed on a "coherent set of stimuli or meaningful activities and events" (Witmer and Singer, 1994).

The state of presence can be explained with the term fidelity, derived from the Latin word "fidelis," meaning faithfulness or loyalty. A virtual environment is deemed to be of high fidelity when the user's actions, senses and thought-processes closely or exactly resemble those that would be experienced while in the same situation as in the real world. VR experts have classified fidelity into different parts including functional (Swezey and Llaneras, 1997), physical (Champney et al., 2017) and psychological fidelity (Rehmann et al., 1995). An example of a low fidelity virtual environment would be a driving simulator that uses a gamepad instead of a steering wheel, while the driver's FOV is limited to that of an LCD screen. Whereas, an example of a high fidelity virtual environment would be an airplane simulator that has all the relevant controls and visual layout, exactly matching that of a cockpit from a real-world model, allowing pilots to conduct their skill training in the virtual world to prepare for flying in the real world.

Incentives for Adopting Immersive VR Into Post-secondary Education

One principle underlying the development and evaluation of the VR experience is experiential learning, which is aligned with the constructivist theory of learning. Educational simulation is grounded in the pedagogy of mastery learning (Guskey, 2010; Alaker et al., 2016). Users are generally more motivated to participate in a virtual environment, which can be instantly adjusted to differing levels of challenge, accommodating varying amounts of cognitive ability (Shin and Kim, 2015). VR can safely provide answers to inaccessible and intangible concepts that would otherwise be considered too dangerous or unethical to perform in real life (Grenier et al., 2015). It is a safe, ethical and repeatable system that produces objective measures of performance while providing real-time feedback to users (Alaker et al., 2016). Non-immersive VR has already been adopted in desktop and distributed platforms, allowing users to share a common virtual space, despite the users being physically located in geographically different locations (Hu and Wang, 2015). Immersive VR users have shown a piqued curiosity to learn with the HMD hardware, which often results in enhanced learning enjoyment (Moro et al., 2017).

Immersive VR users commonly feel that they have been projected into a different location (place illusion), while experiencing events that are perceived to be real (plausibility illusion; Sanchez-Vives and Slater, 2005). Sometimes, users will feel their own body is different when represented as an avatar with varying characteristics (embodiment illusion; Spanlang et al., 2014). Whenever a student is listening to an instructor or reading literature in order to better understand a concept, the student is mainly acting as an observer. The student may perhaps have the ability to interact with the learning experience by asking the occasional question or by completing exercises that are printed in the textbook, yet with immersive VR the student acts as both an observer and "the center of the system" (Gonzalez-Franco and Lanier, 2017). Place, plausibility and embodiment illusions are created by computer generated stimuli that may persuade a user's brain to respond as though the illusions were real. When multiple senses are incorporated into the user-to-object interaction within the virtual world such as vision, audition, and tactile/proprioception, a coordination of brain mechanisms are required to process this afferent sensory input and interpret the data coherently (Kilteni et al., 2015). In other words, immersive VR allows a user to learn how they would feel and respond (physiologically, tactfully, and procedurally) when interacting with virtual situations that the brain treats as real.

Obstacles Inhibiting the Adoption of Immersive VR Into Post-secondary Education

One obstacle inhibiting the adoption of immersive VR may involve the ability of educators to schedule immersive VR into their traditional methods of teaching, potentially being unaware about VR technology and how it could be integrated into the curriculum (Cochrane, 2016). It is possible that some universities have concluded that the amount of knowledge or skill gained from using immersive VR is not worth the financial risk. Another possibility is the specific level of detailed knowledge the HMD VR hardware requires in order to use it properly, posing yet another barrier to entry (Gutierrez-Maldonado et al., 2015). Perhaps VR's biggest obstacle to being accepted into post-secondary education systems is its psychometric validation, where stakeholders must carefully judge the degree to which virtual environments offer training in skills that can be obtained in other less expensive or complex modalities, which are free from simulator sickness (Parsons, 2015). There are two obstacles that inhibit the adoption of immersive VR into post-secondary education: (a) Software—There is a lack of applicable content for each discipline and most of what is available is mainly marketed toward self-learners, (b) Hardware—HMDs default to being entertainment systems that were not originally intended for classroom use (Jensen and Konradsen, 2018).

Criticisms of Immersive VR in Post-secondary Education

Immersive VR offers a modern learning channel that caters to multi-sensory learning styles, which sometimes can be more effective than traditional learning methods (Bell and Fogler, 1995; Gutierrez-Maldonado et al., 2015). However, there is meta-analysis literature stating that there is no adequate evidence supporting the consideration of learning-style assessments into general educational practice (Pashler et al., 2008). Perhaps the most convincing argument for adopting immersive VR into post-secondary education systems would be the already existing disciplines that have integrated such simulations into their curriculums, such as full-room and team simulated robot-assisted (da Vinci Surgery) endovascular procedures in surgical education (Rudarakanchana et al., 2015). Unfortunately, medical treatment injuries from these simulated endovascular procedures, due to faulty simulation trainings, have resulted in hundreds of lawsuits due to individual product liability cases (Moglia et al., 2016). The amount of evidence supporting the transfer of user surgical skill from simulation (da Vinci Surgery) applications to real-world settings has sometimes been found to be insufficient (Moglia et al., 2016). In matters of affordability, the incorporation of immersive VR into post-secondary educational systems was initially limited by the cost of the equipment used, yet commercialization of consumer headsets have brought down costs considerably (Gutierrez-Maldonado et al., 2017). Mobile phone technology has reached a level where immersive VR can be readily adapted into HMD format, simply by using low-cost Google Cardboard or Samsung Gear VR headsets (Hussein and Nätterdal, 2015). Although there is little data supporting the use of mobile phone HMD VR technology in post-secondary education, this accessible option is expected to be a "necessary tool in education in the near future" (Hussein and Nätterdal, 2015). Based on a survey that was presented in 2015 by the Educause Center for Analysis and Research (ECAR), 92% of university students within the United States have mobile phones that are capable of accessing enterprise level systems and VR software applications (Cochrane, 2016).

Aim of This Review

This review aims to uncover how post-secondary programs are incorporating immersive VR into post-secondary educational curricula. Its focus involves an interdisciplinary consideration, due to immersive VR's applicability across a wide variety of disciplines. The core assumption is that students optimize learning and practical skill acquisition through experiential learning and hands-on experience, thus a brief summary of each case when immersive VR's positive outcomes will be noted when applicable. The focus on post-secondary level education and its associated goal, skill training, is to gain further understanding of immersive VR's potential ability to train users under higher-order thinking conditions. Specific audiences for this review include: post-secondary education developers, program administrators, curriculum developers, technology research labs (video performance and enhancement labs on academic campuses), and potential instructors who are considering immersive VR as a technological option for experiential learning.

RESEARCH QUESTIONS

This state-of-the-art review was designed to answer the following research questions:

1. How is immersive virtual reality being used in post-secondary level education and skill training?
2. What conceptual and theoretical perspectives inform the use of immersive VR in post-secondary education and skill training?

Objectives

The following objectives were derived from the research questions:

1. Review the existing literature regarding the use of immersive VR in post-secondary settings, determining how it has been used within each educational discipline. This criterion focused on literature featuring the use of fully immersive VR, due to its influence on a user's perceived levels of presence and imagination.
2. Identify favorable outcomes from the use of immersive VR when it is compared to other methods. This was to determine incentive reasoning for immersive VR's adoption into post-secondary education.
3. Determine the conceptual rationale (purpose) for each implementation of immersive VR as found throughout the literature. This was to gain better understanding of immersive VR's role in post-secondary education.
4. Identify learning theories and recommendations for the incorporation of immersive VR into post-secondary education. This may provide perspectives for immersive VR's adoption into post-secondary education.

TABLE 2 | Search criteria and terms.

Inclusion criteria	Exclusion criteria
• Report stated immersive VR usage for post-secondary curricula (graduate, undergraduate or college) or skill training • Mentioned the potential use of immersive VR in the future, despite conducting an intervention with an alternative method. • All methods of immersive VR including qualitative, quantitative, descriptive, and review reports were accepted. • Reports were accepted in all languages in article, conference, book, or magazine format.	• VR platform was not immersive or report does not introduce or discuss possible usage of immersive VR technology. • Participants were not specified as post-secondary students (the exception is the investigators were performing the study as part of post-secondary curricula). • The report stated that "VR was used" but the exact platform, nature of simulation modality, or hardware configuration failed to confirm immersive VR hardware.

Search terms used: "virtual reality" OR "Head-mounted display" OR HMD.
AND undergraduate OR college OR post-secondary OR postgraduate.
AND curricul OR educat* OR teach OR learning OR training.*
These terms were entered into the databases mapped to the following fields: title, abstract, subject heading word, and keyword heading word. Each search was limited to reports published on March of 2013 (emergence of Oculus Rift Developer Kits) to January 2019.

METHODS

Search Strategies

The initial literature search was performed during October 2017 and then updated in January 2019. Acceptable reports were required to have been published since March of 2013 as this was the date that Oculus Rift Developer Kits became first available. This date focused on the "unprecedented" adoption of HMD VR before the mid-2010s as stated by Elbamby and colleagues. After discussing the research question in consultation with a university librarian, the following bibliographic databases were searched (2013 to present): Education Research Complete (EBSCO*host*), ERIC (EBSCO*host*), MEDLINE (Ovid), EMBASE (Ovid), IEEE Xplore (IEEE/IEE), Scopus (Elsevier), Web of Science: Core Collection (Thomson Reuters and Clarivate Analytics). The search strategy included a combination of subject headings and keywords to combine the concepts of HMD Virtual Reality, post-secondary students, education, and training. Refer to **Table 2** for the inclusion and exclusion standards of each report.

Each report's screening process was performed by the lead author. All reports that indicated the use of virtual reality, in their title or abstract, were reserved to complete the first pass. For the second pass, all reserved reports from the first pass had their full texts screened again to confirm the context of immersive VR usage. Methodological quality of each report was not formally assessed beyond the study design used.

Determining the Purpose of Immersive VR

For each report, a designated purpose of immersive VR's implementation was applied to rationalize its function, throughout the literature screening process. Each purpose was based on the screening of keywords found from the literature in order of appearance: report title, keywords (index terms), and abstract. In the absence of an abstract, the main text was screened instead. **Table 3** shows the keywords used to define immersive VR's purpose in post-secondary education.

TABLE 3 | Determining the purpose of immersive Virtual Reality in Post-secondary Education.

Keywords in title, index terms, abstract, or main text	Assigned purpose
Augmented Reality or Guiding	Highlighting
Attitude, Enjoyment, or Interest	Engagement
Education, Training, Teaching, or Learning	Skill Training
Interaction, Response, Real, Gesture, Role Play	Interactivity
Low Cost, Cost or Portability	Convenience
Empathy, Influence or Motivate	Suggestion
Leadership, Team Collaboration, or Virtual Teams	Team Building
Risk-assessment, Accident avoidance Safety	Safety
A report with four or more above qualifying labels	Various

RESULTS

The search resulted in a total 1,495 reports being found. After the first pass, 215 reports remained after titles and abstracts were screened, along with duplicates removed. During the second pass of screening, the full texts of 215 reports were screened to further confirm eligibility (see **Figure 1**). This resulted in a net total of 119 reports being included in this review. It is noteworthy that in the previous search of October 2017, there were 874 reports found with 58 studies deemed eligible after the screening process, resulting in a 105.17% increase in eligible immersive VR literature in post-secondary education in the span of 15-months.

The 119 reports included in this review discussed the use of immersive VR in experimental, proposal, review, or curricular format. Note that some of the reports discussed usage of immersive VR across two or more disciplines, while others may not have included a specific discipline in their description. **Table 4** provides a breakdown of the literature by discipline under each of the following headings: Arts and Humanities, Health Sciences, Military and Aerospace, and Science and Technology.

Where Immersive VR Was Implemented

The majority of immersive VR usage was reported from the field of Science and Technology, specifically in the Education discipline ($n = 17$). Within the same field, the disciplines of Computer Science and Engineering—General constituted second and third-most of immersive VR usage at $n = 6$ and $n = 4$, respectively. The field of Health Sciences' most common disciplines were Psychology and Surgical Education—General at $n = 16$ and $n = 9$, respectively. Within the same field, Anatomy represented the third most common discipline at $n = 4$. The field of Arts and Humanities' most common disciplines to report on immersive VR were Music and Design Thinking at $n = 3$ and $n = 3$, respectively. Military and Aerospace was the field to include the minority of reported instances of immersive VR usage with Aerospace at $n = 1$ and Military at $n = 2$.

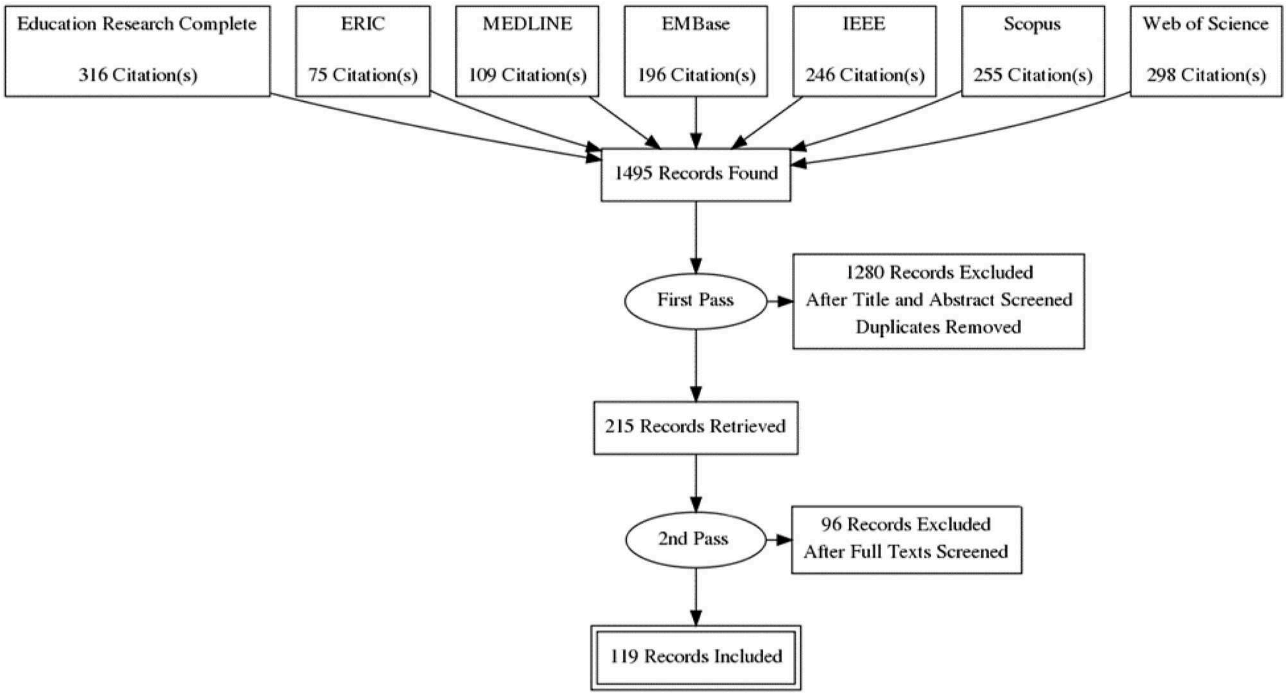

FIGURE 1 | PRISMA flow diagram of search results.

TABLE 4 | Frequency of immersive Virtual Reality literature across educational disciplines.

Heading	Frequency of use in literature	Total
Arts and Humanities	2x Art, 2x Business, 3x Design Thinking, 2x History, 2x Journalism, 3x Music, 1x Political Science, 1x Religious Studies	16
Health Sciences	4x Anatomy, 1x Dentistry, 3x Nursing, 1x Optometry, 3x Paramedicine, 3x Physical Education, 16x Psychology, 2x Public Health, 2x Rehabilitation, 9x Surgical Education—General, 3x Surgical Education—Neurosurgery, 2x Veterinary Education	49
Military and Aerospace	1x Aerospace, 2x Military	3
Science and Tech	3x Architecture, 2x Astronomy, 1x Chemistry, 6x Computer Science, 2x Driving, 17x Education, x3 Engineering—Civil, 2x Engineering—Computer, 1x Engineering—Electrical, 4x Engineering—General, 2x Engineering—Mechanical, 1x Engineering—Numerical Control, 1x Engineering—Pneumatic, 1x Forensics, 1x Geology, 1x Industrial Plant Operation, 1x Information Interfaces, 3x Physics	52
Various	4x Various	4

Objective 1—How Immersive VR Was Used in Post-secondary Education

Descriptions summarizing the use of immersive VR across each discipline are presented in **Table 5**. It was found that the field of Science and Technology had the majority of literature featuring the use of immersive VR, which is congruent with the findings Freina and Ott reported in 2015. The greatest distribution of reports in this review were found in Education disciplines, next to Psychology in the field of Health Sciences, unlike Freina and Ott's report from 2015 which had most of the representative disciplines being Computer Science, Engineering, and Mathematics. While this review focused on the use of immersive VR at the post-secondary education level, Freina and Ott's review in 2015 was inclusive to all levels of education, including middle school. This paper's focus on higher level education could explain why disciplines such as of Education and Psychology had the greatest proliferation of immersive VR usage, possibly due to VR's ability to support environments that allow for more control than what would be available in real life, especially when dealing with intangible concepts. Having access to a platform that can subject users to intangible stimuli such as fear, addiction, and violence was found to be a definite incentive for Psychology to adopt immersive VR.

The incentives for immersive VR being incorporated into post-secondary education and skill training may include one or more of the following: the maintenance of ethical principles, overcoming problems concerning time and space, increasing the physical accessibility of environments that are not normally accessible and/or overcoming what would normally be a dangerous situation (Freina and Ott, 2015). Surgical Education's demand for immersive VR can be explained by ethical principles, which allows users to train technical skills without subjecting patients or the users themselves to the possibility of harm (Ziv

TABLE 5 | Literature summary of immersive VR usage across educational disciplines.

Heading	Discipline	References	Purpose	Description
Arts and Humanities	Art	Kuhn et al., 2015; Leue et al., 2015	Skill Training/Highlighting	Google Glass implemented in art galleries.
Arts and Humanities	Business	Lee et al., 2017	Engagement	Experiment: Compared Google Cardboard HMD units to non-immersive VR. Google Cardboard users reported greater levels of enjoyment and interest than the non-immersive users
Arts and Humanities	Business	Schott and Marshall, 2018	Convenience/Interactivity	A virtual environment of a Pacific Island allowed users to find avatars of community members and government officials, who explained how the island's relationship with tourism acted as the main source of income. The project was based on a "situated experiential education environment."
Arts and Humanities	Design Thinking	Cochrane, 2016	Interactivity	Proposal: A curriculum for the field of new media production and design, where artwork and graphical design showpieces can be displayed in virtual showrooms and allow user interactivity.
Arts and Humanities	Design Thinking	Cochrane et al., 2017	Team Building	Proposal: A curriculum for the field of visual design, where students can collaboratively share their artwork through Google Maps, providing 360-panoramic views of their project ideas.
Arts and Humanities	Design Thinking	Rive and Karmokar, 2016	Team Building	Proposal: VR design communities to team-collaborate online.
Arts and Humanities	History	Checa et al., 2016	Skill Training/Engagement	Experiment: Compared HMD VR to regular video for historical virtual environments tour. Students' overall satisfaction was found to be rated higher for the immersive VR method.
Arts and Humanities	History	Yildirim et al., 2018	Skill Training/Interactivity/ Engagement	VR glass experience featured historical 360-degree views of Kaaba to learn about Islamic History. Users could interact with learning points to receive audio information. Users stated during interviews that VR in history course activities would be beneficial.
Arts and Humanities	Journalism	Cochrane, 2016	Engagement	Panoramic VR video to enhance readers' experience.
Arts and Humanities	Journalism	Markowitz et al., 2018	Engagement/Skill Training/Suggestion	HMD VR (Oculus) users experience climate change (ocean acidification) from the perspective of either a human scuba diver or piece of coral reef. Users reported positive knowledge gained and improved interest about climate change.
Arts and Humanities	Music	Orman et al., 2017	Highlighting/Skill Training	Experiment: Compared HMD VR to no VR to enhance a user's wind band conducting ability. HMD VR learning environment demonstrated greater conducting ability than those not using VR
Arts and Humanities	Music	Hong-xuan, 2016	Skill Training/Engagement	VR musical teaching system was found to enhance student enthusiasm and learning.
Arts and Humanities	Music	Kilteni et al., 2013	Engagement	Experiment: Behavioral changes in a user's hand drumming ability, while performing as an appropriately perceived avatar while using HMD VR.
Arts and Humanities	Political Sciences	Hui-Zhen and Zong-Fa, 2013	Skill Training/Suggestion/Team Building	Proposal: HMD VR classrooms to encourage communication between students and teachers.
Arts and Humanities	Religious Studies	Johnson, 2018	Convenience/Skill Training	360-videos of each religion were shown with HMD VR, requiring users to identify each based on narrative and environmental cues. Students learned empathetic understanding, ritual and behavior involving religious theory.
Health Sciences	Anatomy	Moro et al., 2017	Highlighting/Skill Training/Engagement	Experiment: Immersive VR compared with non-immersive for cranial anatomy learning. No differences found between immersive and non-immersive VR, AR or tablet devices on student learning, except immersive VR promoted user immersion and engagement and promise to enhance student learning in anatomical education.
Health Sciences	Anatomy	Maresky et al., 2018	Skill Training/Interactivity	Experiment: Immersive VR compared with independent study for cardiac anatomy learning (Sharecare VR). VR condition demonstrated enhanced learning performance and student engagement.
Health Sciences	Anatomy	Albabish and Jadeski, 2018	Skill Training	Proof of concept: Dissection-based human anatomy course (for thorax and abdominal regions) both for on-site and distance learning.
Health Sciences	Anatomy	Stepan et al., 2017	Skill Training/Engagement	Experiment: Randomized controlled study compared online textbooks with VR HMD (Oculus) to enhance student neuroanatomical knowledge (ventricular and cerebral). HMD VR was shown to be more engaging and similar to online for knowledge acquisition.

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
Health Sciences	Dentistry	Hoffman et al., 2001; Sabalic and Schoener, 2017	Engagement/Convenience	3D goggles to patients, depicting relaxing virtual environments, in an effort to reduce anxiety during dental procedures.
Health Sciences	Nursing	Kleven et al., 2014	Various	Proof of concept: Both medical and non-medical users learn applicable material in a Virtual University Hospital.
Health Sciences	Nursing	Smith et al., 2018	Skill Training/Interactivity	Experiment: Immersive VR compared with desktop to enhance student learning on decontamination skills. No significant difference found between groups, but immersive VR system showed greater interactivity capability.
Health Sciences	Nursing	Aebersold, 2018	Skill Training/	Report summarizes VR concepts in nursing, providing simulation design ideas that are supported by theoretical concepts.
Health Sciences	Optometry	Leitritz et al., 2014	Highlighting/Skill Training	Experiment: Measured user's ability to draw an optic disc, comparing conventional binocular indirect ophthalmoscopy vs HMD AR ophthalmoscopy (ARO). ARO found to allow for learning various retinal diseases.
Health Sciences	Paramed.	Cochrane, 2016; Cochrane et al., 2017	Safety	Proposal: A curriculum for students to use VR (Google Cardboard) to analyze potential safety risks, prior to entering paramedical situations.
Health Sciences	Paramed.	Ferrandini Price et al., 2018	Skill Training	Experiment: HMD VR (Samsung Gear) compared with clinical simulation (live actors) to enhance student rapid treatment ability in Mass Causality Incidents. HMD VR found to be as efficient as clinical simulation. HMD VR users showed lesser stress levels than clinical simulation.
Health Sciences	Physical Education	Li, 2014	Skill Training/Highlighting	HMD VR used for sports training and telemetry data.
Health Sciences	Physical Education	Pan, 2015; Choiri et al., 2017	Skill Training/Interactivity/Safety	HMD VR to imitate real training situations and compensate for lack of equipment. Enhance an athlete's mental concentration.
Health Sciences	Psychology	Gutierrez-Maldonado et al., 2015	Skill Training	Experiment: HMD VR compared to non-immersive stereoscopic computer while performing a virtual interview on a virtual client who was diagnosed with an eating disorder. No difference found.
Health Sciences	Psychology	Gutierrez-Maldonado et al., 2017	Skill Training/Engagement	Experiment: Follow-up. HMD VR compared to non-immersive stereoscopic computer while performing a virtual interview on a virtual client who was diagnosed with an eating disorder. No difference found. No difference in learning. HMD VR more engaging.
Health Sciences	Psychology	Lin, 2017	Interactivity	VR goggles for users in a survival horror game to analyze fear coping strategies.
Health Sciences	Psychology	Gupta and Chadha, 2015	Skill Training/Suggestion	HMD VR to overcoming physical withdrawal symptoms from cigarette and drug addictions.
Health Sciences	Psychology	Parsons and Courtney, 2014	Interactivity	Experiment: Compared HMD VR version of the Paced Auditory Serial Addition Test (PASAT) with paper-and-pencil version. HMD VR has extra capability over paper-and-pencil. VR-PASAT unanimously preferred.
Health Sciences	Psychology	Kalyvioti and Mikropoulos, 2013	Skill Training	HMD VR for testing/training short-term memory of dyslexic users featuring environments with household objects, geometric shapes and virtual art galleries.
Health Sciences	Psychology	Kniffin et al., 2014	Safety/Skill Training	Experiment: Used HMD VR to compare diaphragmatic breathing to attention control training for the enhancement of self-regulatory skills in female students exposed to virtual aggressive males. Concluded that HMD VR effective for training self-regulatory skills.
Health Sciences	Psychology	Jouriles et al., 2016	Interactivity/Safety	Experiment: VR (goggles) Measure bystander behavior in response to sexual violence. Concluded that immersive VR allows researchers to determine behavioral effectiveness.
Health Sciences	Psychology	Lamb et al., 2018	Interactivity	Experiment: VR goggles were compared with desktop educational games, video recorded lecture and hands-on paper cut-outs to determine user blood-brain hemodynamic responses while interacting/learning about DNA structures. Hemodynamic responses were analyzed with functional near-infrared spectroscopy. Results suggested that greater cognitive processing, attention and engagement occurred in VR goggle and desktop education game conditions.
Health Sciences	Psychology	Parong and Mayer, 2018	Skill Training	Experiment: Immersive VR (The Body VR) compared with desktop slideshow to determine student cellular biology learning ability and

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
				interest. Segmented VR learning was compared to continuous VR learning. Desktop slideshow showed greater learning ability, yet lower interest level. Segmented VR showed greater learning ability than continuous.
Health Sciences	Psychology	Fominykh et al., 2018	Convenience	This paper presents a detailed conceptual framework for therapeutic practice with VR. A virtual environment of a beach scene relaxation scenario will change from calm to stormy, depending on the user's heart rate. Results showed the system may be useful for implementation of therapeutic training with biofeedback.
Health Sciences	Psychology	Wiederhold et al., 2018	Convenience	Mentions immersive VR use to supplement treatments for low-back pain, anxiety, PTSD, stroke, post-surgery palliation, etc.
Health Sciences	Psychology	Leader, 2018	Interactivity/Highlighting	Immersive VR and AR for psychotherapy, featuring adjustable clinic designs to optimize therapy for clients.
Health Sciences	Psychology	Singh et al., 2018	Engagement/Interactivity	Electroencephalogram measures of cognitive processes were recorded as a user's avatar hands were switched between varying levels of realism. The realistic virtual hands led to users noticing more tracking inaccuracies.
Health Sciences	Psychology	Formosa et al., 2018	Skill Training/Engagement	HMD VR (Oculus) allowed users to enter a lounge room to experience positive symptoms associated with schizophrenic spectrum, complete with auditory and visual hallucination. Results showed an increase in user knowledge and empathetic understanding).
Health Sciences	Public Health	Real et al., 2017a	Skill Training/Suggestion	Experiment: Compare HMD VR with control group for training best-practice communication skills in pediatricians, working with clients who refused vaccinations. HMD VR found valid for training communication skills and reducing vaccine refusal.
Health Sciences	Public Health	Real et al., 2017b	Skill Training/Suggestion	A curriculum featuring immersive VR to address influenza vaccine hesitancy was developed. User's verbally spoke with vaccine-hesitant caregiver avatars (controlled by another user) with open-ended questioning, empathy and education without medical jargon. VR showed promising results.
Health Sciences	Rehab.	Wen et al., 2014	Interactivity/Convenience	VR to monitor stroke patients (motion capture) during exercise while under the guidance of a therapist (HMD VR) who may provide electrical stimulation, despite being in a different location than patient.
Health Sciences	Rehab.	Chen et al., 2018	Skill Training/Engagement	Patients used HMD VR (HTC Vive) to perform upper body tasks for rehabilitation. Virtual environment allowed users to move objects in four different arm positions, which could detect up to 5-degrees of freedom.
Health Sciences	Surgical Education—General	Oyasiji et al., 2014	Highlighting	Google Glass to guide surgeons by providing AR images of portal and hepatic vessels in patients' surgical sites.
Health Sciences	Surgical Education—General	Mathur, 2015	Convenience/Skill Training	HMD VR low-cost surgery-based training for engineering education to enhance student learning.
Health Sciences	Surgical Education—General	Nakayama et al., 2016	Interactivity/Skill Training/Suggestion	Motivate student attitude toward surgical education in urology.
Health Sciences	Surgical Education—General	Huang et al., 2015	Skill Training/Interactivity	VR to simulate myringotomy procedures.
Health Sciences	Surgical Education—General	Olasky et al., 2015	Skill Training	Practice surgical peg-transfer tasks while in an adjustable environment.
Health Sciences	Surgical Education—General	Harrington et al., 2018	Engagement/Skill Training	Experiment: Single-blinded randomized cross-over study compared 360-video HMD VR (Samsung Gear) with two-dimensional video, depicting laparoscopy procedures, to determine attention, information retention and appraisal. HMD VR condition showed greater user engagement and attention with no difference in retention.
Health Sciences	Surgical Education—General	Yoganathan et al., 2018	Skill Training	Experiment: Prospective randomized controlled study compared 360-video HMD VR with two-dimensional video, depicting a surgical reef knot, to enhance surgical student knot tying skill. VR condition showed greater knot tying success rates.
Health Sciences	Surgical Education—General	Andersen et al., 2018	Skill Training	Experiment: An educational interventional cohort study offered additional immersive VR training over the control group, during mastoidectomy dissection training. Results showed that skills acquired in VR further increased student performance.

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
Health Sciences	Surgical Education—General	Benabou et al., 2018	Skill Training	Experiment: Prospective randomized controlled trial compared HMD VR (Sony Playstation 4 VR) with controls to determine surgical (laparoscopic) two-handed efficiency. VR group showed greater dominant and non-dominant hand speed while also increasing user perceived task performance.
Health Sciences	Surgical Education—Neuro	Gallagher and Cates, 2004; Schirmer et al., 2013b	Skill Training	Review: VR applications in neuroscience were found to be focused on skill acquisition, technical task-based applications and team/collaboration.
Health Sciences	Surgical Education—Neuro	Shakur et al., 2015	Skill Training/Highlighting	Users performed neurosurgical tasks such as ventriculostomy; bone drilling, pedicle screw placement, vertebroplasty and lumbar puncture on virtual patients.
Health Sciences	Surgical Education—Neuro	Schirmer et al., 2013a	Skill Training	Experiment: Repeated measures assessing the knowledge of neurosurgery trainees both before and after experiencing a stereoscopic ventriculostomy simulator. VR shown to increase knowledge across all simulation tasks.
Health Sciences	Veterinary Education	Seo et al., 2017, 2018	Skill Training/Engagement	Experiment: HMD VR compared to traditional box method for users to create and manipulate canine skeletons. HMD VR shown to increase user interest.
Military and Aerospace	Aerospace	Bucceroni et al., 2016	Safety/Skill Training	Users pilot a virtual unmanned aerial system (UAS) within a simulated environment that resembles a real-world location.
Military and Aerospace	Military	Champney et al., 2017	Skill Training	Experiment: Room-clearing task training conditions, ranging from high fidelity HMD VR to training video only, showed HMD VR may have faster skill acquisition.
Military and Aerospace	Military	Greunke and Sadagic, 2016	Skill Training/ Convenience/Interactivity	HMD VR systems were used to train Landing Signal Officers (LSOs), outside of formal training facilities (2H111), the skills necessary to help pilots land their aircraft safely.
Science and Tech	Agriculture	Thompson et al., 2018	Skill Training/Safety	360-degree video recordings from high-clearance applicator cabs during nitrogen fertilizer management were shown to users with HMD. Details for optimal recording of 360-degree video were mentioned.
Science and Tech	Architecture	Newton and Lowe, 2015	Skill Training	Used open-sourced software (Simulation Engine) to allow students perform various building construction tasks.
Science and Tech	Architecture	Sun et al., 2017	Skill Training	Proposal: "Bounded Adoption" strategy for HMD VR to learn skills such as component recognition, construction phases and adjusting traffic parameters.
Science and Tech	Astronomy	Tajiri and Setozaki, 2016	Interactivity/Skill Training	Experiment: Compared HMD VR to desktop computers for enhancing college students' understanding of position and direction of celestial bodies. HMD VR claimed to have extra capability.
Science and Tech	Astronomy	Rosenfield et al., 2018	Interactivity	A report on The America Astronomical Society's WorldWide Telescope (WWT) project, allowing astronomical images to be projected into planetariums and HMD VR.
Science and Tech	Chemistry	Lau et al., 2017	Skill Training/ Convenience/Safety	3D VR glasses were implemented to enhance students' abilities in a textile chemical coloring virtual environment.
Science and Tech	Computer Science	Liang et al., 2017	Interactivity	Experiment: Compared user's personal experience level between HMDs and monoscopic desktop-display-screens for VR puppet story; child-operated with hand-gesture controls. HMDs outperformed the monoscopic displays.
Science and Tech	Computer Science	Liarokapis et al., 2002; Stigall and Sharma, 2017; Wang, 2017	Skill Training/Highlighting	HMD AR was used to create training markers and provide" gamification strategies" in software development.
Science and Tech	Computer Science	Timcenko et al., 2017	Team Building	Experiment: Mediaology students used HMD VR to promote team collaboration in game design. When compared to no VR, no difference found in team building ability between users.
Science and Tech	Computer Science	Teranishi and Yamagishi, 2018	Interactivity/Skill Training	VR learning application that allows users to assemble personal computer hardware, with Leap Motion and HMD, with improved visual systems that reduced user eye fatigue.
Science and Tech	Computer Science	Hahn, 2018	Team Building	HMD VR (HTC Vive) was used for text browsing in a digital library, where both librarian and students users worked together.

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
Science and Tech	Education	Potkonjak et al., 2016; Akçayir and Akçayir, 2017	Various	Review: AR usage found to have increased in educational curricula and promotes enhanced learning achievement. VR of laboratories was noted to have increased capability and safety outside of real world.
Science and Tech	Education	Jensen and Konradsen, 2018	Various	Review: Performed a quality assessment and analysis on 21 experimental studies, featuring the use of immersive VR in education and training.
Science and Tech	Education	Yang et al., 2018	Skill Training	Experiment: HMD VR compared with paper-and-pencil condition to determine effect on student creativity, flow, attention and stress. VR condition showed greater quality, creativity, attention. VR environment allowed for 3D drawing and painting on a human model to create gear.
Science and Tech	Education	Dolgunsöz et al., 2018	Skill Training/Engagement	Experiment: VR Goggles were compared with two-dimensional video (about Chernobyl or Bear Habitat) to enhance EFL writing performance. VR was shown to possibly improve writing performance in the long term (1-month later) and be more engaging.
Science and Tech	Education	Tepe et al., 2018	Safety	VR Goggles, depicting a warehouse environment, allowed users to perform tasks in response to a fire.
Science and Tech	Education	Alfalah, 2018	Various	A report detailing institutional supports, motivations for adoption and teaching staff perceptions for the incorporation of VR into education curricula.
Science and Tech	Education	Makransky and Lilleholt, 2018	Engagement	Experiment: Crossover repeated-measures compared HMD VR (Samsung Gear) with desktop, depicting a laboratory simulation, to determine several factors, including user enjoyment and perceived learning. VR was found to be preferred over desktop for various reasons as detailed in report.
Science and Tech	Education	Murcia-Lopez and Steed, 2018	Interactivity	Experiment: Efficiency of bimanual 3D block puzzles was measured between HMD VR (Oculus) and physical assembly exercises. VR users showed results that were similar to physical assembly. VR performance was promising.
Science and Tech	Education	Al-Azawi and Shakkah, 2018	Suggestion	Report summarizes VR concepts in education, with the goal to motivate instructors to adopt its use in their teaching methods.
Science and Tech	Education	See et al., 2018	Convenience/Highlighting	Report summarizes VR concepts in massive open online course education, detailing potential obstacles, issues with adoption, practices and requirements.
Science and Tech	Education	Bryan et al., 2018	Engagement/Highlighting/ Skill Training	Report details gamification strategies with Google Maps. The objective is for users to find a country flag by answering questions about each location they encounter.
Science and Tech	Education	Misbhauddin, 2018	Engagement/Interactivity	Proposal: A VR framework to enhance learning experiences in classroom settings. Framework includes recording of lecture, visualization of instructor communication, user input for verbal note-taking.
Science and Tech	Education	Hickman and Akdere, 2017	Skill Training/Engagement/ Team Building	Proposal: Compare 360-video recorded images with computer generated avatars in HMD VR, desktop with HMD VR, high-cost and low-cost hardware, to determine student engagement and learning outcomes. Modules includes intercultural business exchanges, where user contributions affect project success.
Science and Tech	Education	Chin et al., 2017	Engagement	HMD VR (Google Cardboard) for education is briefly described and exemplified with SplashSim- users experience stages of the water cycle from the perspective of a water droplet.
Science and Tech	Education	Zaphiris and Ioannou, 2017	Skill Training	Book: Conference presentations of immersive VR systems for training in teacher education (bullying prevention).
Science and Tech	Education/Psychology	Hashimura et al., 2018	Interactivity	Experiment: Used HMD VR (Oculus) and motion controls to determine attention capacity (head, eye and hand movement) while under cognitive load (sort English words in VR space). VR showed possible ability to measure a user's cognitive load.
Science and Tech	Engineering—Civil	Wang et al., 2018	Skill Training	The construction of 3D building information models for quantity surveying practice in immersive VR were detailed in this report.
Science and Tech	Engineering—Civil/Driving	Veronez et al., 2018	Convenience/Safety/Skill Training	Driving setup (Oculus HMD and Logitech G27 Racing Wheel system) to enhance learning for road design. Users can test-drive their roads during development.

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
Science and Tech	Engineering—Civil/Driving	Likitweerawong and Palee, 2018	Safety/Skill Training	Immersive VR driving setup (Oculus) to provide users with basic driving lessons and rules before actual road-tests. User skill evaluated by completion of checkpoints on a virtual driving course including parking, speed and cornering.
Science and Tech	Engineering—Computer	Alhalabi, 2016	Skill Training	Experiment: Effectiveness of four different VR setups analyzed to determine student performance on engineering tests. All forms of VR found to improve performance. HMD VR with tracking shown to excel over CAVE, no-tracking HMD VR and no VR.
Science and Tech	Engineering—Computer	Akbulut et al., 2018	Skill Training	Experiment: MultiPeer Immersive VR compared with traditional teaching material to determine student performance on sorting algorithms.VR system showed an improvement on student test results over traditional methods.
Science and Tech	Engineering—Electrical	Liang and Xiaoming, 2013	Skill Training/Convenience	Students used VR workbench software to design analog and digital circuits, encouraging autonomous exploration.
Science and Tech	Engineering—General	Haefner et al., 2013	Various	Curricula: Recommendations on how to implement practical VR coursework in engineering education by encompassing skill development, interdisciplinary teamwork and time management training.
Science and Tech	Engineering—General	Ndez-Ferreira et al., 2017	Team Building/Suggestion	Virtual Mobility: The UbiCamp Experience is a 3D immersive virtual environment that allows groups of users to visit iconic buildings, monuments and universities, promoting cultural and language learning.
Science and Tech	Engineering—General	Lemley et al., 2018	Highlighting	Deep learning achieved by eye-tracking was tested by comparing a standard eye tracker with AR/VR eye-tracking datasets across high-res HMD VR and low-res smart devices.
Science and Tech	Engineering—General	Starkey et al., 2017	Skill Training	Experiment: Systematic disassembly of a product was performed across three interfaces (computer desktop, iPad, immersive VR). Student learning was found to be the same for each condition, yet immersive VR showed greater student satisfaction and perceived learning.
Science and Tech	Engineering—Mech	Muller et al., 2017	Skill Training/Interactivity	Immersive VR workshops were reported to allow mechanical engineering students to expedite the learning process by interacting with virtual workbenches.
Science and Tech	Engineering—Mech	Im et al., 2017	Skill Training/Engagement	Proposal: HMD VR (Oculus) and Leap Motion allowed users to disassemble and reassemble engines. Results showed high user interest, immersion, satisfaction, perceived learning and effectiveness.
Science and Tech	Engineering—Numerical Control	Hu and Wang, 2015	Skill Training	Proposal: Incorporating VR technology courses for environment shape design, animation, interactive functions and internet related content.
Science and Tech	Engineering—Pneumatic	dela Cruz and Mendoza, 2018	Convenience/Skill Training	HMD VR, depicting a lab environment, allowed users to operate pneumatic components.
Science and Tech	Forensics	Liu et al., 2017a	Skill Training	Proof of Concept: Details on the development of a crime scene simulation were provided, complete with virtual suspects who would run away if the user failed to maintain line of sight. The project aims to teach users how to prevent damaging crime scene evidence.
Science and Tech	Geology	Ables, 2017	Skill Training/Interactivity	Dynamic topographic data was digitally rendered onto a virtual 'sandbox,' showing different types of terrain within the virtual environment. Users were able to interact with the terrain.
Science and Tech	Industrial Plant Operation	Nazir et al., 2015	Skill Training/Safety	Experiment: Power Point was compared to immersive VR (stereoscopic glasses) for Distributed Situation Awareness (DSA) skill training for industrial plant operators. Immersive VR showed enhanced dynamic security assessment ability in students over PowerPoint method.
Science and Tech	Information Interfaces	Khuong et al., 2014	Highlighting	HMD VR assisted in constructing a block structure with one of two different highlighting guidance information systems: overlay and adjacent.
Science and Tech	Physics	Kozhevnikov et al., 2013	Skill Training	Experiment: HMD VR compared with non-immersive VR to determine which would enhance students' ability to solve two-dimensional relative motion problems. HMD VR performed better than non-immersive VR on solving 2D relative motion problems.

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TABLE 5 | Continued

Heading	Discipline	References	Purpose	Description
Science and Tech	Physics	Matsutomo et al., 2017	Highlighting	VR was used to show real-time graphics of magnetic fields between objects.
Science and Tech	Physics	Kuhn et al., 2015	Highlighting	Immersive VR (Google Glass) was used to determine water-level in a glass to achieve specific tones in physics (acoustics) education.
Various	Various	Dunbar et al., 2017	Highlighting/Safety	Visionless Interfacing Exploration Wearable (VIEW) substitutes the vision sense with wearable haptic feedback, assisting individuals with recognizing obstacles and avoiding walls when navigating a space.
Various	Various	Suh and Prophet, 2018	Various	Review: Determined the trends, theoretical foundations and research methods of immersive VR studies.
Various	Various	Zikky et al., 2018	Various	Report briefly mentions immersive VR programs for distance learning including social media, military skydiving, university campus, lab safety, chemistry and solar systems.
Various	Various	De Paolis et al., 2017	Various	Book: Conference presentations of immersive VR systems for training in industrial processes, tannery processes, motor fine skills rehabilitation, industrial heritage, collaboration, safety training, automotive mechanics and journalism.

et al., 2003; Freina and Ott, 2015). This same ethical principle may also explain the demand of immersive VR in other disciplines such as Dentistry, Nursing, Optometry, Paramedicine, Public Health, Rehabilitation, and Veterinary Education. The field of Health Science's main incentive to incorporate immersive VR is assumed to involve concepts of experiential learning, which allows users to learn by interacting with various environments affiliated with their disciplines. Experiential learning principles may explain the demand of immersive VR for the majority of disciplines in Science and Technology as well as Arts and Humanities. The increase of physical accessibility to environments that are not normally accessible would apply toward disciplines such as Astronomy, while VR's ability to overcome dangerous situations would apply to fields such as Military and Aerospace. Some universities (Maryland University College) are acting to ensure they remain on the technological "cutting edge," allowing students to learn by creating content (Becker et al., 2017).

Objective 2—Favorable Outcomes From the use of Immersive VR

Thirty eight experiments were found in the 119 reports, mostly comparing immersive VR (HMD) with one of the following non-immersive platforms: desktop display screen, 2D video, mobile phone, digital tablet or stereoscopic desktop display screen. Non-VR comparators included live actors, real-world analogs, "traditional methods," pencil-and-paper or nothing as a control. Of these 38 experiments, 35 reported to have found a positive outcome favoring the use of immersive VR with: 13 showing an increase in user skill or knowledge, 10 showing an increase in user engagement or enjoyment, 8 stating immersive VR had some form of extra capability over traditional methods, and 4 stating both an increase in user skill and engagement.

When favorable outcomes were noted from the reports, only experimental processes were considered, since the absence of a comparator, be that either some form of established non-immersive VR or traditional method, may weaken quality inferences to be made. This review reported only the outcomes from reports that had such comparators in their study design and found that 35 out of the 38 experimental outcomes were positive, showing mainly an increase in user skill, knowledge, engagement, and enjoyment. Some reports found immersive VR to have additional capability over those of traditional methods, such as the ability for users to train on an avatar that was diagnosed with a rare disease, which could not be replicated on a traditional model. Immersive VR should not render traditional methods obsolete, such as pencil-and-paper tests, since those methods are already well-established and free from potential simulator sickness.

This review did not assess the quality of each study's experimental design as found throughout the literature, however a review conducted by Jensen and Konradsen (2018) reported the quality assessment of 21 HMD VR experiments, showing a "below average quality" as outlined by the *Medical Education Research Study Quality Instrument*. Jensen and Konradsen identified in 2018 a number of setups where HMD VR is useful for skill training including the training of cognitive skills related to spatial and visual knowledge, psychomotor skills related to head-movement, visual scanning, observational skills, and affective control of emotional response to stressful or difficult situations. Future quality assessments of HMD VR experimentation are warranted as optimal setups in learning and skill training contexts are found, along with continuous improvements to VR hardware and software.

Objective 3—Conceptual Rationale of Immersive VR in Post-secondary Education

This review aimed to understand the literature's reasoning for implementing immersive VR, with the use of a conceptual method to determine each system's rationale. This method, based on keywords found in each report's title, index terms, and abstract, allowed for identification of immersive VR's purpose to further understand its role in each context. The majority of reports had the intention of using immersive VR for the purpose of skill training, followed by the optimization of interactivity between users and objects within the virtual world. Highlighting of objects in both the virtual or real world were other reasons for the implementation of immersive VR, especially when visual markers were provided to users in the form of AR. The use of immersive VR for the purposes of engagement, safety, convenience, team building, and suggestion were also found. These purposes might be able to justify the reasoning of immersive VR in higher education, despite the literature rarely showing pedagogical rationales for its use (Savin-Baden et al., 2010).

Regardless of the sophistication of a virtual system's hardware, the rationale of each report affected how a virtual environment was designed, implemented, and presented in the literature. A conceptual pattern of rationale was found, detailing the purpose of each instance of immersive VR's implementation. Each simulation's goal included one or more of the following purposes: skill training, convenience, engagement, safety, highlighting, interactivity, team building, and suggestion.

Skill Training

This purpose resulted in a virtual environment that focused on the development of knowledge and enhancement of a user's competency in a specific task. An example of this purpose includes the military training room-clearing tasks as reported by Champney et al. (2017). Note that it is possible for the skill training to involve teacher-to-student interaction, such as the virtual environment as outlined in the gesture-operated astronomical virtual space as reported by Tajiri and Setozaki (2016).

Convenience

These virtual environments focused on reducing the difficulties and/or resources required to train the same task in the real world. This purpose included factors such as time, location, and cost. An example of immersive VR being used, with a purpose focused on cost convenience, would be the low cost surgical training system a reported by Mathur (2015). For location convenience, this would feature a VR system designed to either allow multiple users to interact with one another, despite being in different geographic locations, or provide a portable system that allows training for a user at any convenient location. An example of immersive VR being used with a location convenience purpose would be the therapist-to-patient training VR system as reported by Wen et al. (2014). Liang and Xiaoming's report in 2013 discussed the concept of a "self-simulation laboratory," used to reduce workspace requirements- a concept that expands on location convenience by featuring a multitude of different electronic engineering equipment that can be experienced within a single space. An immersive VR system that focused on time convenience would expand the windows of opportunities available to beyond what a user is normally allowed. Real-world time constraints that restricted a student's hours of lab availability, plus the preparation and clean-up time required, could be circumvented with VR simulation (Lau et al., 2017).

Engagement

This purpose focused on the implementation of virtual environments that encouraged a user's desire to learn the presented material found in the simulation. This purpose included the use of virtual environments that gained a user's interest, yet expanded further by including VR features such as interaction, immersion, and imagination. Purposes of engagement allowed a user to feel involved in the learning process, usually by being offered challenges or interactive elements within the educational virtual environment. An example of immersive VR being designed with a purpose focused on engagement would be the Jaunt VR video program study, which featured scenic views of Nepal, as reported by Lee et al. (2017).

Safety

A virtual environment that focused on safety may have included some or all of the following: (a) The practice of awareness skills necessary to reduce the probability of accidents occurring, (b) The practice of technical or non-technical skills necessary to handle an abnormal operating condition, (c) The ability to interact with virtual objects that would be deemed too dangerous in the real world. Some virtual environments were mentioned to have been programmed to allow for damage to occur within the virtual world, allowing users to safely learn from mistakes that would normally cause real-world machinery to collapse or cause personal injury (Potkonjak et al., 2016). Dangerous motors and gearboxes in mechanical devices were reported to be exposed in the virtual world, allowing users to see working parts in action (Potkonjak et al., 2016). Taljaard stated in 2016 that virtual field trips allow users to visit simulated places, which could be inaccessible or dangerous. For example, geologists could experience a VR field trip that takes place on the top of a volcano (Taljaard, 2016). An example of immersive VR being implemented with a purpose focused on safety would be the Distributed Situation Awareness study, featuring safety awareness training in industrial plant operators, reported by Nazir et al. (2015). Another example would be the virtual environment Jouriles and colleagues presented in 2016, which was used to measure bystander behavior in response to sexual violence.

Highlighting

This purpose focused on virtual environments that emphasized key elements and variables of objects, supplementing users with additional information. Highlighting was inclusive but not limited to AR. It was also capable of providing quantitative feedback to users, based on their performance on specific tasks within the virtual world. An example of immersive VR being implemented, with a purpose focused on highlighting, would be the software editing training markers as reported by Stigall and Sharma (2017). Another example of highlighting, featuring the use of AR, would be the use of Google Glass in art galleries to provide the user with supplementary information, reported by Leue et al. (2015).

Interactivity

Although interaction is the core emphasis for many immersive VR systems, a simulation with interactivity as the main purpose would attempt to make the virtual environment feel as natural as possible. Interactivity also focused on optimizing the user control, arranging the system to respond to user input information both quickly and accurately, granting users a sense of real human-computer interaction (Liang and Xiaoming, 2013). When computer engineers reported an attempt to optimize user control by reducing latency, increasing computer processing speed or improving motion tracking; the main purpose focused on interactivity from a hardware perspective. An increase in interactivity from a software perspective would be accomplished by programming the virtual object to respond appropriately to multiple forms of user input or by increasing user-friendliness. Purposes of interactivity may have included virtual environments that were designed to feature optimal accessibility, such as the virtual multiplayer child-operated puppet story as presented by Liang et al. (2017).

Team Building

A virtual environment that focused on team building may have included some or all of the following: (a) The practice of technical and/or non-technical skills in groups of trainees so that they achieve proficiency in a skill before the real procedure is performed (Rudarakanchana et al., 2015), (b) The promotion of team collaboration during production and planning. An example of immersive VR being implemented with purpose focused on team building would be the team collaboration in game design curriculum as reported by Timcenko et al. (2017).

Suggestion

This purpose was focused on the use of immersive VR to improve a user's attitude toward a community, cultural movement or service. Immersive VR was reported to be capable of stimulating enthusiasm within the learning of students, changing the way they think about certain perspectives (Hui-Zhen and Zong-Fa, 2013). An example of immersive VR being implemented, with a purpose focused on suggestion, would be Real et al. (2017a) study on best-practice communication skills, encouraging patients to receive vaccinations. Another example featuring the use of immersive VR to discourage specific behavior, would be the cue reactivity study as reported by Gupta and Chadha (2015), aimed at discouraging cigarette smoking for users with an addiction problem.

Suh and Prophet (2018) reported a classification of research themes and contexts for immersive VR by using the stimulus-organism-response (S-O-R) framework, where the variables of their found 54 studies were classified to determine relationships. Several factors were found to be related between immersive VR's system features and sensory, perceptual and content stimuli (Suh and Prophet, 2018). Content stimuli included immersive VR topics such as learning and training, psycho- and physiotherapy, virtual tours, interactive simulation, and gaming stimuli (Suh and Prophet, 2018). The 119 reports as identified from the literature in this review is relatable to Suh and Prophet's (2018) reported classification system, especially for the topics identified as content stimuli.

Objective 4—Theories and Recommendations for Incorporating Immersive VR Into Post-secondary Education

This review found two papers recommending a social constructivist approach for how immersive VR could be incorporated into post-secondary education curricula (Haefner et al., 2013; Cochrane, 2016). Social constructivist approaches include proposals on how student-created virtual environments are mainly led by the students themselves, using a team collaborative style. Experiential learning allows the students to use their newly created virtual environments to role-play their actions in simulated scenarios, aiming to achieve mastery over their discipline. This is reminiscent of Gonzalez-Franco and Lanier's (2017) idea on the student acting as "the center of the system," providing the computer-generated virtual environment triggers the user's learning response as though the virtual stimuli matches that of the real world. The training of student awareness for paramedic clinical practice by using VR 360-degree interactive images, projected by HMD (smartphone), allows for the facilitation of student-created content in authentic simulation (Cochrane et al., 2017). Although Cochrane's recommendations were exemplified in design thinking, journalism, and paramedicine; the method's potential transferability seemed convincingly capable of being used in other disciplines within the fields of Arts and Humanities or Health Sciences. The theory of implementing a virtual event that makes the user feel central to the environment, resulting in an authentic illusion, is a key feature that must be retained when adapting VR learning frameworks from one discipline to another. Haefner and colleagues' recommendations (2013), which mentioned interdisciplinary teamwork, also possessed convincing transferability beyond just the discipline of Engineering. A future study that focuses on a curriculum that is feasible and vastly adaptable to most disciplines would be a definite recommendation for future research. **Table 6** summarizes the educational theories associated with the use of immersive VR.

DISCUSSION

This review focused on how immersive VR was used in post-secondary level education and skill training, determining if any new educational perspectives have emerged, with the goal of obtaining an improved understanding of the state of the art as found from the literature. The most important considerations when conducting this method of literature search included: (a) attaining an unbiased selection of papers for review, (b) accepting only the literature that stated the use of fully immersive VR (HMD hardware or similar), (c) limiting the literature by date of publication to no earlier than March of 2013.

TABLE 6 | Summary of educational theories associated with immersive Virtual Reality.

Theory	Description	References
Cognitive Load Theory	Learning and instruction that optimizes the amount of cognitive load a user experiences within the capacity of working memory. Immersive VR features multiple modes of information that is simultaneously processed by multiple sensory modalities including sounds, images, texts, tactile cues.	Paas et al., 2016; Liu et al., 2017b
Conceptual Blending Theory	Recommends AR users to move "fluidly" between the physical and virtual world. This creates a conceptual blend as users layer multiple, distinct "conceptual spaces," or different "source domains," which enhances learning.	Enyedy et al., 2015
Constructivist Learning Theory	Assumes that knowledge development occurs best through the building of "artifacts" (physical or digital), which can be experienced and shared. Constructivist strategies in VR are effective, because they empower learners to author their own scenarios in which they have an emotional investment.	Papert and Harel, 1991; Liu et al., 2017b
Flow Theory	A positive experience associated with immersive VR leads to optimal learning states induced by intrinsic motivation, well-defined goals, appropriate levels of challenge and feedback.	Csikszentmihalyi, 1990; Liu et al., 2017b
Generative Learning Theory	Practice of learning information by transforming it into usable form by selecting (spending attention on relevant information), organizing (arranging information into coherent structure), and integrating (connecting verbal/image representations with each other and with prior knowledge from long-term memory).	Parong and Mayer, 2018
Interest Theory	Users learn better when they perceive value in the learning material, either intrinsically (individual interest) or as elicited by the situation (situational interest).	Wigfield et al., 2016; Parong and Mayer, 2018
Jefferies Simulation Theory	The development process of simulations includes context, background and design characteristics, resulting in dynamic interactions between the facilitator and learner through the use of appropriate educational strategies.	Jeffries and Jeffries, 2012; Aebersold, 2018
Kolb's Experiential Learning Theory	A four step theory (concrete experience, reflective observation, abstract conceptualization and active experimentation) that form a continuous cycle- reminiscent as users experience immersive VR.	Kolb, 1984; Aebersold, 2018
Motivation Theory	VR learning may enhance user focus, due to an increase in engagement, resulting in further investment of energy to allocate cognitive resources during difficult parts of the lesson.	Parong and Mayer, 2018
Presence Theory	Based on the following immersions: *Actional*—VR empowers users to experience new capabilities as actions are performed with novel/intriguing consequences, *Symbolic/Narrative*—Users learn semantic associations from content of experience, *Sensory*—Immersive VR's ability to encourage a user to imagine being in a different actual location, *Social*—Interactions among other users (or perhaps artificially intelligent avatars) deepens sense of being part of the setting.	Dede, 2009; Liu et al., 2017b
Situated Learning	Virtual environments allow users to interact with objects and apply them within the setting itself, fostering tacit skills through experience and modeling.	Liu et al., 2017b
Stimuli—Organism—Response	The stimuli found in virtual environments affect both a user's cognitive and affective states, which in turn leads to behavioral changes (technology adoption behavior).	Mehrabian and Russell, 1974; Suh and Prophet, 2018
Control Value Theory of Achievement Emotions (CVTAE)	Learning can be facilitated through positive achievement emotions, such as enjoyment, especially when instructional design elicits and promotes appraisal of student autonomy and intrinsic value.	Pekrun, 2016; Makransky and Lilleholt, 2018

Curricular Recommendations

Immersive VR programs could be incorporated into an academic curriculum as either a full-course program or as supplementary material to an already-existing course. Immersive VR for supplementing a large classroom size would possibly be best performed by finding relevant software, in the form of 360-panormic images or videos for mobile phones, depicting environments that resemble lecture materials for users to experience. For example, students of surgical or nursing education could experience 360-operative video, similar to the one used in Harrington and colleagues' surgical study in 2018. Supplementing a small classroom size would possibly allow for relevant software to be experienced on an immersive HMD VR consumer model, similar to the cardiac anatomy setup (Sharecare VR) in Maresky and colleagues study in 2018.

For full-course programs that may attempt to integrate immersive VR, Alfalah (2018) reported the following:

- Faculty members should be prepared to allocate time for training in the development of software and utilization of immersive VR hardware.
- Detail a realistic and practical plan for the transformation or creation of the course.
- Increase the awareness to faculty members about the technology integration via staff emails, learning management systems, seminars, and posters.
- Consider administrative support to reduce faculty member load.
- Enable collaboration between faculty members to share ideas for enhancing the system.

Full-course programs that prefer to feature student-developed immersive VR programs could either be: *Simple*—Videos adapted into 360-degree format for mobile phone VR by using GoPro cameras with their videos merged into a single equirectangular video by Kolor Video Pro and Giga software (Harrington et al., 2018), or *Advanced*—Software creation as an immersive VR program for consumer based HMDs, developed by a graphics rendering engine (Timcenko et al., 2017). It is possible for an immersive VR program to be programmed so that it can switch between HMD VR and desktop PC controls, which would allow for users who are sensitive to simulator sickness to have access to a non-immersive alternative. The option to add platform crossover versatility to software would be expected to require more development time.

Cochrane in 2016 summarized a post-secondary educational framework that allowed students to devise and submit their own VR content in order to learn and classify AR projects, featuring disciplines including journalism, paramedicine, and graphic design. For example, paramedicine would feature students using immersive VR (mobile) to conduct pre-practice of a critical care scenario before they entered a simulation room where they performed resuscitation procedures (Cochrane, 2016). Cochrane in 2016 and 2017 summarized six informing pedagogies and their definitions for the application of mobile VR in education: Rhizomatic Learning—"Negotiated ecology of resources," Social Constructivism—"Collaboration tools for project planning (e.g., Google Docs)," Heutagogy—"Student-generated content: 360 degree camera rig and stitching software," Authentic learning: situated content—"Shared 360 video (e.g., YouTube 360 via HMD and Google Cardboard), Authentic learning: situated context—"360 degree immersive environment simulation," Connectivism—"Community Hub (e.g., Google Plus, Facebook, and Twitter)."

The key requirements of a successful practical VR course in interdisciplinary engineering education were found to be as follows: (a) primary emphasis on VR task design while maintaining student creative freedom, (b) clearly defined tasks for each individual group member's role, (c) the use of software platforms that were open source with strong community followings (Haefner et al., 2013). Based on the student group configuration and information from instructor-to-student collaboration, the students were recommended to define each individual group member's role in accordance to their knowledge and interests. In smaller groups, status meetings of the project's development were expected to be easier to organize and yield qualitative, well-structured project results (Haefner et al., 2013). Larger groups that consisted of more than 10 students would require a project manager (student designated) who is proficient in handling conflict management, with less emphasis on sub-task support (Haefner et al., 2013). It was important for the students to provide continuous progress updates, within the status meetings, so that any issues regarding design of the VR project are detected early (Haefner et al., 2013).

Considerations of Virtual System Design

The purpose of a virtual environment will determine how it is designed and implemented. A post-secondary educational virtual environment can be divided into two types: an environment that represents the real world (e.g., historical location) and/or a computer generated 3D object (e.g., interactive control panel; Lee and Wong, 2008). Depending on whether or not the system is designed to be portable and the amount of interaction a user needs to have with the virtual environment will determine its varying HMD hardware and input devices. If the user is expected to interact with the virtual environment and perform actions that are meant to accurately represent those that would be performed in real life; the input hardware is expected to maximize fidelity (e.g., a haptic arm that provides force feedback during surgical simulation). Likewise, if the user is not expected to interact with the virtual environment or the user's actions do not have to accurately represent those that would be performed in real life; the input hardware can be of low fidelity (e.g., using a gamepad to move within the virtual environment instead of walking).

Although low fidelity simulation may initially seem less useful than high fidelity, low fidelity virtual environments are associated with lower hardware costs and allow for acquiring "procedural knowledge" at the expense of "higher-order skills and strategic knowledge (Champney et al., 2017)." It is important to note that high fidelity virtual environments are associated with greater hardware costs and may "overwhelm and distract early procedural learning" (Champney et al., 2017). An example of public-speaking skill development, featuring low amounts of user interaction, would be a virtual environment depicting a large crowd, where the user is tasked with standing on stage to be exposed to this social anxiety stimulus. The use of exposure therapy in VR simulation in this manner would be designed to habituate a user's fear thought-process into a more adapted one, removing the pathological kind that distorts reality and increases escapist tendencies (Bissonnette et al., 2016).

It should be noted that a user's level of technical proficiency should be factored into how virtual objects are intended to be interacted with. A user with a university background in mechanical engineering would most likely have no trouble utilizing complex button-operated input controllers to interact with a virtual object (e.g., Virtual Workshop as reported by Muller et al. (2017). Likewise, a user who is inexperienced with technical hardware would likely benefit with a simpler input device to interact with virtual objects [e.g., Liang et al. (2017) child-operated virtual puppet story with gesture control, detected by Leap Motion].

Limitations of This Review

Limiting the literature search to March of 2013 and onward allowed this review to focus on a specific point when educational perspectives were formed at a time when immersive VR's rate of availability was greater than before. This date limit, however, may have come at a cost as some papers not included may have discussed educational perspectives, formed prior to this date, which may still be in use. By accepting only the literature featuring the use of immersive VR, this review was able to determine educational perspectives that were potentially and optimally invoked by concepts such as experiential learning, immersion, interactivity, and imagination. This consideration also allowed this review to find positive outcomes determined by the literature when immersive VR was compared with non-immersive VR. This review focused on immersive VR's performance in post-secondary educational settings, containing interpretations that may not be adequate for less advanced levels of education. Further defined subtypes of post-secondary education terms, such as Masters or Bachelor, were not used in this review's search method, which may have impacted the ability to find all applicable literature.

Conclusion

This review on the use of immersive VR in post-secondary education and skill training has revealed recommendations and purposes for how it could be implemented into curricula. Common positive outcomes, featuring the use of immersive VR, have shown to promote student engagement and skill acquisition.

Immersive VR brings convenient, engaging and interactive alternatives to traditional classroom settings as well as offers additional capability over traditional methods. This review has highlighted detailed reports that have successfully implemented immersive VR into their curricula. There is a diverse assortment of educational disciplines that have each attempted to harness the power of this technological medium. It is expected for immersive VR to become further adopted into academic settings in the future. Will your facility be the next to implement immersive VR?

AUTHOR CONTRIBUTIONS

BC, SE, and MR co-conceptualized the review study. BC completed the literature search and analysis in consultation with and guidance from MR. BC led the manuscript writing process. SE and MR contributed to the writing process and revisions. All authors approved the final version.

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METHODS
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The MARquette Visualization Lab (MARVL): An Immersive Virtual Environment for Research, Teaching and Collaboration

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The MARquette Visualization Lab (MARVL) is a large-scale immersive virtual environment for research, teaching, collaboration and outreach at our mid-sized liberal arts university. MARVL consists of multiple display surfaces including an extra wide front wall and floor, and two side walls. This resource includes stereoscopic viewing, motion tracking and space for a large audience. MARVL's versatile configuration facilitates viewing of content by 30 people, while also projecting on the entire width of the floor. This feature uniquely facilitates comparative or separate content visible simultaneously via "split mode" operation (two 3-sided environments), as well as detailed motion for applications such as gait analysis and performing arts. Since establishing the lab, its members have received numerous queries and requests pertaining to how system attributes and applications were determined, suggesting these and related decisions remain a challenge nearly three decades since the first CAVE was constructed. This paper provides an overview of MARVL including the processes used in identifying a diverse group of cross campus users, understanding their collective vision for potential use, and synthesizing this information to create the resource described above. The subsequent design, qualitative and quantitative approaches to vendor selection, and software decisions are then discussed. Steps implemented for dealing with simulator sickness and latency are presented along with current approaches being implemented for project development with end users. Finally, we present results from the use of MARVL by several end users identified in the early planning stage, and recent upgrades to the system.

Keywords: immersive visualization, virtual reality, augmented reality, mixed reality, simulation, student-centered learning

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INTRODUCTION

Research suggests immersive experiences that allow for motion in a realistic environment promote active learning, critical thinking, informed decision making and improved performance (Patel et al., 2006). For example, a diver is more likely to recall specific instruction when it is learned and practiced in water rather than on land (Baddeley, 1993). This was the motivation to establish the

MARquette Visualization Lab (MARVL), a facility designed to be used by interested members of our community to (1) create technologically advantageous visualization content, (2) demonstrate how visualization technology can be used in learning, research, and industry, and (3) ultimately teach the theory rooted in this technology.

Since establishing MARVL, its members have received numerous requests pertaining to how system attributes and applications were determined. The allure of immersive systems, especially with a resurgence of virtual and augmented reality devices, is prompting interest from potential end users across disciplines, some without prior experience of important hardware and software and considerations. In the current work we provide an overview of MARVL including the processes used in identifying a diverse group of users, understand their collective vision for potential use, and synthesize this information to create a unique resource that differentiates our institution with a particularly strong background in education among immersive facilities locally. The subsequent design, qualitative and quantitative approaches to vendor selection, and software decisions are then discussed. We then present lessons learned during early operation of our large-scale immersive visualization (IVE) system and results of its use by several end users identified in the early planning stages. Finally, we discuss ongoing costs and recent upgrades implemented within MARVL.

MATERIALS AND METHODS

During the planning process, members of the Marquette University community generally listed in **Table 1** were identified from responses to an email sent to department chairs throughout the university. Meetings were then held over several months with interested staff and faculty members of all academic ranks regarding their potential use of a visualization facility. Some of these individuals were intrigued but did not have a specific application in mind. However, most potential end users shared extensive visions with specific objectives geared toward research and teaching, as well as industry collaboration and outreach. Perhaps not surprisingly for our educational institution, several potential end users envisioned using the forthcoming facility in their classes to better help students understand and realize the complexity within or systems or scenarios. While discussing the vision of each end user, members of MARVL were particularly careful to help potential end users, when needed, to identify unique ways of achieving a proposed vision in a manner that takes advantage of stereoscopic viewing and could not be conducted using a desktop computer, large monitor or standard projection system.

Several potential large-scale IVEs were discussed upon learning of each end user's application and intended use. Approaches discussed generally included a projection-based cylindrical or dome structure, a 4-6 walled CAVE-type (CAVE Automatic Virtual Environment) system (Plato, 1974; Cruz-Neira et al., 1992), or a large-scale panel-based system with narrow bezels (Febretti et al., 2013). **Table 1** indicates that several of our end users focused on applications involving rooms as structures that would be stationary with right angles (e.g., civil engineering, nursing, theater). While a curved system would not preclude the viewing of such structures, a CAVE intrinsically lends itself to these applications without inhibiting use by other applications. Although exceptional systems have recently been created using panels with ultra-small bezels that are attractive for a number of reasons, our end users were unanimous in their dislike for this approach. Most of these end users were too distracted by the bezels despite their modest dimensions. End users also identified collaboration via a shared visualization experience as paramount, which dampened enthusiasm for a series of tethered head-mounted displays in communication with one another. This feedback by potential users of MARVL suggested that a CAVE-type environment would be beneficial and most favorable to the greatest number of users. CAVE systems consist of between three and six walls of a room onto which a specific environment is projected and adapted through the movements of one or more users within it. Five vendors capable of providing CAVE-type solutions were contacted regarding the attributes for the MARVL system identified by its potential users as discussed in greater detail below.

Components of the Visualization System

Visualization systems generally contain the four components:

(1) Structure, projectors and screens - structural elements such as modular framing, vertical and floor projection surfaces, glasses with emitters for creating a 3D experience, stereoscopic 3D projectors and cabling
(2) Image generators (i.e., computers) - a series of computers containing high-end, but not necessarily specialized, components and synchronization electronics used to control content viewed in the large-scale immersive environment
(3) Visualization software - Commercial or open-source software, sometimes specialized for a particular application, that facilitates viewing of content in stereoscopic 3D
(4) Tracking system - cameras and associated interaction devices that allow the system to know the users precise position in space, and adapt the rendered content being viewed based on the user's perspective and actions

Desired Attributes Expressed by End Users

As alluded to above, potential users of MARVL from Engineering, Arts and Sciences, Health Sciences and Nursing made it clear that a CAVE-type environment would be beneficial to the greatest number of users. Moreover, responses during the planning stage suggested a system of limited size could actually preclude investigators with more established visions from using the facility (e.g., performing arts, gait analysis). There are flexible systems available from several vendors that feature a reconfigurable visual environment with the ability to move or open screens on the side walls of a CAVE. This option can provide a large front display configuration that was desirable to many potential users at our institution. The benefits afforded by this option may be offset by

TABLE 1 | Potential end users identified during the planning stages of MARVL.

End user's department	College	Application
Biomedical Engineering	**Engineering**	**Linking neural activity to function and behavior**
Construction Engineering and Management	**Engineering**	**virtual walkthroughs of buildings and research productivity improvement**
Civil and Environmental Engineering	**Engineering**	**3D imaging of civil infrastructure, naval training, historical sites, etc**
Biological Sciences	**Arts and Sciences**	**co-localization of structure and function**
Biomedical Engineering	**Engineering**	**Next generation gait analysis**
Mathematics, Statistics and Computer Science	**Arts and Sciences**	**Discrete event simulation, assembly, clearance and tolerance stacking**
Clinical Laboratory Science	Health Sciences	Extracting additional data from flow cytometry results using visual analytics
Civil and Environmental Engineering	**Engineering**	**project scheduling and cost estimation**
N/A	**Nursing**	**Improved nurse training using realistic clinical environments**
Biomedical Engineering	**Engineering**	**Correlating local blood flow alterations with markers of disease**
Performing Arts	**Communication**	**Optimizing stage lighting and *a priori* review of sets by directors**
Strategic Communication	Communication	Electronic media, design and user experience
Physical Therapy	**Health Sciences**	**Viewing of medical imaging data**
Biological Sciences	**Arts and Sciences**	**protein structure, electron density maps**
Biological Sciences	Arts and Sciences	Structure and motion of cilia and flagella

The applications in bold have gone on to be implemented in MARVL since its creation.

alignment issues and the chance for failure of mechanical parts inherent in an articulating structure. Anecdotal feedback from centers that had employed this approach indicated that changes to the configuration were infrequent, for many of these reasons. Members of the MARVL therefore decided the system would consists of an extra wide front wall and floor, with standard-sized side walls. These attributes were selected for a number of important reasons:

1. An IVE with an extra wide front wall facilitates viewing of content by a large audience, while also projecting on the entire width of the floor. In contrast, a flexible IVE in the open position only has a portion of the floor projected.
2. An extra wide IVE also permits rendering of multiple environments. For example, a comparison between two building attributes could be rendered side by side to evaluate preferences, or a realistic Intensive Care Unit, for example, containing beds for two simulated patient scenarios with a curtain between them could be rendered with application to nursing education.
3. An extra wide IVE further permits detailed motion within the environment for applications such as gait analysis and/or performing arts.
4. In contrast to a standard cubic IVE, there are relatively fewer CAVEs with an extra wide front wall and floor (Kageyama and Tomiyama, 2016), therefore differentiating the MARVL facility from other IVEs locally and around the country.
5. An extra wide IVE avoids potential issues associated with keeping articulating parts aligned.

Proposed Vendor Solutions and Onsite Demonstrations

After contacting representatives from five vendors, faculty members in the Opus College of Engineering for which the IVE was to be purchased and housed sought bids from two vendors willing to offer quotes for a system with attributes discussed in the previous section (denoted here as Vendor A and Vendor B to limit commercialism). While every attempt was made to obtain similar quotes, differences did exist due to vendor preferences, technical capabilities and component availability. **Figure 1** provides a schematic illustration of systems proposed by the two vendors that address their interpretation of design requirements articulated by the collection of end users. **Table 2** provides an at-a-glance comparison of the initial quotes from each vendor.

Given the similarities in quotes between vendors, each vendor was asked to offer a demonstration (i.e., demo) at our institution. Potential end users throughout campus were invited by email to attend these demos, which were scheduled at equivalent times on back-to-back days. Attendees were noted and a questionnaire was then emailed directly to each potential user to obtain his or her impressions from each demo. Care was taken to keep attributes consistent between vendors during demos. Each vendor was provided with electronic files of the same content for demonstration before arriving to campus. Vendors arrived one day before their demo to setup associated equipment and troubleshoot potential issues. Demos did not include the full systems described in the accompanying quotes from each vendor, since each system is custom and can only be fabricated once ordered. However, the demos did include the primary components that impact perceived image quality. These components primarily include the projectors and screen material specified by the vendor, which were setup in an interior room with no windows to control ambient light. The demos from each vendor therefore used two projectors of their specified model that were partially blended on equivalently-sized screens as shown in **Figure 2**. The screen used during the demo also matched the screen material specified by both vendors.

In addition to qualitative feedback, contrast and uniformity was quantified across the projected surface demonstrated by each vendor. Specifically, a professional photographer employed

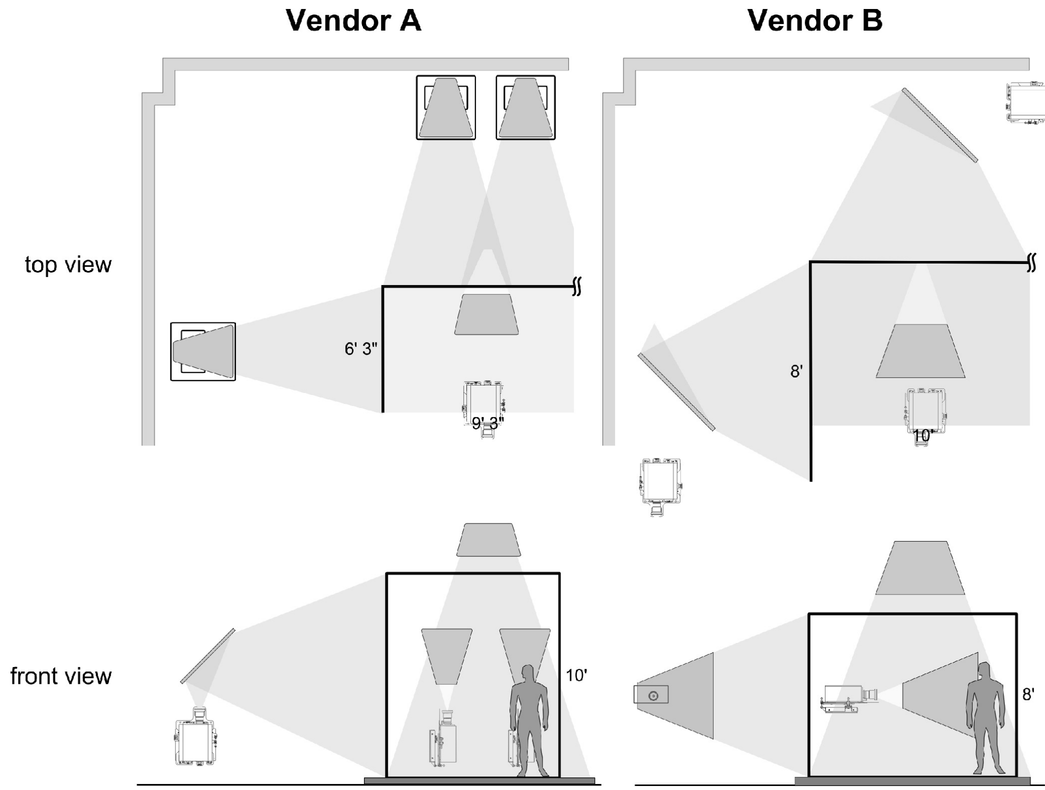

FIGURE 1 | Schematic illustrations of systems proposed by two vendors that address design requirements articulated by the collection of end users. The figure illustrates the differences in vendor designs by examining the projector arrangement on the left side of the visualization space. The right side of the spaces proposed is a mirror image of those shown on the left side. Both designs use projectors that project a 16:10 widescreen image, but Vendor A initially suggested using more projectors and arranging them vertically, which makes the projected area taller but less deep.

by our institution obtained digital images of a checkerboard test pattern that was displayed and photographed before the start of each vendor demo. Images were taken after vendors had acknowledged that they optimized the combination of screen and projectors to the best of their ability within the allotted time. The time allotted for setup was consistent between vendors. Care was taken to ensure that the exposure settings on the camera were consistent when obtaining photographs. The test image used for the demos is shown in **Figure 3** (top) along with the intensity profile generated from a horizontal query of 8-bit grayscale values through the indicated portion of the image (bottom) using the Plot Profile function within ImageJ[1]. This represents the ideal (i.e., best case) output from photographs of this image as projected during each demo. The photographs obtained from each demo were similarly analyzed offline with ImageJ to quantify contrast and uniformity between white and black levels across the projected surface demonstrated by each vendor.

Image Generators

As mentioned above, image generators used to display content in an IVE consist of high-end, but not necessarily specialized, components. Quotations were therefore obtained from two preferred vendors of our institution. This approach minimized costs and additional markup that would be passed along to our institution if image generators were obtained from either vendor. Both vendors accommodated our request to keep costs down via this approach. There are several ways the image generators could be configured. The configuration discussed in the results section was recommended by technical staff within our institution to deliver solid performance while also managing cost.

Visualization Software

The software expected to be used within the large-scale MARVL IVE based on end users identified during planning is listed in **Table 3**, along with the application, associated details and approximate cost at the time of system construction. Where possible, open source and trial licenses (coupled with software vendor demos) were to be implemented to keep costs down and ensure we purchase software solutions that are most appropriate for a wide range of users. Open source solutions were recommended based on extensive discussions with leading visualization researchers around the country and focused on those with a large base of users and available documentation.

[1] https://imagej.nih.gov/ij/

TABLE 2 | At-a-glance comparison of vendor system specifications from their initial quotations.

Items	Attribute	Vendor A	Vendor B	Differences
1	Size of viewable surface (width × height × depth)	18′5 1/4″ × 10′0″ × 6′3″	20′0″ × 8′0″ × 8′0″	Vendor A: 2 feet higher Vendor B: 1.5 feet wider and ∼2 feet deeper
2	Pixels of viewable surface (width × height × depth)	3,556 × 1,920 × 1,200	3,000 × 1,200 × 1,200	Vendor A: 556 (19%) more front wall pixels and 720 (60%) more height pixels
3	Footprint (width × height × depth)	40′2 1/4″ × 12′9 3/4″ × 17′5 7/8″	36′9 3/16″ × 11′9 1/16″ × ∼17′5 7/8″	Vendor A: footprint is ∼3 feet wider
4	Projector specifications	WUXGA 3-chip DLP - 6,300 lumens	WUXGA 3-chip DLP - 7,000 lumens	Vendor B: 700 lumens brighter, contrast was equivalent
5	Number of projectors	8: 4 front, 2 floor, 1/side	6: 2 front, 2 floor, 1/side	Vendor A: 2 extra front projectors
6	Screen Material	Stewart Filmscreen AeroView 70	Stewart Filmscreen AeroView 70	none
7	Tracking System	6 camera ART system with controller and interaction device	6 camera ART system with controller and interaction device	none
8	Standard Warranty	Projectors: 3 years parts and labor 3rd party equip: 1 year Return to Factory	1 year warranty with parts coverage	Vendor A: additional 2 years on projectors
9	Approx. Cost	$670,000	$605,000	Vendor B: $65,000 less
10	Approx. Cost with equal # of projectors (i.e., 8)	$670,000	$675,00	∼$5,000
11	Optional preventative maintenance	Customizable upon request	Customizable upon request	none

Differences in viewable surface size and pixels of viewable surface are a function of the number of projectors specified and their orientation. For example, the system initially proposed by Vendor A used four partially-blended projectors in portrait mode on the front wall to increase resolution on the primary viewing surface. The side walls are then each generated by a single projector in portrait mode to maintain a matching pixel resolution. The system initially proposed by Vendor B used two partially-blended projectors in landscape mode on the front wall. The side walls are also each generated by a single projector, but in landscape mode, and a portion of the available pixels in the depth dimension are not used. Attributes for image generators and software are not listed since these were to be obtained through existing agreements with preferred university vendors.

RESULTS

System Selection

The test patterns generated during the demos of each vendor as digitally captured are shown in **Figure 4**. Quantification locations (top, middle, and bottom) correspond to the lines in **Figure 4** located at approximately 10, 50, and 90% of the viewable height, respectively, and illustrate the level of uniformity and contrast levels across the projected surfaces offered by each vendor during their demonstration. The results of this quantification indicate that Vendor A provided a combination of screen material and blended projection of the test pattern that was superior to that offered by Vendor B in the instances tested at our institution.

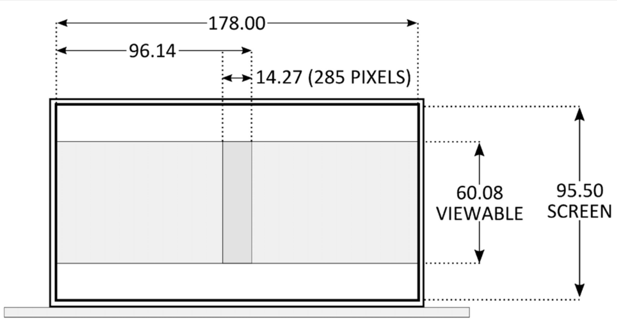

FIGURE 2 | Specification for vendor demonstrations using key equipment impacting image quality.

These benefits of more seamless blending and uniformity also extended to content provided by MARVL that was shown during Vendor A's demo. Feedback from potential users indicated, almost unanimously, that the Vendor A team was more prepared since they had configured 3D content sent by end users for viewing and were more knowledgeable of the details in their quoted solution when asked related questions. In response to feedback from potential end users around the time of these demonstrations, Vendor B provided a revised quote for a system with resolution similar to that provided by Vendor A. Similarly, end users liked the increased depth of the solution offered by Vendor B, which prompted a revised quote from Vendor A that included one additional projector per side of the proposed IVE.

Based on feedback obtained from potential users following on-site demonstrations by each vendor, the quantitative metrics mentioned above, consideration of important differences between system attributes such as resolution and size, and upon consideration of system price, Vendor A was contracted with to install the structure, projectors, screens and tracking system for MARVL, consistent with the details provided in their revised quotation. A rendering of the system as envisioned prior to installation is shown in **Figure 5**. The time to functionality upon selecting a vendor and generating purchase orders was 34 days, which included installation and completion of punch-list items.

Specifications of Image Generators and Operation

It was determined that content for use within the large-scale IVE provided by Vendor A would be driven by hardware

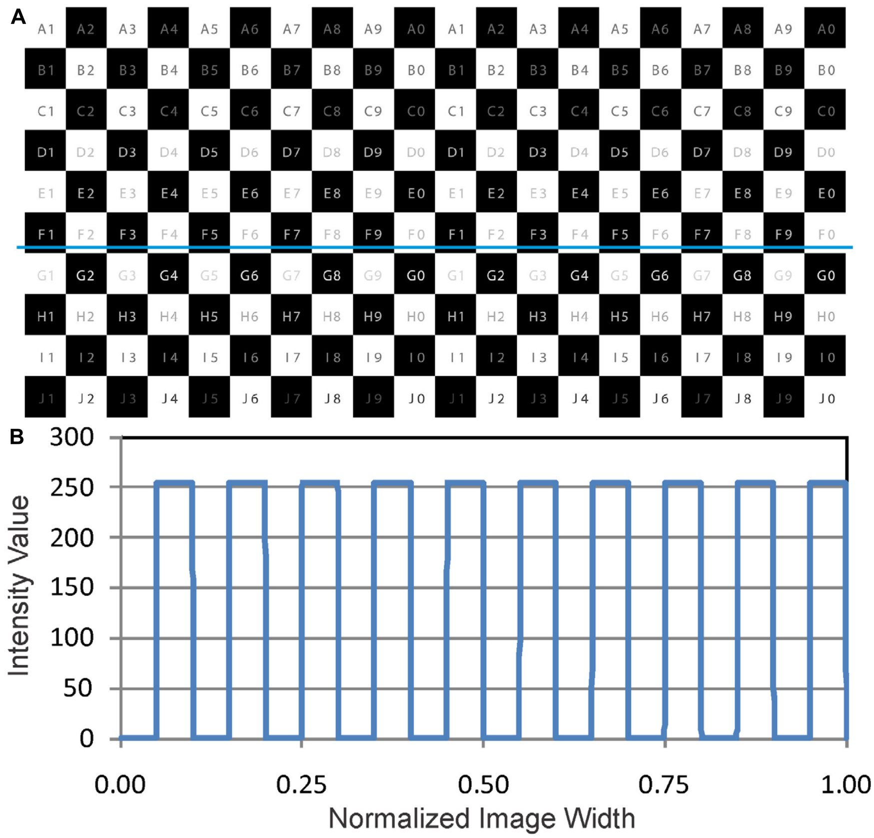

FIGURE 3 | A test image for the demos is shown **(A)** along with the intensity profile generated from a horizontal query of values through the indicated portion of the image **(B)**. This represents the ideal (i.e., best case) output from photographs of this image as projected during each demo.

TABLE 3 | Software solutions identified for potential users of MARVL.

Application	Software	Commercial or Open Source	Approximate Cost
Viewing molecular structures	Visual Molecular Dynamics (VMD)	Open Source	$7,500*
Viewing virtual toolkit (vtk) data	ParaView	Open Source	$7,500*
Viewing imaging data and finite element results	Avizo with xscreen and xskeleton extensions	Commercial	$18,000
Generating virtual environments and adding texture and realism	Unity with GetReal3D for Unity	Commercial	$20,000
Integrating other commonly used 2D applications into the 3D visualization system	Conduit Core, NX, ESRI ArcGIS, SolidWorks and GetReal3D for Showcase Cluster	Commercial	$39,000
Installation, configuration and training	All of the above	both	$29,000
		TOTAL	$121,000

**These software packages are open source, but some vendors charged an implementation fee as listed. The costs above were for the first year of operation, after which time software solutions were to be re-evaluated based on user needs.*

consisting of six image generators. This included a primary image generator (Z820 E5-2670 workstation with 1 TB HDD and 32 GB RAM; Hewlett-Packard, Palo Alto, CA, United States) containing a single graphics card (Quadro K5000; Nvidia Corp., Santa Clara, CA, United States), which communicated control to five additional Z820 image generators via a local Ethernet network isolated from the institutional network. Image generators beyond the primary node were configured with two Nvidia Quadro M4000 graphics cards and a single Quadro Sync Interface Board. The graphics cards collectively provide 10 output channels, one for each of MARVL's ten projectors (Mirage WU7K-M projectors with Twist; Christie Digital, Cypress, CA, United States). Images rendered by the 10 projectors are warped and blended to cover multiple display surfaces including the extra wide front wall (four projectors) as well as the floor, and two side walls (two projectors each). The result is stereoscopic projection and enhanced depth cues over a viewable dimension of 18′6″ (front) × 9′3″ (height) × 9′3″ (depth). Resolution is ∼4 K on the front wall, with a total system resolution of 15.7 megapixels. All image generators were dual-booted, running Xubuntu Linux and

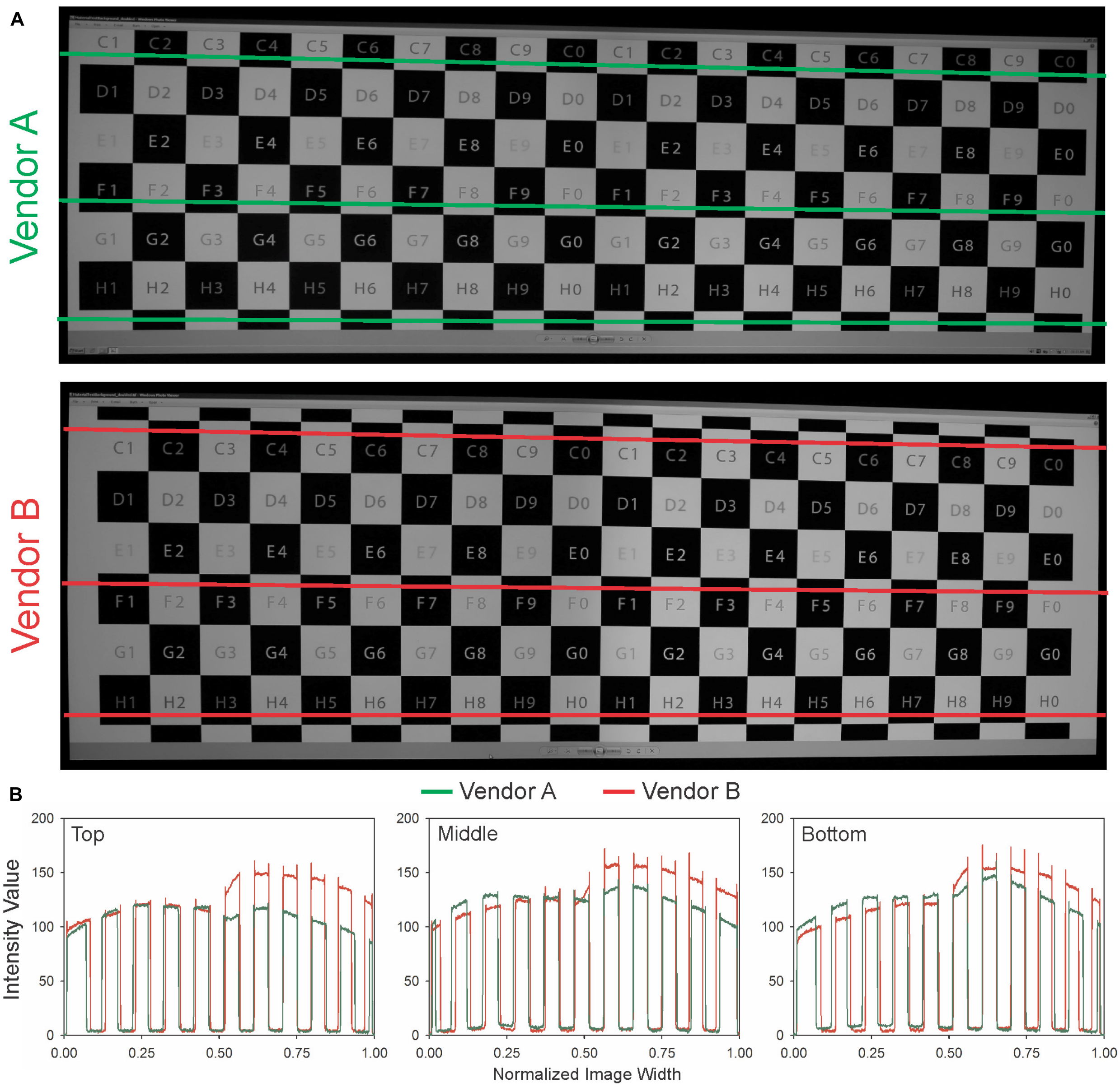

FIGURE 4 | Images of the test pattern generated by the systems of each vendor and captured as digital images by our professional institutional photographer **(A,B)**. The horizontal lines represent spatially-equivalent locations where each photograph was analyzed offline to quantify uniformity and contrast between white and black levels across the projected surface. The three green and red lines are located at approximately 10, 50, and 90% of the viewable height, respectively **(A)**, and the colors correspond to those in the quantification below the images. Quantification of these test patterns **(B)** illustrate uniformity and contrast between white and black levels across the projected surfaces offered by each vendor during their demonstration.

Microsoft Windows 7 Professional 64-bit. Interaction within the virtual environment is afforded by a tracking system consisting of 6 ARTTRACK2 cameras and two FlyStick2 wireless interaction devices (Advanced Realtime Tracking; Weilheim, Germany).

The subsequent initial operation of MARVL's large-scale IVE is shown in **Figure 6**. This figure demonstrates how synchronization signals propagated at the time, and how they impact multiple components within the visualization space (left). Multiple layers of calibration are necessary to align all the projectors in used in the space (right). Original plans did not use SLI Mosaic, because it was unstable in previous driver versions. However, on Windows, SLI Mosaic does handle rotation. On Linux, rotation conflicts with the stereoscopic 3D settings, so rotation must be implemented in each application's configuration files.

Software Selections

The potential software costs outlined in **Table 3** were intractable with our available budget, particularly when several packages required annual renewal. Fortunately, several other options were

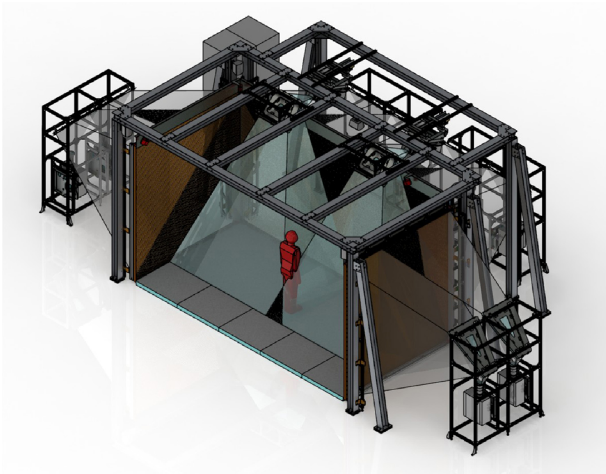

FIGURE 5 | Rendering of the immersive virtual environment selected for MARVL as envisioned prior to installation.

gaining prominence around the time our system installation was being completed. Members of MARVL subsequently explored other cost-effective options that appeared robust and could provide the functionality needed by our end users. These options centered around Blender (Blender Foundation; Amsterdam, Netherland) and the Unity game engine (Unity Technologies, San Francisco, CA, United States). The combination of these programs would become the basis for all projects conducted in MARVL to date. Briefly, Blender is generally used for mesh processing and to prepare models for immersive visualization. Within Blender all model objects are set to have a consistent scale and default orientation, and their origin is established in a sensible position near an object's center of gravity. In some cases, the decimate filter within Blender is used to reduce an object's vertex count. After the models are prepared, it is a straightforward procedure to import them into Unity using a typical workflow. An environment is created to house models, the models are positioned in the scene, lighting is established, and complementary features or data are added as needed for a particular application. MiddleVR (Le Kremlin-Bicêtre, France) was added to the Unity project, providing support for displaying the virtual scene across the clustered set of image generators, as well as to provide a user movement system via the ART FlySticks and tracking system. The total cost for this collection of software packages was approximately $25,000 upon establishing the MARVL large-scale IVE and software renewals have cost approximately $3,000 annually to date.

It is worth noting that the presentation of software solutions at the time when we were planning our system was generally less of a consideration for most vendors. Even some of the most prominent CAVE research papers do not spend much time discussing software, which future work from respected groups has subsequently published pertaining to specific software developed for a given application (Febretti et al., 2013; Nishimoto et al., 2016; Renambot et al., 2016). In contrast we treat Unity, and our leveraging of Blender as part of this process, as a standard solution. This relates back to our facility being within an educational institution and being able to assist in the content creation and presentation process for a variety of applications, rather than developing a particular software solution that is then to be used by end users within a particular discipline.

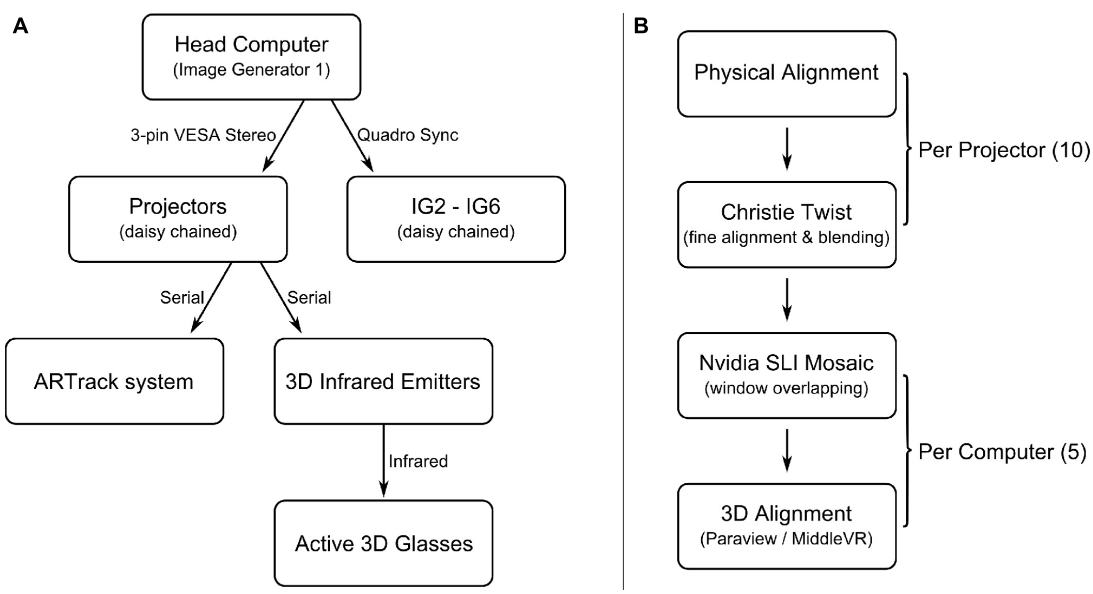

FIGURE 6 | Alignment and synchronization of MARVL. This illustrates how synchronization signals propagate, and how it impacts multiple components within the visualization space **(A)**. Multiple layers of calibration are necessary to align all the projectors in used in the space **(B)**. The original plans did not use SLI Mosaic, because it was unstable in previous driver versions. On Windows, SLI Mosaic handles rotation. On Linux, rotation conflicts with the stereoscopic 3D settings, so rotation must be implemented in each application's configuration files.

As mentioned above, we developed a list of planned applications, and a list of necessary software to match during the planning stage of our large scale IVE. The initial version of this facility was configured to dual boot between Xubuntu and Windows, in order to provide the greatest amount of flexibility in software. For the first year of operation, we ran most simulations in ParaView VR and Blender Game Engine on Linux, and Unity with MiddleVR on Windows. We continued to run experiments and trial versions of other software, but as we gained more development experience, we settled into a more consistent content development pipeline of using Blender and Unity for nearly all applications. As new content challenges arrived, such as a new 3D model format, video playback, or other interaction devices, in most cases were able to integrate them into Unity in order to bring them to our large scale IVE.

Project Development Process and Decision Points With End Users

With hardware and software selections in place to form a functioning immersive facility, MARVL personnel have settled into a process for projects and decisions made in conjunction with our end users. Although not rigid, MARVL personnel typically ask versions of the following four questions when new projects have been proposed by potential end users.

(1) How does the application that the experience and content addresses benefit from an immersive approach?
(2) What is the purpose of the immersive experience and its associated content?
(3) What resources and personnel are available to support content creation and delivery?
(4) What measures will be obtained from the immersive experience, and can they be evaluated statistically in potential support of the added effort spent on immersive content creation and delivery.

To date, MARVL personnel have not made the decision about which projects move forward within our facility. If questions 1 and 2 above have tractable answers, and the project has a champion, then it has historically moved forward organically by its own motivation. Given our focus on education within our institution and college, applications favoring educational objectives have been a priory. Those projects with defined outcomes and measures that could result in external funding or manuscript submission have similarly moved forward frequently, as efforts on such projects have the ability to grow MARVL and its user base. Historically, the only projects that we have strongly suggested not progress have been those desiring to recreate physical spaces in their current or near current form that we can reasonably travel to near campus, and content that would not have distinct benefits to immersive viewing upon creation. Currently we do not charge for educational projects since our content development personnel is partially supported by the college. In short, we operate as service organization for the college and university, while also having investigator-driven research goals that are now starting to be realized through grants and contracts.

Data Collection

Most projects to date have used existing data. For example, our computational fluid dynamics content discussed below uses converged simulation results that are viewed in new ways, including comparatively between groups of experiments or with complementary data not often viewed when looking at CFD results using conventional approaches. In most cases, data are not generated during an immersive viewing session within our large scale IVE. Although the ARTTRACK camera system is registering the location of the FlyStick within the tracked space, this information is streamed and not stored. When applications have required storing of associated data, separate data acquisition systems have been brought into the immersive space for that purpose and results have been stored either remotely or on a dedicated share of our network attached storage (NAS) drive, depending on end user preference. Even the performance and visual arts work featured below is based on an existing framework of materials. MARVL personnel do not necessarily have a preference for the use of data-driven content relative to free 3D sculpting (for example) that would not be based on data. This outcome has simply been a byproduct of the visions expressed by of our end users to date. The data-driven experiences to date, together with the background of current MARVL personnel in film, animation and graphic design has also organically led to our focus on a high degree of realism within the content that is created.

Simulator Sickness

During the installation and calibration of MARVL's large scale IVE, enabling head-tracking was a major milestone required to convincingly immersive users within the space so they would temporarily forget about the boundaries of the screens and their current location in the room. However, our early experiences using head-tracking with classes of students quickly indicated that this hallmark of many immersive systems (i.e., head-tracking) was not well-received by our audience. When discussing this issue with other immersive facilities, we were reassured that issues pertaining to simulator sickness were much less of a concern with large-scale IVE than with head-mounted displays because the users' vision was not fully dominated by the display. However, upon opening MARVL to larger audiences, only a few users in the room (i.e., the person being tracked and those closest to him or her) were experiencing the immersion to the desired degree, while other patrons (i.e., secondary users) had a suboptimal experience for several reasons. Most noticeably, the head motions of the tracked user were visible to the entire audience, which created a high amount of camera motion. This camera motion was especially pronounced as a result of the subtle motions that accompanied tracked users standing or speaking. The secondary users experienced stereopsis issues because their heads were rarely aligned with the stereo axes tracked from the primary user's head. If the secondary users looked at the side projection screens when the primary user was not, the stereo axis would be ∼90° off. Fortunately, we were able to resolve these issues by disabling headtracking. Instead of attaching the virtual cameras to a position read from the tracking system, we chose a position and orientation representative of a seated height in the center of the room and locked the virtual cameras to that point. The stereo axis of each screen was aligned to the face normal of each screen, which allowed the audience to see a stereo image on all screens, at the expense of a more pronounced screen boundary.

Motion to photon latency (Solari et al., 2013) became a major concept to measure head-mounted virtual reality system latency around 2013. Unfortunately, this metric was not discussed during the design phase of our facility. It was assumed that powerful computer hardware and high-quality components would be enough to avoid issues, but we did not have a method for predicting system latency until our system and facility were fully functional. We did not conduct a rigorous timing of the headtracking latency, but there is a slight noticeable lag when using tracked controllers and head-tracking together. Factors that contributed to our latency were 60 to 120 Hz rate conversion on the projectors, GPU buffering due to external synchronization, VRPN-based system complexity, and MiddleVR's cluster synchronization method. Innovative optimizations like asynchronous time warping and instanced rendering were coming to head-mounted displays, but those technologies were difficult to apply to a clustered configuration such as that of our large-scale IVE. We were able to make minor improvements to our latency issue through software configuration changes, but without head-tracking, we were no longer obligated to move the camera position for every frame, making the camera position appear to be more stable and stationary, except during deliberate movements. There are also a few design guidelines we now follow in order to reduce eye fatigue and avoid simulation sickness. For example, whenever text or UI elements are used, they are always placed on the convergence plane. When a speaker is in the immersive space, they stand on the edges of the front screen, especially if there is a scene utilizing negative parallax.

Example Content

Some examples of content created and visualized through collaboration with the original end users identified during the planning stage are shown in **Figure 7** and discussed in more detail below. We begin these examples by describing the processes above implemented for a project aimed at training of nursing students using realistic clinical environments.

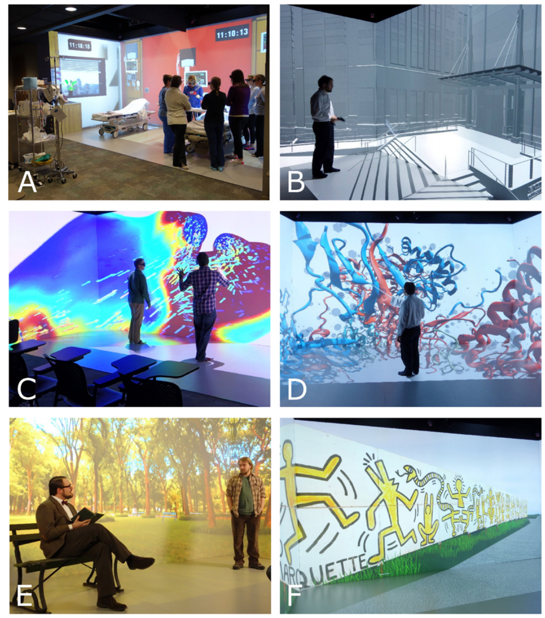

FIGURE 7 | Example content from end users identified during planning of the visualization space. Written informed consent was obtained from all individuals in the featured content. Applications include augmenting training experiences for nursing students **(A)**, enhanced viewing of civil engineering infrastructure, architecture, and computer aided design models **(B)**, immmersive visualization of biomedical computational fluid dynamics results **(C)**, viewing of protein structure and electron density maps **(D)**, performing arts **(E)**, and visual arts **(F)**.

Augmenting Nurse Training Opportunities Using Realistic Clinical Environments (Figure 7A)

The use of simulation is common in nursing education. Many institutions have dedicated physical areas designed to resemble specific clinical environments, including applicable equipment for nursing students and other healthcare trainees to hone their skills. Unfortunately, often there is not enough space at a given institution to physically replicate all the clinical or home health care environments that students will experience in practice. Moreover, it can be difficult and, in some cases potentially unsafe, to place trainees into a real clinical environment. A large-scale IVE has the potential to mitigate these space and safety issues with virtually constructed environments. **Figure 7A** shows an example of a program implemented with this in mind.

Faculty within the College of Nursing at our institution were familiar with immersive approaches as a result of the nearby Virtual Environments Group (formerly known as the Living Environments Lab) (Brennan et al., 2013a). Several faculty members therefore reached out to MARVL during the planning stage and joined its personnel during visits to other immersive visualization facilities. As alluded to above, the ultimate goal of our nursing collaboration was to extend the number of clinical training facilities beyond what was physically possible within the existing simulation lab in the College of Nursing. For example, the existing simulation facility includes rooms mimicking surgical units, but not an emergency room. As a first step before creating new immersive, virtual spaces for training, our collaborators sought to quantify the ability of nursing students to learn in an immersive facility meant to replicate an existing clinical environment. Although the creation of such content is contrary to the details mentioned in our project development section above (i.e. not to recreate an existing physical space in close proximity), MARVL personnel agreed it was important to ensure students could transfer learned skills in an immersive environment to a similar level as they could in the physical environment before extending the collaboration to additional clinical environments that were not physically available. MARVL personnel therefore visited the physical space (Conover, 2014) to photograph elements to be replicated virtually. MARVL's visualization technologist worked with four animation students from a local technical college to create 3D models of the environment, using Blender, 3D Studio Max, and Unity. Members of MARVL will frequently invite students and occasionally work with animation consultants as needed in the content creation process, depending on the scale and objectives of a particular project. Here again the location of MARVL within an educational setting has led to a tendency to involve undergraduate and graduate students in research and immersive experiences whenever possible.

Upon completion of the virtual space, ~50 Master's level nursing students from our institution were randomly assigned to learn nursing skills in a physical clinical environment or MARVL's IVE (Conover, 2014). The skills taught focused on acute care assessments, aseptic technique, naso-gastric tube insertion, tracheostomy suctioning, and Foley catheter insertion. During an orientation session, students completed a questionnaire regarding comfort and prior exposure to immersive visualization approaches including virtual reality. Each week of the course thereafter, all students met in the physical clinical environment where they received a demonstration of that week's skill, which was then practiced by half of the students in the immersive version of the physical clinical environment. Students in both the physical and immersive environments were given an equal amount of time to practice and perform a repeat demonstration of the skill that was presented in the combined group teaching session. Student skill performance in both groups was assessed using the same performance rubric. At the end of the course, students who trained in the immersive environment also took their final exam in the physical environment to determine whether these students could transfer their learning from the immersive environment to reality. Students who trained in the immersive environment performed at least equal to those of the other group on all skills tests. It is worth noting that MARVL's end user nursing collaborators felt that interaction with details within the virtual environment would be crucial for the translation of skills. Therefore, rather than using a haptic approach or virtual reality gloves, we opted to recreate the clinical sights and sounds with a dynamic environment and position physical material that students needed to interact within into the immersive space. This underscores the utility of the extra wide IVE for which this and other applications were designed.

Additional content has subsequently been created for use with nursing students in MARVL using an approach similar to that discussed above. For example, our most recent collaboration used content that was created to immerse students in a simulated study abroad trip to Peru. Photos of the study abroad clinical spaces the students would experience were used to generate content and representative audio was selected from royalty free sources. Students navigated the immersive space and interacted with a physical Spanish-speaking actor trained in the clinical experience prior students had encountered. Pre-test and post-test questionnaires were used together with a wireless data acquisition system to temporally quantity changes in respiration, heart rate, galvanic skin response and other measures related to anxiety and preparedness during several simulations prior to the study abroad experience.

3D Viewing of Civil Engineering Infrastructure, Architecture, and Computer Aided Design Models (Figure 7B)

Advances in immersive visualization make it possible to conduct careful study of architectural features and civil engineering infrastructure, including better understanding of sightlines and building information modeling. Whether the objective is pre-visualization prior to erecting a structure (**Figure 7B**), or reconstruction of building complexities from the distant past that are made accessible for the first time for a new generation, such study is made possible by the procedures implemented within MARVL's large-scale IVE. The interactivity provided by an IVE offers the chance to focus attention on the details, decisions and/or symbolic meaning that may accompany each portion of a project. The basis of the control system used to navigate within structures in MARVL is a three-dimensional optical tracking system affording movement in any direction using the FlyStick2 as discussed in more detail below.

Correlating Local Blood Flow Alterations With Markers of Disease (Figure 7C)

Computational fluid dynamics (CFD) is a method of simulating fluid passing through or around an object using digital computers. This approach is common for several researchers at our institution (Bowman and Park, 2004; Borg, 2005; Borojeni et al., 2017; Ellwein et al., 2017). The use of CFD is a common way of calculating blood flow patterns within lumens of the body in order to better understand a particular disease. These simulations can routinely involve millions of elements for which the governing equations of fluid flow are iteratively solved tens of thousands of times to represent a single second of physical time such as one heartbeat. Despite modern biomedical CFD simulations producing 4D (i.e., spatial and temporal) results, these results are often viewed at a single point in time, on standard 2D displays, and rarely incorporate associated data. **Figure 7C** shows an example of how members of MARVL are using immersive visualization as an approach to mitigate these issues and extract more information from CFD results (Quam et al., 2015) by combining them with available complementary data related to a given application.

Protein Structure, Electron Density Maps (Figure 7D)

During the planning stages of our facility, the end user for this application recounted how he was already using 3D visualization and analysis of protein structure in his publications and classes, but that the implementation of such structures was mostly through 2D and prerendered images using desktop monitors. The end user sought to make better use of the 3D models by presenting them in an immersive and interactive way to assist students in understanding complex 3D structures. This approach is common in immersive visualization and virtual reality. The end user's prior workflow relied on the open source program, PyMOL[2], to convert the protein data bank files into

[2] https://pymol.org/2/

3D models. PyMOL's options for exporting its generated meshes were limited at the time of implementation, so MARVL provided personnel support to recreate the models using Visual Molecular Dynamics (VMD)[3] as an alternative. Upon optimizing the visual representation, the end user worked with MARVL personnel to import mesh data into Blender, and then Unity. The functionality within Unity was programed to display a series of structures in a linear sequence like an interactive 3D slideshow, as well as display captions, and provide navigation of the space around the structure, but now scaled up to room-size within MARVL's large-scale IVE (**Figure 7D**).

Performing Arts (Figure 7E)

Our collaboration in this area began to yield a more immersive way of visualizing lighting and stage design in hopes of limiting edits following physical construction of sets. The collaboration has also focused on dynamic evolution of sets with a focus on small-scale theater, but with a larger audience than could be accomplished with one or more tethered head-mounted displays. As its first production, MARVL worked with the Department of Digital Media and Performing Arts with the Diederich College of Communication at our institution to present *The Zoo Story* (**Figure 7E**). This Edward Albee play about two men in Central Park ran for 6 shows and sold over 200 tickets. The director's vision called for dynamically changing the projected set to coincide with character evolution. This has fostered new ways of achieving digital excellence for productions in the region using an innovative approach to set design that uniquely engages actors and audiences. The Zoo Story was not offered in stereoscopic 3D, but each of the subsequent performances in MARVL included stereoscopic backgrounds with live and virtual actors as most recently portrayed in William Shakespeare's *Macbeth* (Hauer, 2017).

Visual Arts (Figure 7F)

Our institution is fortunate to have a dedicated museum on campus. The Haggerty Museum of Art opened in late 1984 as a teaching facility. The goals of the Haggerty Museum of Art are to enhance the undergraduate educational experience by engaging students in various disciplines to think about the world and their subject matter through the lenses of the visual arts. With this in mind, MARVL has transformed work from the Haggerty Museum of Art permanent collection to be experienced in new ways, such as recreating large pieces within era-appropriate representations, and when important pieces may be on loan from the museum. For example, Salvador Dali's *Madonna of Port Lligat* comes to life in 3D as an interactive piece with togglable annotations about its history and content. Similarly, a 100-foot-long mural painted by Keith Haring for the construction site of the HMA can also be viewed, *in situ*, as it was in 1983 (**Figure 7F**). These versions allow for accessibility and for minute details obscured in a typical installation to be clearly seen.

[3] https://www.ks.uiuc.edu/Research/vmd/

DISCUSSION

The MARquette Visualization Lab has become a valuable campus resource through its first few years of operation. Since its creation, its members have received numerous queries and requests pertaining to how system attributes and applications were selected. Hence, the goal of the current work was to provide an overview of the process used in creating MARVL, including those used in identifying end users, understanding their potential applications, and synthesizing this information into its subsequent design and operation. We described our qualitative and quantitative approaches to vendor selection along with initial and current software decisions. While companies do offer out-of-the-box turnkey solutions, such systems did not meet the diverse needs and variety of applications expressed by our potential end users. Despite the custom setup of our system discussed above, it was (and continues to be) imperative for us to have a set of processes in place that are general enough for most applications that present. It is important to note that the approaches used to gather input from potential end users, decide on a CAVE-type IVE, and assist in vendor selection were conducted with frequent feedback and transparency at our institution. While the processes described seems to have worked well at our institution, it is reasonable to surmise that other institutions may want to consider different approaches in order to best meet the needs of their end users and overall objectives.

Development of Subsequent Resources

With the development of MARVL's large-scale IVE came the need for additional space and resources to be used in the development and testing of content. MARVL's Content Development Lounge (CDL) was established in a room adjacent to the large-scale IVE (**Figure 8**). The CDL is accessible through a set of double doors, which also permits transport of larger equipment into the IVE as needed. In contrast to a typical classroom or lab, the CDL was designed to be an inviting place for potential contributors to create and share content, hold meetings for ongoing or new projects, and serve as a recording and debriefing site for experiences held in the adjacent large-scale IVE. The CDL includes spacious leather seating, programmable indirect lighting and ergonomic pods with local task lighting. There are several pass-through gang boxes with removable wall plates between the large-scale IVE and CDL to permit communication between the two locations. The CDL contains high-end workstations with 3D monitors and a smaller-scale display system with the same stereoscopic viewing and tracking technology included in the large-scale IVE.

Consistent with a theme of transparency and fostering collaboration that is apparent throughout Engineering Hall where MARVL is located, the entrance of the CDL contains a holographic rear projection system that allows viewers to look at, and through, the screen. The Holo Screen (Da-Lite; Warsaw, IN, United States) displays digital signage of scheduled events and content being featured in current initiatives. The Holo Screen is coupled with a 3D ready projector and emitter that permit seamless viewing of content among all MARVL's display surfaces using a single type of stereoscopic glasses during featured

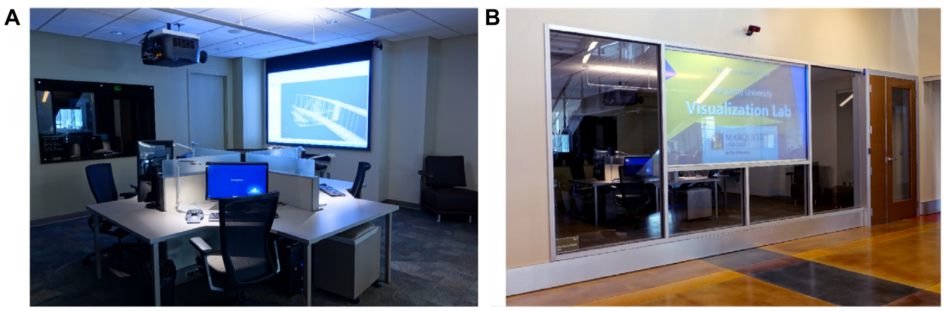

FIGURE 8 | MARVL's Content Development Lounge (CDL) was established in a room adjacent to the large-scale IVE. The interior of the CDL **(A)** contains high-end workstations, state-of-the-art display systems and tracking equipment for use in developing digital content, which can also be viewed from its exterior **(B)**.

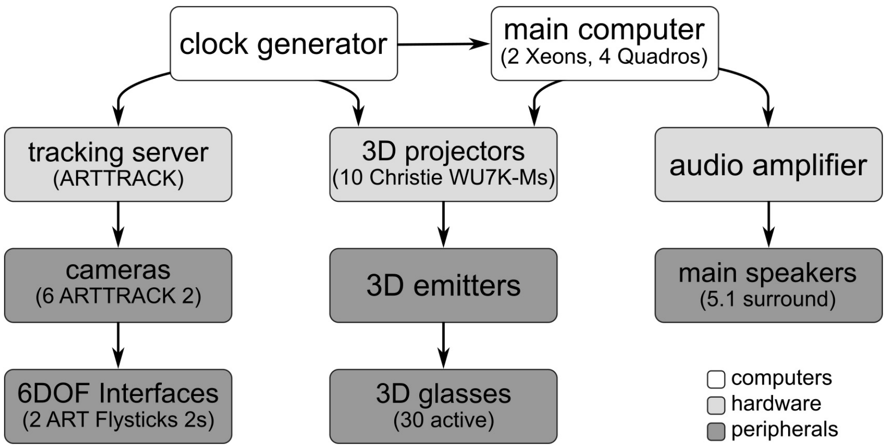

FIGURE 9 | Schematic illustration of the current hardware setup in MARVL's large-scale immersive environment.

exhibits and events. In theory, these tiered resources for use in developing immersive content (desktop - > single projector systems - > large-scale IVE) are designed to minimize cost and optimize the use of MARVL's key resources.

A NAS device is used to share project files and resources among all lab users. Although the institution provides a shared server for this purpose, MARVL required our own file server due to the expected storage and bandwidth requirements. Typically, executable programs are stored on the NAS, and all image generators launch the program simultaneously when the content is loaded. This is referred to by MiddleVR as the server starting a simulation. However, we noticed a significant reduction in launch times after we mirrored the shared folder to each computer's local SSD drive, instead of loading the program through the network. This mirroring is done automatically through an rsync script.

When MARVL opened, the initial NAS device was a Drobo B800FS, but this unit was recently replaced with a Synology RS12919+. The upgrade increased the total available storage from 18 to 62 TB, but the primary motivator for the upgrade was a need for increased network transfer bandwidth. Both devices used a RAID 6 system to prevent data loss from mechanical drive failures, but a series of USB drives also serve as an offline mirror backup. The backup is run manually, using the Hyper Backup software running directly on the Synology server.

Limitations

One early discussion among end users pertaining to the arrangement of MARVL concerned the use of display surfaces on the floor vs. ceiling. The vision for MARVL involves its use as a differentiating factor in educational experiences and extramural grant applications. With the presence of a 6-sided IVE nearby (Brennan et al., 2013b) and input from our end users, it was determined that a fully immersive (i.e., 6-sided) system would not be pursued. End users also expressed a preference for projecting on the floor rather than ceiling. However, there were some limitations to overcome with this decision. When walking into a physical structure in real life, most individuals will direct their gaze upward to examine the space. It was therefore important to include this experience. Taking architecture (**Figure 7B**) as an example, the absence of a projected ceiling within MARVL required implementing additional functionality into its interactivity tool in order to appreciate the higher portions of structures and elements, and to simulate a patron's gaze from the lower locations. A deliberate choice was therefore made not to implement a collision system so that the virtual camera used in MARVL would be completely uninhibited. This decision facilitates exploration anywhere within created or reconstructed content, including below virtual floors and through walls. The movement of a virtual camera within structural environments is therefore controlled by a script moving the view from a conventional horizontal position to a vertical one directed toward the top of a structure by rotating the camera upward. While in this rotated view, movements for further exploration of the structure are still enabled. More specifically, the current implementation used with civil engineering, architecture and related structures within MARVL simply uses a button press to toggle between forward, upward or downward facing gazes. Additional camera control implemented into the interaction device works to provide end users with control of the virtual camera's height. For example, the thumb control on the FlyStick2 interactivity tool can be tapped in the up or down directions to instantly transport patrons to the various levels of the structure. This represents one approach that worked well for our facility, and others are likely available.

The MARquette Visualization Lab is spatially restricted to our campus in downtown Milwaukee, Wisconsin. In some cases, this created an impediment to collaborations. For example, clinicians interested in viewing biomedical CFD results at nearby hospitals and clinics often do not have the time to frequently travel ∼5 miles to view patient-specific results. Members of MARVL have therefore started to use head-mounted displays to remotely deliver content created for MARVL's large-scale IVE. Specifically, members of MARVL now have experience developing exceptional content for the Oculus Rift, Oculus Quest, Samsung GearVR and Microsoft HoloLens, among others.

Recent Updates, Expenses and Current Uses

At launch, our intent was to support as many software packages as possible, therefore the system was configured to dual boot between Windows 7 and Linux (Xubuntu 12.04). ParaView was the first program to run in the IVE, which required custom launcher scripts written in Bash, and a customized build of ParaView. After several experiments with other software, we found the most success with the combination of Unity 4 and MiddleVR. With only a few exceptions, most MARVL projects are now built on Windows 10, MiddleVR 1.7, and Unity 2018.4.

Due to the wide shape of our installation, some users desired to use the IVE as a large format display, but due to the clustered nature of the system, we could not use pre-existing software without unreliable workflows such as high-bandwidth VNC feeds or OpenGL redirection techniques. Therefore, we developed several projects that use desktop-style functionality such as web browsing, video playback, and presentations. These applications were utilitarian, but never fully showcased by MARVL because they only use a subset of its features. For example, these applications use the IVE's stereoscopic features and its high resolution, but do not necessarily emphasize immersion or feature sets of the more established desktop programs they emulated. Hence, when the opportunity to upgrade the image generators arrived, we opted to change the system architecture from a 6 node cluster to a single, more powerful image generator that could accommodate both the immersive experiences of a large-scale IVE, but also improvised experiences with standard desktop software. Our large-scale IVE now uses four nVidia Quadro P4000s with 8GB of VRAM each, powering all 10 projectors from a single workstation. An nVidia Quadro Sync II card is required to synchronize the GPUs with each other and the tracking system. The CPU configuration is two Intel Xeon Gold 6134s, with 8 cores and 16 threads running at 3.2 gHz each, with 96GB of DDR4 RAM. The dual CPU option was chosen not for performance reasons, but because a second physical CPU doubles the amount of PCIe bandwidth to the GPUs, which is a common bottleneck in multi GPU setups. This computer upgrade was approximately $17,000. Other hardware upgrade costs to date included are projector lamp replacements ($9,000) and an onsite service call for a heating issue for the ceiling mounted projectors that display content for the floor ($5,000). A schematic illustration of the current hardware setup in MARVL's large-scale immersive environment is shown in **Figure 9**.

The MARquette Visualization Lab's user base continues to grow. In addition to the original end users discussed in detail above, more recent applications continue to include interactive engineering class content aimed at better understanding complex principles and a focus on more efficient scientific data visualization through the combined use of data reduction and accentuation tools to study and communicate the most important features in scientific results. Several of the initial application areas have also continued to create content for derivative immersive experiences, such as the preparation of nursing students for study abroad experiences discussed above, and five additional theatrical performances.

In summary, the approach employed here has set the stage for MARVL to be an important resource at our institution. Nearly all of the end users' applications uncovered during planning stages of the facility (**Table 1**) have since been implemented. Careful selection of the workflow and processes implemented to create this resource has therefore resulted in cross-functionality with current head-mounted displays and limited the expenses incurred through enhancements to date. We are optimistic, based on interest in MARVL to date, that at least a portion of the current information will be useful for other institutions who are also considering developing an immersive visualization facility.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available to avoid commercialism and to maintain the confidentiality of vendors evaluated as part of the current work. Requests to access the datasets should be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Both authors contributed conception and design of the study. JL wrote the first draft of the manuscript. Both authors wrote sections of the manuscript, contributed to manuscript revision, read, and approved the submitted version.

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Using Virtual Reality to Assess Reading Fluency in Children

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Here we provide a proof-of-concept for the use of virtual reality (VR) goggles to assess reading behavior in beginning readers. Children performed a VR version of a lexical decision task that allowed us to record eye-movements. External validity was assessed by comparing the VR measures (lexical decision RT and accuracy, gaze durations and refixation probabilities) to a gold standard reading fluency test—the One-Minute Reading test. We found that the VR measures correlated strongly with the classic fluency measure. We argue that VR-based techniques provide a valid and child-friendly way to study reading behavior in a school environment. Importantly, they enable not only the collection of a richer dataset than standard behavioral assessments but also the possibility to tightly control the environment.

Keywords: reading fluency, virtual reality, lexical decision task, eye-tracking, beginning readers

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INTRODUCTION

Virtual reality (VR) techniques are a collection of software and hardware technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments, in which the user becomes a participant in a "virtually real" world (Psotka, 1995). An essential ingredient of VR technology is a tracked head-mounted display (HMD) that makes it possible for participants to see new views of the visual world as they move their head (Jensen and Konradsen, 2018). The key concept of VR is *immersion* (Jennett et al., 2008; Howard-Jones et al., 2014), a sense of "being" in the task environment, of being physically present in a non-physical world (Freina and Ott, 2015). The main motivation for using VR in education and training is that it provides the opportunity to experience situations that cannot be accessed physically (for review, see Freina and Ott, 2015; Stuart and Thomas, 1991) because of problems in time (e.g., visit different historical periods), distance (e.g., exploring the solar system or the functioning of a cell), dangerousness (e.g., training fire fighters to make decisions in life threatening situations) or ethics (e.g., performing surgery by non-experts). Here, we explore a very different advantage of using VR technology in an educational situation, namely the possibility to assess reading skills in a potentially noisy and distracting environment (i.e., classroom). Indeed, running experiments with children in a school environment is often a complex process that sometimes requires to control or measure eye movements and attention. We show that VR technology can provide such controls in a user-friendly way.

One of the keys to success in today's world is becoming a skilled reader, and behavioral investigations of the mechanisms involved in achieving this skill are therefore of utmost importance. However, VR has rarely been used to study reading, which is hardly surprising, because reading provides a way to create a virtual reality without the need to use a computer-based system (Nell, 1988; Jacobs, 2015). Reading, quite naturally, allows one to shape events in a person's brain. Much like a VR system, reading bridges gaps of time, space, and acquaintanceship (Pinker, 1994; Ziegler et al., 2020). The feeling of "getting lost in a book" (Nell, 1988) is probably very similar to the immersion in an artificially created virtual world. So why would one want to use VR to study reading? One possible reason has been put forward in the context of cognitive assessment and rehabilitation: "The potential power of VR to create human testing and training environments which allow for precise control of complex stimulus presentations as well as providing accurate records of targeted responses is a cognitive psychologist's dream!" (Rizzo and Buckwalter, 1997). In recent work in our group, we have started to use VR to study reading behavior in adults (Mirault et al., 2020) and there has been a general rise in the use of VR techniques in cognitive psychology in general (for a review, see Mirault, 2020).

The goal of the present study was to test to what extent a VR system can provide a valid and reliable reading fluency assessment technique in primary school children. There are several reasons for why this is an interesting and potentially important issue. First, recent HMD systems (i.e., VR goggles) allow the recording of head (3D location and velocity) and eye movements (i.e., fixation locations, fixation durations). The eye movements recorded during silent reading provide a direct measure of reading fluency and the impact of linguistic complexity on reading behavior (Mirault et al., 2020; see Rayner, 1998, for a review of early research on eye movements and reading). Currently, the recording of eye movements requires a rather sophisticated laboratory setup and a rigorous calibration procedure, in which the head must be fixed using a chin rest and/or a bite bar. This complicates the use of eye movement measures in a classroom context. Second, most psycho-educational reading assessments take place in a school setting where children are potentially distracted by environmental factors. The immersive potential of VR technology makes it possible to blend out much of these distracting factors, thus facilitating testing in a classroom setting. Third, the assessment of the visual, orthographic and attentional factors involved in reading (Facoetti et al., 2010; Ziegler et al., 2010; Zorzi et al., 2012; Stein, 2014; Grainger et al., 2016) requires "the precise control of complex stimulus presentations" (Rizzo and Buckwalter, 1997), such as a fixed distance to the screen, which determines visual angle and stimulus size. Fourth, since VR goggles have become affordable in the past years (Ray and Deb, 2016) making their wide use in schools possible, it is crucial to investigate whether the reading and eye movement measures obtained with this technique are robust and externally valid. Finally, very little research on VR has been conducted with primary school children (Eleftheria et al., 2013) and it remains to be shown that VR systems can reproduce classic laboratory benchmarks of reading, such as effects of lexicality, frequency and length (Grainger and Jacobs, 1996; Coltheart et al., 2001; Perry et al., 2007, Perry et al., 2010). This is important if these systems were to be included in more sophisticated systems, in which participants can interact with letters, words and sentences in a virtual game environment (Pan et al., 2006).

To start simple, in the present experiment, we had children in primary school (grade 2) make lexical decisions about words and pseudowords while wearing VR goggles. This allowed us to measure their reaction times, accuracy, initial fixation durations, total fixation durations, and number of fixations. Besides lexicality (words vs. pseudowords), we varied the length of words and pseudowords to test whether our measures are sensitive to word length, which is an excellent marker for the automatization of reading skills (Ziegler et al., 2003). To test the external validity of our VR test, we compared the VR measures with a One-Minute Reading (OMR) aloud test of words and pseudowords (similar to TOWRE, see Torgesen et al., 2012), which can be seen as the gold standard for measuring reading fluency (Bertrand et al., 2010). We expected to find faster and more accurate responses to words than to pseudowords. With respect to eye movements, we expected to see fewer and shorter fixations to words than to pseudowords. Finally, if our VR-based measures correlate strongly with the OMR gold standard, this could be taken as evidence that VR-based measures obtained during silent reading could potentially replace or complement more classic reading aloud assessments. This is important because the main goal of learning to read is fast, efficient, silent reading for meaning.

METHOD

Participants

A total of 102 children aged between 7 and 9 years were recruited from two schools in Marseille (France). Participants were either native speakers of French or grew up in a French-speaking environment since birth or early childhood. They reported having normal or corrected-to-normal vision and were naïve to the purpose of the experiment. Their parents signed an informed consent form in accordance with the provisions of the World Medical Association Declaration of Helsinki prior to the experiment. Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (No. 17/051).

Apparatus

The VR environment was created using the software Unity (Unity Technologies ApS) and displayed on a WQHD OLED screen (2,560 × 1,440 pixels) covering up to 100° of visual angle with a refresh rate of 70 Hz. Eye movements were recorded using the infra-red eye-tracker in the virtual reality headset Fove 0 HMD (FOVE, Inc.). The headset size was adapted to children with a strap at the back of the device in order to make this comfortable for the children and to achieve good immersion (i.e., no lights from the classroom). Children were free to move the head and the design of the experiment allow them to continually see the stimulus in front of their head location. Recording was binocular with a high spatial accuracy (<1°) and a sampling rate of 120 Hz (however, we recorded at 70 Hz in order to match the refresh rate of the screen). The position of the head was obtained by combining a USB Infra-Red position tracking camera with a refresh rate of 100 Hz and an Inertial Measurement Unit (IMU) placed in the headset. A recent graphic card (NVIDIA GeForce GTX 1650) was mounted on a laptop computer (ASUS ROG STRIX G) to display the VR environment in the Fove headset. The VR environment was also duplicated on the laptop LCD screen running with a high refresh rate (144 Hz) for the experimenter. The response was provided by pressing buttons on a gamepad (Trustmaster Dual Analog 4).

From the eye tracker, we recovered 6 measures: three for the origins (x, y, and z) and three for the Gaze Intersection Point (GIP). We defined the Origins as the viewer-local coordinates mapped from eye tracker screen coordinates to the near view plane coordinates. The GIP is given by the addition of a scaled offset to the view vector originally defined by the helmet position and central view line in virtual world coordinates (from *Eye Tracking Methodology*; Duchowski, 2007).[1]

Design and Stimuli

We created 100 items: 50 words and 50 pseudowords (see Stimuli on OSF link at the end of the article) that ranged in length from 4 to 8 characters (10 words and 10 pseudowords for each size). The words had an average frequency of 997.76 parts per million (ppm) (based on the Manulex frequency counts: Lété et al., 2004) which is equivalent to 5.99 Zipf (van Heuven et al., 2014). The pseudowords were constructed to look like real French words and were always pronounceable.

Procedure

In this study, children participated in two tasks: a VR lexical decision task (VR-LDT) and a One-Minute Reading (OMR) aloud test. In order to counterbalance task order, half of the children started with the VR-LDT while the other half started with the OMR. For the VR-LDT, they were seated in front of a school desk at 70 cm from the infra-red position detector and were free to move their head and torso. Testing did not occur in the classroom but in a small room right next to the classroom. Two children were tested at the same time. While one was doing the VR-LDT test, the other one did the OMR test. The instructions were explained to the children as a game, in which they had to detect "true" and "false" words. At the beginning of the experiment, the orientation and the position of the headset were tared, then, the participant's eye position was calibrated using a 5-dot calibration phase. Dots appeared on the VR screen in green with a decreasing size. Children were instructed to focus on the center of the dots. They had the possibility to remove the headset at any time of the experiment. The instructions were repeated one more time and the experiment was initiated if the child was ready to start. Each trial started with a fixation dot during 1,000 ms located in the center of the screen (here, we use the term *screen* to refer to the calibrated visual field of the virtual environment). Then, the stimulus was displayed in black in the center of the virtual environment. We displayed the stimulus in monospaced vectorial police (no pixelization even if you zoom-in or zoom-out), with a font-size of 36 (it cannot be compared to normal font size to because of the depth of the Z axis). The background was a neutral virtual environment with a brown floor and a blue sky; the horizon line was light blue. Participants had to read the stimulus and press the right trigger on the gamepad if the word existed in French or the left trigger if not, as fast and as accurately as possible. We shuffled the list with all the items ($N = 100$) in order to create a random stimulus presentation and we used the same shuffled list for all children. Gamepad and desk were cleaned with a bactericidal wipe between each participation. There were no practice trials and feedback during the experiment, but the experimenter gave oral examples and invited the children to press the correct button. The experimenter then provided oral feedback and an explanation for any errors made.

Concerning the OMR test, we used the LUM test ("Lecture en Une Minute") developed by Khomsi (1999). It consists of two reading aloud tests: one with a table of 35 existing words (in French), the other with a table of 30 pseudowords. The tables are presented in five rows. The test is explained to the child and then he or she starts by reading two test words (outside the table) that do not count in the number of words read. Then the timer is started when the child reads the first word in the table. Children were instructed to read the words from left to right and then to move to the next line. Scoring the test first involved counting the number of correctly read words and discarding incorrectly read words (mispronounced or not read after 5 s). After one minute the test was stopped. The number of correctly read words is the fluency value. If a child read all the words correctly in less than one minute, then the time to do so was recorded, and the number of words correctly read per minute calculated from that.

Pre-Processing the Eye Movements

We used the *emov* package (Schwab, 2016) in the R statistical computing environment (Pinheiro et al., 2014). This package implements a dispersion-based algorithm (I-DT) proposed by Salvucci and Goldberg (2000) which measures fixation durations and positions.

Analysis

We used Linear Mixed-Effects models (LMEs) to analyze our data, with items and participants as crossed random effects, including by-item and by-participant random intercepts (Baayen et al., 2008). Items in these analyses were the words/pseudowords. LMEs were used to analyze response time and fixation durations while Generalized (logistic) LMEs were used to analyze error and refixation rates. The models were fitted with the *lmer* (for LMEs) and *glmer* (for GLMEs) functions from the lme4 package (Bates et al., 2015) in R. We report regression coefficients (b), standard errors (SE) and $|t\text{-values}|$ (for LMEs) or $|z\text{-values}|$ (for GLMEs) for all factors. Fixed effects were deemed reliable if $|t|$ or $|z| > 1.96$ (Baayen et al., 2008). All durations were inverse transformed (−1,000/duration) prior to analysis.

Following the main analyses, we will present post-hoc analyses concerning length and frequency effects and cross-task correlations.

RESULTS

Prior to analysis we excluded participants who did not finish the experiment ($N = 2$) and those for whom there was a technical incident during the experiment ($N = 10$). The remaining group was composed of 90 participants.

[1]All code used to program the experiment and to analyze the data can be found at: https://osf.io/m8j2z.

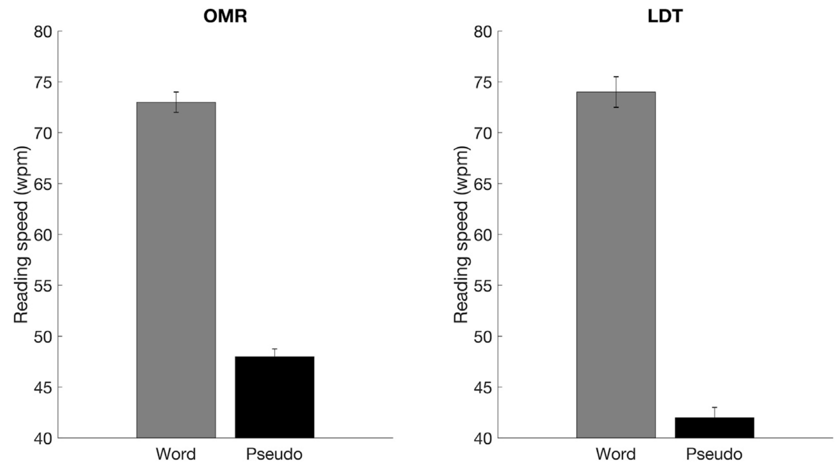

FIGURE 1 | Mean correct word/pseudoword per minute for the One-Minute Reading test (OMR; left) and reading speed in the Lexical Decision Task (LDT; right) for words and pseudowords. Error bars represent 95% CIs.

Effects of Lexicality

Lexical Decision Error Rates

We observed a significant effect of lexicality in lexical decision error rates (b = 1.18; SE = 0.12; z = 9.81), with children making fewer errors to words (M = 5.30%; 95% CI = 4.68) compared to pseudowords (M = 13.38%; 95% CI = 7.11).

Lexical Decision Response Times

Prior to analysis, we excluded 3.32% of data points for being 2.5 SD below or above the participant's mean such that extreme outlier values do not affect the inferential statistics. This is a standard procedure in experimental psychology (Ratcliff, 1993). We observed a significant effect of lexicality in lexical decision response times (b = 0.29; SE = 0.02; z = 13.87), with participants responding more rapidly to words (M = 1,627.87 ms; 95% CI = 197.70) than to pseudowords (M = 2,625.10 ms; 95% CI = 277.65). **Figure 1** shows the condition means with response times transformed into reading speed.

One-Minute Reading Test

More words were read aloud correctly per minute than pseudowords (b = 24.84; SE = 1.49; z = 16.67)**.** The condition means are shown in **Figure 1**.

Refixation Probability

We observed a significant effect of lexicality in refixation rates (b = 1.29; SE = 0.23; z = 5.48), meaning that participants made fewer refixations to words (M = 0.68; 95% CI = 0.09) than to pseudowords (M = 0.79; 95% CI = 0.08).

Fixation Durations

We recorded the first fixation duration (FFD), which is the duration of the first fixation on the word / pseudoword, and gaze duration (GD), which is the sum of all fixations on the word / pseudoword before the eyes left the stimulus. For each measure, we deleted durations beyond 2.5 standard deviations from the grand mean (FFD = 2.78%; GD = 3.18%) prior to statistical analysis. We observed a significant difference between words and pseudowords for FFD (b = 0.82; SE = 0.12; t = 6.55) and for GD (b = 1.19; SE = 0.19; t = 6.03), with longer durations for pseudowords compared to words. Condition means are reported in **Figure 2**.

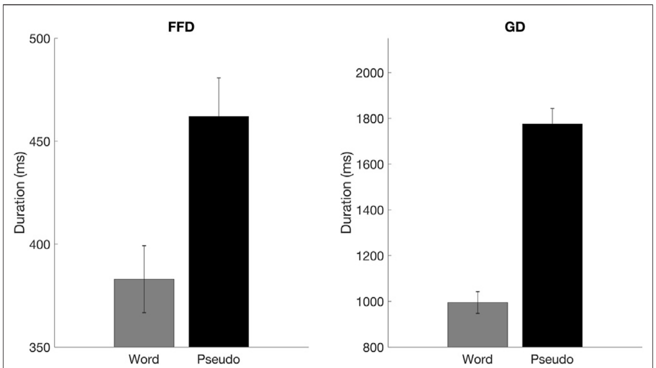

FIGURE 2 | Mean first fixation duration (FFD; left) and gaze duration (GD; right) for words and pseudowords. Errorbars represent 95% CIs. The Y-axis scale is adapted to each measure.

Effects of Length

The average values for all dependent measures for the different lengths are shown in **Tables 1** and **2**.

Length Effects for Words

Concerning the length effect for words, we observed significant effects for all the dependent measures (Lexical Decision Error rate: b = 0.15; SE = 0.07; z = 2.04, Lexical Decision Response Time: b = 0.04; SE = 0.00; t = 4.82; Refixation rate: b = 0.67; SE = 0.06; z = 9.97, FFD: b = 0.31; SE = 0.05; t = 6.29, and GD: b = 0.61; SE = 0.06; t = 9.58).

TABLE 1 | Average lexical decision response times and error rates, and averages of the three eye-tracking measures for each length (in number of letters) for words.

	4	5	6	7	8
ER (%)	4.40 (4.17)	4.08 (4.02)	5.53 (4.64)	5.55 (4.65)	7.23 (5.26)
RT (ms)	1,398 (165.73)	1,686 (238.79)	1774 (253.68)	1958 (276.55)	2021 (315.63)
Refix (proba)	0.49 (0.10)	0.64 (0.09)	0.73 (0.08)	0.78 (0.08)	0.79 (0.08)
FFD (ms)	390 (76.19)	450 (88.74)	410 (73.11)	414 (82.76)	393 (77.55)
GD (ms)	695 (165.15)	1,018 (225.78)	1,156 (243.36)	1,319 (255.69)	1,396 (288.86)

TABLE 2 | Average lexical decision response times and error rates, and averages of the three eye-tracking measures for each length (in number of letters) for pseudowords.

	4	5	6	7	8
ER (%)	15.64 (7.38)	14.73 (7.20)	10.58 (6.25)	13.78 (7.01)	12.22 (6.66)
RT (ms)	2,548 (337.86)	2,983 (531.04)	3,090 (406.37)	3,250 (499.67)	3,493 (525.61)
Refix (proba)	0.69 (0.09)	0.76 (0.08)	0.81 (0.07)	0.85 (0.07)	0.86 (0.06)
FFD (ms)	598 (119.60)	649 (160.00)	590 (117.60)	481 (100.55)	446 (91.25)
GD (ms)	1,580 (321.83)	2,102 (505.23)	2,187 (383.35)	2,341 (431.77)	2,583 (482.55)

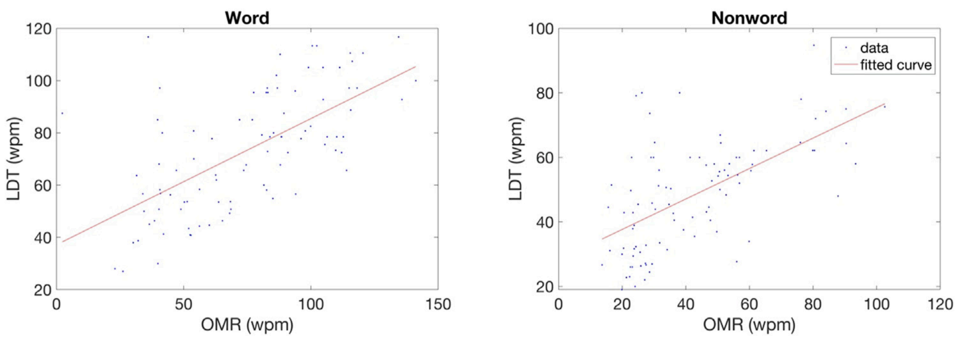

FIGURE 3 | Scatter plots showing the relation between performance on the One-Minute Reading test (OMR) and the lexical decision task (LDT) for words (left panel, R^2 = 0.40) and pseudowords (right panel, R^2 = 0.35). Lines are best fitting linear regressions.

Length Effects for Pseudowords

Concerning the length effect for pseudowords, we observed significant effects for Lexical Decision Response Time (b = 0.27; SE = 0.00; t = 4.49), Refixation rate (b = 0.54; SE = 0.06; z = 8.38), FFD (b = 0.02; SE = 0.00, t = 3.41), and GD (b = 0.36; SE = 0.05; t = 7.06). We found a marginally significant effect for Lexical Decision Error rates (b = 0.08; SE = 0.05; z = 1.63), with errors tending to decrease as pseudoword length increased.

Cross-Task Comparisons

Reading Speed

The comparison of reading speed for words and pseudowords in the lexical decision task and the One-Minute Reading test can be found in **Figure 1**. We calculated the correlations between average reading speed per child in these two tasks separately for words and pseudowords. The correlations were highly significant for both words (r = 0.63, $p < 0.05$) and pseudowords (r = 0.59, $p < 0.05$). **Figure 3** shows the scatter plots of these correlations.

We also examined the relation between gaze durations, a gold standard for estimating word reading fluency in eye-movement research (e.g., Rayner, 1998), and Lexical Decision (r = −0.76, $p < 0.05$) and One-Minute Reading speed (r = −0.62, $p < 0.05$). The scatter plots of the correlations are shown in **Figure 4**.

Finally, we examined the complete set of correlations across our different dependent measures. **Table 3** provides the matrix of correlation coefficients between all dependent measures. We highlight values of $|r| > 0.6$. We observed 2 negative correlations with gaze durations (GD): with the OMR and LDT reading speeds, meaning that faster readers (higher reading speed) had shorter gaze durations. We also noted 3 positive correlations: one between the OMR and LDT reading speed scores, one between the refixation rate and first fixation durations, and another between refixation rate and gaze duration. The two latter correlations suggest that participants who made longer first fixations tended to refixate more often, hence the longer gaze durations.

DISCUSSION

The goal of the present study was to provide a proof-of concept that a virtual reality set-up can be used to measure reading fluency

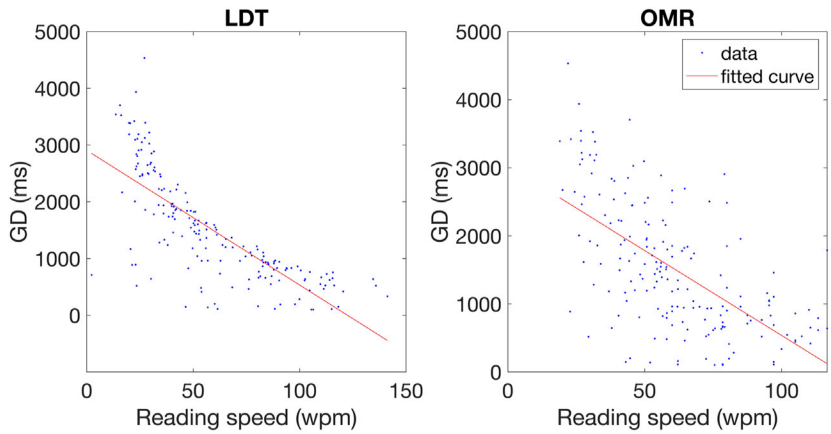

FIGURE 4 | Scatter plots showing the relation between gaze duration (GD in milliseconds) and reading speed (wpm) in the Lexical Decision Task (LDT–left panel, R^2 = 0.58) and the One-Minute Reading test (OMR–right panel, R^2 = 0.38) averaged across words and pseudowords. Lines are best fitting linear regressions.

TABLE 3 | Correlation matrix for the different dependent measures (OMR–One Minute Reading speed; LDT–Lexical Decision reading speed (wpm); FFD–first fixation duration; GD–gaze duration; Refix–refixation probability; ER–Lexical Decision error rates).

	OMR	LDT	FFD	GD	Refix
LDT	**0.72**				
FFD	−0.19	−0.35			
GD	**−0.62**	**−0.76**	0.55		
Refix	−0.29	−0.45	**0.66**	**0.71**	
ER	0.24	0.56	−0.16	−0.31	−0.19

Reported values correspond to correlation coefficients.

and eye movements during silent reading in primary school children. The internal validity was assessed using two classic benchmark measures of reading, effects of lexicality and word length. The external validity was assessed by comparing lexical decision performance and eye movement measures obtained in the virtual reality setting to a gold-standard reading fluency measure (OMR test). It is important to note that our research follows the AERA recommendations of "Standards for Educational and Psychological Testing" (American Educational Research Association (AERA), 2014).

Concerning internal validity, first of all, there were clear effects of lexicality in all our behavioral and eye movement measures obtained in the virtual reality setting. Children made more errors on pseudowords compared to words and took longer to respond to pseudowords compared to words. The two eye tracking measures (FFD and GD) also showed that children spent significantly more time inspecting pseudowords compared to words, and in line with this, children also re-fixated pseudowords more often than words. Secondly, there were clear effects of length on all our dependent measures except for lexical decision error rates to pseudowords. All other measures provided evidence that longer stimuli were harder to process, with longer response times and more errors in the lexical decision task, and longer fixation durations and more re-fixations in the eye movement measures. Given that the effects of word length are excellent measures for automatization of reading processes, they could be used to detect children who have not yet fully automatized word recognition procedures. That is, children who still exhibit some form of serial processing that is characteristic of dyslexia (Ziegler et al., 2003).

Concerning external validity, we found that the VR-LDT and OMR tasks produced almost identical effects of lexicality. Moreover, there was a very strong correlation between the VR-LDT and OMR reading speed measures. It is, of course, the case that silent reading and reading aloud measures naturally correlate and this alone should not be taken to suggest that VR methods produce more robust correlations with reading aloud than classic silent reading tasks. Yet, the high correlation is not a trivial result because the OMR task is a reading aloud (production) measure that requires the exact pronunciation of a letter string, while the LDT task is a silent reading/visual word recognition measure that does not require the computation of word's pronunciation (Grainger and Jacobs, 1996; Dufau et al., 2012). In addition, OMR requires individual and supervised testing (i.e., an adult has to record the number of words read aloud), while the VR-LDT test can be done in an unsupervised, automatized fashion. The fact that these measures correlate so strongly points to a promising avenue for individualized high-quality assessment of reading fluency that does not require the intervention of an expert assessor.

Concerning the strong correlation between reading speed (wpm) in the lexical decision task and gaze durations (r = −0.76) found in the present study, this is in line with one prior study investigating such a relation with standard eye movement recording techniques during sentence reading (Schilling et al., 1998). However, given the results of more recent investigations that have revealed much lower correlations (Kuperman et al., 2013; Dirix et al., 2019), it seems likely that the high correlation found in our study is linked to the fact that the eye movement measures were obtained with isolated stimuli and not for words presented in a sentence context. In particular, the work of Dirix et al. (2019)

demonstrates the limits of using lexical decision as a proxy to real-life reading, hence the importance of complementing this measure with eye movement measures as in the present work.

A major limitation of the present study is that we have not yet used any of the typical features of virtual reality environment related to the construction of a highly interactive 3D spatial environment. Also, as children moved their heads in our study, they did not get different views of the word they were looking at. While we fully acknowledge these limitations, it is important to note that these interesting aspects of VR were clearly beyond the scope of the present article. The primary goal of our study was to provide a proof-of-concept that VR technology can provide a reliable, valid, and child-friendly way to measure reading fluency in children, without the intervention of skilled assessors, and in a normal school environment. We successfully demonstrated that one can obtain reliable word recognition and eye movement measures with a procedure that can be applied in noisy school environments.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below. https://osf.io/m8j2z.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (No. 17/051). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JM created the VR scripts, the analysis scripts and participated in the design of the experiments, in the creation of the stimuli, in the collection of the data and wrote the first draft of the manuscript. J-PA participated in the creation of the stimuli, in the analysis of the results, in the design of the experiments and in the data collection. JL helped in the creation of the stimuli and participated in the design of the experiments. JG participated in the design of the experiments and in the writing of the manuscript. JZ participated in the design of the experiments and in the writing of the manuscript.

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A Simulation Design of Immersive Virtual Reality for Animal Handling Training to Biomedical Sciences Undergraduates

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Background: One area of biomedical research concerns is applying new treatments to cure human diseases, moving bench-side research to the bedside practice. While using animal models is crucial in the research process, researchers should strictly adhere to the moral 4R framework to protect animal welfare—replacement, reduction, refinement, and responsibility. Virtual reality (VR) applies computer technology to create a simulated environment, allowing players to immerse and interact with animated 3D contexts. We developed a virtual animal-holding simulator (ViSi) using immersive virtual reality technology for students studying in the undergraduate biomedical sciences programme. The specific objectives of the paper are to 1) describe the development of the VR courseware for animal training and 2) describe the learning experience among students.

Method and Result: An evaluation of the courseware was conducted among Year one and two biomedical sciences students. Students who participated in ViSi responded positively about their involvement in the virtual environment experience and their concentration on the assigned task.

Discussion: ViSi is a reliable simulation technology that can train animal handling skills, which replaces real animals, while learners' multi-cognition could still be enhanced with simulation training. Thus, the impact of immersive VR technology integrated into skills training is promising, although few technical problems are to be resolved.

Keywords: immersive virtual reality, 4R principles, simulation, animal handling, biomedical research, undergraduate, teaching and learning

INTRODUCTION

Biomedical research has been developed over the past three decades. One of the essential purposes is to investigate the treatment of human diseases for the sake of patient wellness (Caron-Flinterman et al., 2005), especially in the fields of regenerative medicine (Mason and Manzotti, 2010) and vaccine development (Koff and Schenkelberg, 2020). During undergraduate biomedical science training, students receive integrated and multidisciplinary training ranging from research activities (Clark, 1997) to professionalism and inter-professional collaboration (McNair, 2005; Baingana et al., 2010).

Animal models are commonly used in biomedical research to investigate the mechanism of disease development and explore the therapeutic advancement of effective treatments. Even though the translation of animal experiments from bench to bedside for clinical trials is less than 8% (Mak et al., 2014; Polejaeva et al., 2016), animal studies are a core element of studying the physiological responses. While the 3R principle has long been applied in contemporary scientific practice (Russell et al., 1959), the 4R rules—replacement, reduction, refinement, and responsibility—have been adopted recently to improve the quality of care for experimental animals (Arora et al., 2011). The new 4R framework advocates reduction—to reduce the usage of animals in the laboratory; replacement—to apply an alternative technique to minimise animal suffering; refinement—to fine-tune experimental procedures, and responsibility—to ensure on-going training responding to scientific significance and accuracy for the use of laboratory livestock in academic research.

Immersive virtual reality (VR) technology is a psychological perception that is generated and stimulated by a computer-generated interface to make the user feel "being there" inside an isolated three-dimensional (3D) environment (Biocca and Delaney, 1995; Seth et al., 2011). It develops a perceptual learning style to stimulate, organise, interpret, and memorise to-be-learned information (Kratzig and Arbuthnott, 2006). The concept of simulation supports the integration of professional skill training with theories through the application. In the past decade, VR has been applied to work-based professional training sites to enable trainees to obtain experience-dependent enhancements, such as clinical skills in nursing practice (Kilmon et al., 2010), surgical procedures (Tergas et al., 2013), aviation (De Repentigny et al., 2003), and police and military training (Shendarkar et al., 2008). When commercial VRR hardware becomes affordable (Earnshaw, 2014), it enables rapid adoption and dissemination in academics (Zyda, 2005:; Riva et al., 2007).

The specific objectives of the paper are to 1) describe the development of the VR courseware for animal training and 2) describe the learning experience among students.

MATERIALS AND METHODS

ViSi Simulation

VR can be broadly applied to modern pedagogical exercises supporting active learning processes and cognitive knowledge acquisition (Seaborn and Fels, 2015; Ngan et al., 2017). This is a novel study incorporating VR simulation to teach research technique in an undergraduate biomedical sciences program to the best of our knowledge. Our earlier work described the courseware development's conceptual theory and instructional design (Tang et al., 2020). In brief, the courseware, named virtual animal holding gamified simulator (ViSi), is designed in the context of an animal holding facility, simulating the setting of the technical training of intraperitoneal injection to laboratory mice. It consists of two game levels or learning environments. The first learning environment related to the preparation room in the animal holding facility requires the learner to put on essential personal protective equipment. The second learning environment related to the experimental room for handling animals and performing experimental procedures.

FIGURE 1 | The student player wore the VR gear and played the ViSi. The classmates sat aside engaged in the learning process by discussing the accurate or wrongdoing behaviours performed by the player.

ViSi is a learner-centred game design in which the digital output of the learner's interaction with the VR environment is displayed on the monitor that allows parallel teaching—the student working with the VR environment while others observe the process—could take place (**Figure 1**). The courseware offers two benefits: firstly, it allows students to comment on the right actions or the wrongdoings committed by their classmates; secondly, it enhances students' contextual understanding of using experimental animals in the "virtual facility". (**Figures 2**, **3**).

Sampling and Recruitment

The study was approved by the Survey and Behavioral Research Ethics Committee of the Chinese University of Hong Kong.

The ViSi simulation was adopted in a skill-based training course, "Technique in Biomedical Research", in the 2020–21 academic year. Year one and two students majoring in BSc in Biomedical Sciences enrolled in the course were invited to use the ViSi simulation. The entire class of 50 students attended a 90-min regular practical class using ViSi or observing at the side. Owing to the requirement for social distancing during the covid-19 pandemic, we grouped the students into two 90-min practical sessions. With the time constraint in each practice session, not all students could experience ViSi in this study. A possible solution is to decrease the simulation period to 5 min to prevent uncomfortable disorientation from completing each session in either the preparation or experimental room, thereby allowing more students to experience ViSi.

Students were invited to play the courseware and complete a self-administrated e-survey scoping the experiential learning experience on a voluntary basis. Participants were informed

FIGURE 2 | The student player used the pair of the controllers for training the procedures of intraperitoneal injection to the mouse. The student player **(A)** concentrated on the game; **(B)** located the animal cage on the bench; **(C)** drew the drug from the bottle, and **(D)** held the mouse and performed intraperitoneal injection.

that their participation was entirely voluntary and would not affect their course assessment.

Study Measures and Analysis

Firstly, student performance in the final examination was assessed. One question was designed to examine technical and procedural knowledge in animal handling, which was used to evaluate the impact of courseware on cognitive learning. Secondly, experiential perception of ViSi was measured by two subscales adapted from a validated measure from Witmer and Singer (1998) 1) The presence subscale consisting of six items measures the capability of an individual to felt immersed in the simulation; and 2) the sensory subscale consisting of seven items measures how multisensory reception influences learning. Students were asked to rate their experience on each items using a 7-point Likert scale ranging from "Not at All" to "Completely." At the end of the survey, Students' perceptions of the learning outcomes from the ViSi were also surveyed using institutional standardised post-course evaluation. The internal consistency coefficient (Cronbach's alpha) of the scale was 0.908. Descriptive results were reported in this paper. A one-sample t-test was conducted to measure central tendency.

RESULTS

Among 50 students, 26 had simulation experience (student player). At the same time, the other 24 classmates joined as audiences to discuss and point out the wrongdoings and appropriate actions of the participants in the ViSi simulation (student observer).

Student Performance in the Examination

Figure 4 shows the distribution of the examination score between the student player and observer. The overall mean and standard deviation of the student player and observer score are 7.46, 1.87, 6.20, and 2.53, respectively. There were more than 20 students who scored over seven among student players and seven among student observers. Student players scored higher than the observer group, although no statistically significant difference was observed due to the small sample size.

Experiential Perception of ViSi

Table 1 shows students' positive feedback on using ViSi. The mean score of the items ranged from 4.83 to 5.96. The figures indicate a significant difference between the item mean scores with a test mean value of 4. Thus, the perceptual learning experience with ViSi is positive, reflected in the mean value of over 4.83. In the presence subscale, the majority student player strongly agreed that they felt actively got involved (mean = 5.92) and moved around in the VR environment (mean = 5.67), although the feeling was not too natural. In the sensory subscale, the majority student player concentrated on the assigned tasks (mean = 5.96) and examined the objects from multiple viewpoints (mean = 5.63). Student players largely agreed that they gained hands-on experience from the ViSi.

DISCUSSION

This study aimed to set up an innovative virtual reality environment to promote the safe learning of animal handling skills using VR technology. The past teaching strategies in the

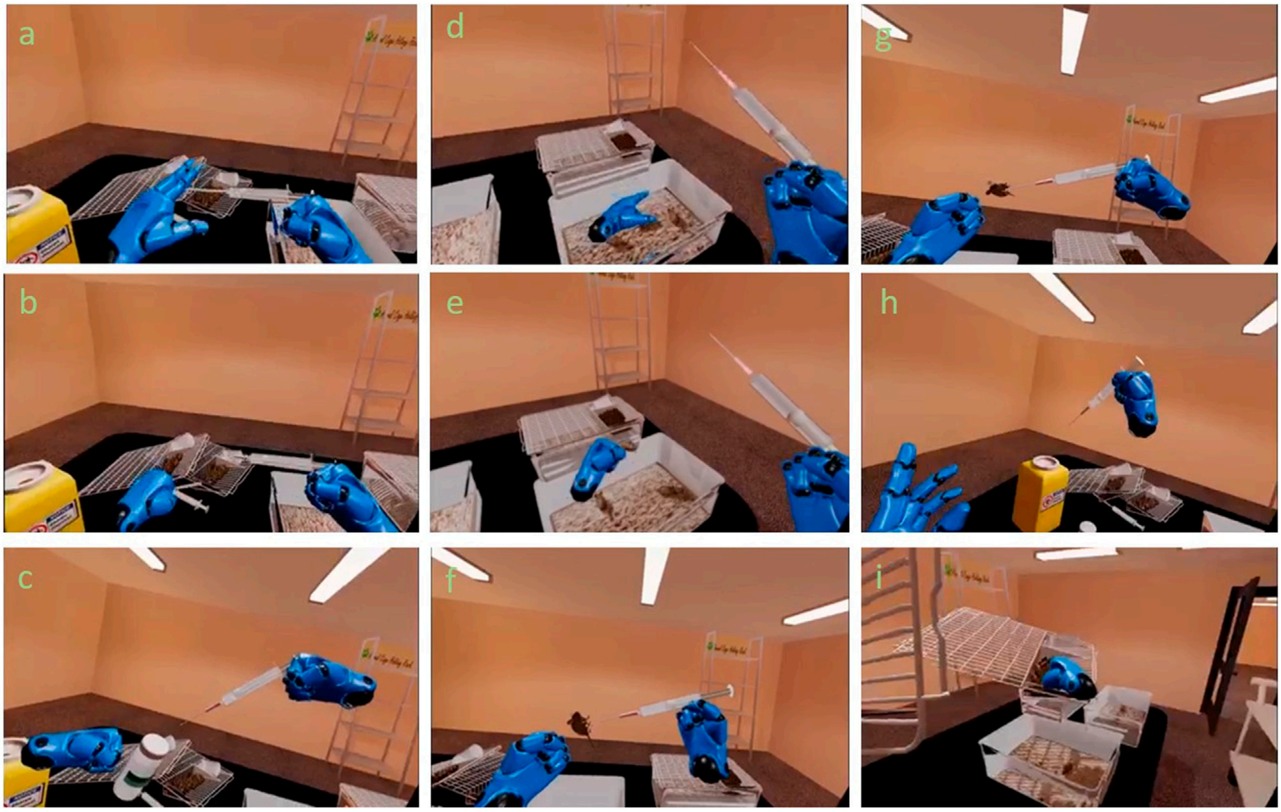

FIGURE 3 | ViSi Game-Mice Injection. The student player was instructed to perform the intraperitoneal injection in the ViSi. **(A–C)**: After opening the cages, the player took the syringe, removed the bottom cap and aspired to the appropriate volume of drug in the syringe. **(D–F)**: The player grasped a mouse from the cage, restrained it in a proper position and prepared for the injection process. **(G–I)**: The player completed the task, put the used syringe into the sharps disposal yellow container and covered the cage.

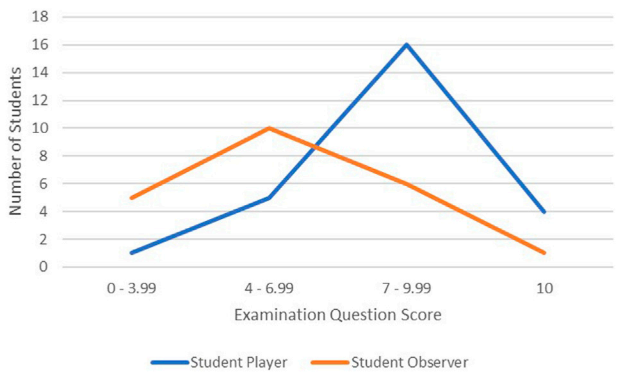

FIGURE 4 | The examination question performance between student player and observer group.

teaching animal handling techniques depend on physical practice. However, in the contemporary time advocating for animals' welfare, educators need to consider any alternative way to fulfil the ethical guidelines and duties (3). Specifically, our ViSi was designed to apply the 4R principles, introducing the moral concepts of animal handling to undergraduate biomedical sciences training. Our results supported the idea that problem-solving tasks incorporated in ViSi enhance examination and experiential learning among students. Although there was no significant difference could be tested due to the small sample size, students engaged in learning using the simulation.

Earlier research show that the implementation of VR simulation is feasible for facilitating technique learning in biomedical research and assessing competencies, including knowledge, attitudes, principles, and skills in health professional education (Konge et al., 2014; Khan et al., 2015; Khan al., 2017). Similarly, ViSi simulation allows students to learn by application, which produces a higher level of engagement using virtual animals. The current literatures show that animal research awareness among students is scarce. A survey studied Indian medical undergraduate "students" views on using animals in basic medical research. About one-tenth were aware of ethical guidelines regarding animal research and believed that animal research required stringent regulations (Nerlekar et al., 2018). Some Brazilian students were uncomfortable using animals during practical classes and refused to stay in the classroom (Rochelle et al., 2016). These responses show the requirement for more educational efforts in addressing ethical reflections that can arise through conflicting situations and low moral awareness.

TABLE 1 | Experiential perception of ViSi among biomedical sciences students.

	Items	Mean	t-value	*p*-value
Control factors	1. How natural did your interactions with the environment seem?	4.83	2.63	0.014*
	2. To what extent did the visual aspects of the environment involve you?	5.67	7.78	0.000**
	3. How natural was the mechanism that controlled movement through the environment?	5.13	4.37	0.000**
	4. How compelling was your sense of objects moving through space?	5.13	4.94	0.000**
	5. How completely were you able to actively survey or search the environment using vision?	5.92	12.11	0.000**
	6. How compelling was your sense of moving around inside the virtual environment?	5.42	6.55	0.000**
Sensory factors	7. How closely were you able to examine objects?	5.21	4.73	0.000**
	8. How well could you examine objects from multiple viewpoints?	5.63	7.54	0.000**
	9. How were you involved in the virtual environment experience?	5.75	9.56	0.000**
	10. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	5.29	4.99	0.000**
	11. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	5.96	9.60	0.000**
	12. Overall, were you able to anticipate what would happen next in response to the actions that you performed?	5.46	7.31	0.000**
	13. Overall, were you able to gain hands-on experience from the VR game?	5.42	6.31	0.000**

Notes: $p < 0.05^*$, $p < 0.01^{**}$, *Test value = 4, Mean = Likert score mean.*

An advantage of using VR simulation in perceptual learning is that students are allowed exposure to a fun atmosphere, which helps to increase learning concentration and retention time for memorisation and prolonged sensory constellations over hands-on work (Goswami, 2008). Consistent with another study (De Jong and Van Joolingen, 1998), our students reported that they engaged in experiential learning, incorporated with game elements that require problem-solving tasks. Specifically, students benefitted by implementing the theoretical knowledge in a simulated setting. However, these advantages are not provided in the traditional classroom teaching medium, mainly delivered by PowerPoint presentations and textbooks (Yahaya and Ahmad, 2017). The majority of participants agreed that they could concentrate on the assigned tasks rather than on the procedural mechanisms to perform those tasks or activities during the simulation. From the observation in the practical sessions, both sides of the students are excited, engaged and enjoyed the digital simulation.

Current students were adaptive to information technology. Most students in our study reported high satisfaction in the sensory reception and seamlessly integrated into the virtual reality, suggesting that the courseware provides them with an immersive and interactive experience. In the ViSi, we adopted Unreal Engine 4 (UE4) to create the VR scene, which provides an actual render process, creating a "lifelike" and immersive experience when the student is inside the task environment. The incorporation of the fun search atmosphere into knowledge development can also enhance students' learning motivation. Furthermore, it provides a new era of strategic pedagogy for other broad-based techniques in research activities that encourage more students to participate in biotechnology industries with interest. Additionally, it improves the quality of teaching, promotes active learning among students, uses different skill training methods during practical sessions, and promotes after-class discussions between students and teachers, rather than a one-way effort. Although they cannot sense the touching animals, an intrinsic limitation of controllers, it is not surprising that students felt naturally immersed in the simulation due to the leverage of gamified setting simulation.

CONCLUSION

ViSi represents an excellent example of how VR guides and enhances learners' cognition of the virtual environment. More importantly, it arouses the learner's critical thinking, stimulates problem-based learning, and shares the learning experience with peers. The impact of VR technology integrated into skills training is promising, although few technical problems are required to be resolved. For example, the learner may feel dizziness or cybersickness after using the head-mounted device, and game engine software has insufficient detection of the learner's posture. VR is in-house developed courseware, which incorporates conventional didactic pedagogy and is novel from both teachers' and students' perspectives. It is a reliable training material that can help students understand animal handling skills and replace the usage of real animals and enhance learners' multi-cognition with the use of simulation. Students appreciated the early exposure to animal handling, especially for drug administration, and found it an opportunity to acquire the humanistic side of science in animal ethics. In future, VR technology can be a supportive teaching pedagogy for perceptual learning in technical practice.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Survey and Behavioural Research Ethics. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

FT is the chief project investigator who oversees and implements the project. AL and JC managed the logistic flow of the practical session. FC contributed to the data collection and analysis. FT and ON made a substantial contribution to the manuscript writing. RL, RS and JC were computer engineers setting up the ViSi.

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Student's Perspectives on Augmented Reality in Pharmacy Education in Hong Kong

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Introduction: Augmented reality (AR) technology has demonstrated potential on various areas of healthcare practice. Its role on medical education is starting to emerge. This study aimed to investigate students' perspectives on using AR as learning tools in undergraduate pharmacy education.

Methods: Four AR micro modules on post-stroke management and chronic obstructive pulmonary disease (COPD) were developed for third year undergraduate pharmacy students to study. Students played the role of pharmacists in the AR micro modules. They collected information to identify patient's chief complaints, history, risk factors, comorbidities, and other problems, and provided recommendation on patient's treatment plans. Teacher guided the discussions and addressed student's enquiries. Student's feedback was collected by pre- and post-intervention survey.

Results: A total of 54 students participated in the current study. The was no significant change in students' perceived knowledge on post-stroke management and COPD, as well as their confidence in providing patient counselling on relevant topics. Students expressed that their learning experience with AR was not positive. Technical problems were the major difficulties that students encountered.

Conclusion: There was no significant difference in pharmacy students perceived clinical knowledge and confidence on patient's counselling after completing the AR modules. Technical issues were the major hurdles that hindered student's learning experience with AR.

Keywords: pharmacy education, augmented reality, pedagogy, active learning, practice experience

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INTRODUCTION

As future healthcare professionals, pharmacy students must be equipped with knowledge and skills to provide patient-centred care in a team-based approach. (Zgheib et al., 2010; Miller et al., 2017; Lang et al., 2019) The Accreditation Council for Pharmacy Education emphasizes that pharmacy programs provide students with the knowledge, skills, and abilities to provide patient-centred care and solve problems. (Accreditation Council for Pharmacy Education, 2015) Practice experience is

Abbreviations: AR, Augmented reality; COPD, Chronic obstructive pulmonary disease; CUHK, The Chinese University of Hong Kong.

essential for students to polish their communication skills and problem-solving skills. (Svensberg et al., 2018; Teramachi et al., 2018) Nevertheless, actual practice experience could be influenced by numerous factors, such as the availability of clinical sites, patient cases, and teaching staff. (Wartman, 2019; Shrestha et al., 2020) As information technology and communication technology advances, it is suggested that the challenges could be overcome by using simulated cases. (Okuda et al., 2009; Ray et al., 2012; Shin et al., 2015)

In recent years, augmented reality (AR) has demonstrated potential on various aspects in the medical field, including diagnosis, assessment, and treatment. (Freeman et al., 2017; Laver et al., 2017; Rothgangel et al., 2018; Chen et al., 2019; Feng et al., 2019) AR is an enhanced version of the real physical world that is achieved through the use of digital visual elements, sound, or other sensory stimuli delivered via technology. (Investopedia, 2020) One advantage of AR in medical education is the ability to visualize body tissues, for example, the skin, organs and muscles. (Sayadi et al., 2019; Yu et al., 2019; Siyar et al., 2020) Another advantage is that AR can repeat a simulated procedure as many times as desired, which is not practical in real patients or real environment. (Izard et al., 2018; Cao and Cerfolio, 2019) Pilot studies suggested that AR was a useful tool to create engaging and easy to use learning experiences in pharmacy education. (Salem et al., 2020; Schneider et al., 2020) Pharmacy students showed improvement in drug knowledge after completing the AR exercise and reported high usability and acceptability of AR for learning. (Salem et al., 2020; Schneider et al., 2020) AR technology can engage students into an active learning environment, which has been proven to be more effective than passive learning. (Ramnanan and Pound, 2017; Styers et al., 2018; Coyne et al., 2019) The technical capabilities of AR can support a learning-by-doing approach stressed by the constructivist learning principles. (Chen, 2010) They are also useful tools for delivering knowledge through embodied cognition, which emphasizes the interaction between learner and the environment. (Dunleavy and Dede, 2013) Nonetheless, AR is still considered as new technology in terms of pedagogy. They have not been widely adopted in the curriculum, and most teachers and students have limited experience of applying AR in education.

The current study aimed to investigate student's perspectives on using AR as learning tools in undergraduate pharmacy education.

METHODS

Study Design and Study Population

Our study population included third year undergraduate pharmacy students from the Chinese University of Hong Kong (CUHK) in 2018/2019 school year. Yearly, we admitted up to 60 pharmacy students. The pharmacy curriculum lasted for 4 years. In the first 2 years, students learnt the basic biological concepts and laboratory skills. In the third year, students had in-depth training on drug pharmacology and therapeutic uses. In the fourth year, students had clerkship training at clinical sites. They needed to review patients' conditions and propose treatment plans for them independently. After graduation, they would receive internship training at workplaces for 1 year before registration.

The AR micro modules were used in the course "Clinical Assessment and Monitoring", which was a 3-units (3 h per week for a total of 13 weeks) compulsory course for third year pharmacy students at CUHK. It was a preparatory course prior to the clinical clerkship for the pharmacy students at the teaching hospital. This course involved classroom teaching on the theories on drug therapy assessment and therapeutic outcomes monitoring skills, as well as practicum in which students needed to apply previous knowledge on therapeutics to evaluate real patient cases in the teaching hospital. Upon completion of the course, students should be able to obtain medication-related information accurately, retrieve laboratory test results and vital signs, identify and utilise drug information resources to assist with patient-specific drug therapy monitoring, and present patient cases comprehensively.

Traditionally, learning activities of "Clinical Assessment and Monitoring" included lectures, discussion, medication chart review, and presentations. Teachers illustrated the technique of patient assessment by showing students some written case summaries, photos, and videos during lectures. Afterwards, students needed to review real patient cases, present the cases in class, and provide their recommendations. In the current study, four AR modules on post-stroke management and chronic obstructive pulmonary disease (COPD) were developed to illustrate clinical cases during lectures. These two topics were chosen for two major reasons. Firstly, pharmacology and therapeutics knowledge on COPD and stroke were covered in the course 'Pharmacology and Therapeutics I' (offered in year 2 semester 2) and 'Pharmacology and Therapeutics II' (offered in year 3 semester 1), respectively. Students taking the course 'Clinical Assessment and Monitoring' (offered in year 3 semester 2) should have adequate knowledge on the pharmacological management of COPD and stroke. Thus, the AR modules could focus on training students' drug therapy assessment skill and patient counselling skill. Conversely, if diseases covered in 'Pharmacology and Therapeutics III' (offered in year 3 semester 2) or 'Pharmacology and Therapeutics IV' (offered in year 4 semester 1) were chosen, extra time and effort would be needed to introduce the fundamental knowledge of disease management. Secondly, COPD and post-stroke management involved different pharmacist assessment skills, such as assessing disease control, inhaler technique, pharmacological and non-pharmacological treatment to improve patients' outcomes, etc. Previous students taking the same course often found them difficult to gather information and give advice when working on the real patient cases. The AR modules allowed students to practise their patient interview and counselling skills before working on the real cases.

Materials

Four AR micro modules on post-stroke management and COPD were launched. In each micro module, students were provided

Case background

Mr. TM Chan, a 68-year-old male, reports that he has bad respiratory problem.

You are conducting a health interview with Mr. Chan at a community outreach event. With further questions, you learn that he has been diagnosed with Chronic obstructive pulmonary disease (COPD) for more than 10 years. He reveals that he recently paid a visit to his family doctor for the flu and poor coughing. He shows you the medication bags with label. He claims that he is getting better with the medications. He asks for your comment and recommendation on whether he should keep getting the medications elsewhere.

A Case background

B Photo of patient's medications (Trigger image)

"The blue one, 4 times a day, 2 puffs each time. I have been using it for 10 years. The red one, twice per day, 2 puffs each time. I have tried my best to follow the instructions. But I sometimes forget to bring them with me when I'm out for work." TM Chan.

"I have a follow-up appointment next week and I will probably get a bunch of drugs. There are still a few unused inhalers at home. I think the drugs are not really useful." TM Chan.

C Script of the video clip (Overlay)

FIGURE 1 | Content of a COPD micro module with case background, picture, and video script.

with a brief description of patient's case background and pictures showing hospital or clinic settings. Students needed to collect information on patient's chief complaint, past medical history, social history, current medications, and laboratory tests results in order to assess patient's disease control and recommend treatment plans. To collect the required information, students needed to use an AR scanning application, Layar, in their mobile device to scan and view the hidden items on each picture. The items included videos, audios, texts, and graphics. Students would be able to identify patient's chief complaints, history, risk factors, comorbidities, and other problems in the process. An example of COPD module was shown in **Figure 1**. A short paragraph describing the case background was first given to students. Then, students should scan the pictures (trigger images) located in different part of the classroom using Layar. By scanning a picture (trigger image) of an inhaled medication, students would get a video describing how the patient used the inhaler (overlay). By scanning a picture (trigger image) of a health questionnaire, students would get a patient interview audio describing patient's lifestyle, smoking habit, and sleep pattern (overlay). With the hidden information collected, students would be able to assess patient's condition and propose treatment plans.

In the classroom, students first worked on the AR cases individually, then discussed the clinical problems shown in the cases with their classmates and provided their recommendation on the treatment plans. The teacher guided the discussion, addressed student's questions, and provided feedback and suggestions to the proposed treatment plans.

Statistical Analysis

Pre- and post-self-evaluation surveys were used to assess the changes in students' knowledge on the relevant topics, evaluate the changes in their confidence on patient counselling, and collect feedbacks from students regarding their learning experience. Students were asked to rate, using Likert Scale of 1 (strongly disagree) to 5 (strongly agree), their self-perceived knowledge and confidence on COPD and post-stroke management in the pre- and post-survey. Data were presented as mean ± standard deviation. The changes in student's score before and after engaging in AR learning activities were assessed by Wilcoxon signed-rank test. Statistically significance was defined as p-value <

TABLE 1 | Student's feedback on AR micro modules.

Changes in students' knowledge	Pre-test (n = 50)	Post-test (n = 44)	*p*-value
I am familiar with COPD.	2.74 ± 0.88	2.80 ± 0.85	$p = 0.79$
I am familiar with post-stroke	2.22 ± 0.95	2.55 ± 0.87	$p = 0.17$
Changes in students' confidence in patient counselling			
I am confident to give a consultation to a COPD patient	2.34 ± 1.02	2.55 ± 0.98	$p = 0.43$
I am confident to give a consultation to a post-stroke patient	2.06 ± 0.98	2.43 ± 0.97	$p = 0.09$
Generally speaking, I am very confident with my patient consultation skills	2.30 ± 0.93	2.61 ± 0.89	$p = 0.15$
Students' feedback			
AR case studies can enhance my interest in learning certain disease topics	3.40 ± 0.83	2.90 ± 1.01	$p = 0.06$
AR supports authentic learning	3.48 ± 0.71	2.81 ± 1.06	$p < 0.01$
AR allows me to experience patient cases which would be impossible to generate in normal classroom environments	3.56 ± 0.81	2.95 ± 1.12	$p = 0.01$
AR develops an immersive learning experience	3.48 ± 0.68	2.84 ± 1.06	$p < 0.01$
I enjoy using AR as a learning tool	3.24 ± 0.85	2.75 ± 1.12	$p = 0.02$

AR: augmented reality; COPD: chronic obstructive pulmonary disease.

0.05. All statistical analyses were performed using IBM SPSS Statistics version 26. All students provided their written informed consent before participating in this study.

RESULTS

A total of 54 third year pharmacy students participated in the current study. There were 50 (92.59%) and 44 (81.48%) students who completed the pre-test and post-test respectively.

Table 1 summarized the changes in student's knowledge, confidence in patient counselling, and their learning experience with the AR micro modules. Students perceived that they were more familiar with COPD and post-stroke management, and were more confident with patient counselling. The changes were not statistically significant. However, students expressed negative feeling on their learning experience and gave lower scores in the post-test when asked whether they enjoyed using AR as learning tools and whether AR could support learning.

Students left both positive and negative comments on the survey. In general, students appreciated teacher's effort in designing the micro modules. They thought that the AR exercise could resemble real life practice, in which they needed to search for scattered patient information. One student wrote "I think it is good, since it is in outreach settings, some medical information about the patient cannot be obtained, and we have to analyze the case based on limited information, which is quite realistic." The major issue students raised was technical problem. A student wrote "Many of us cannot scan very well, especially in the lecture theatre." Another student wrote "Take too much time scanning, but actually can put the images online in advance." Some students though there was not a big difference between AR micro modules and their usual case study exercises.

DISCUSSION

In recent years, the scope of AR application has expanded, ranging from entertainment, urban planning, travelling, education, to healthcare. The use of AR in medical education has increased with the intention of achieving the potential benefits. One advantage is to make a patient case reproducible. (Izard et al., 2018; Cao and Cerfolio, 2019) In pharmacy education, AR exercises allow students to practise their drug therapy assessment skills and patient counselling skills anytime. (Fox and Felkey, 2017; Ventola, 2019) Previous studies had revealed an important benefit of virtual reality (VR) and AR exercises, which was to allow students to make mistakes while showing them the consequences of making a wrong decision. (Davidson et al., 2012; Nifakos et al., 2014) It could strengthen their memories on clinical knowledge and skills. Besides, VR and AR exercises allow each student to participate in the cases. In ward round settings, it is not feasible for each student to interview the same patient. VR and AR exercises can eliminate the time constraint and avoid disturbing the patient. (McGrath et al., 2018; Fealy et al., 2019) In addition, a teacher could run several simulated exercises at the same time, which further reduce the time constraint of teaching staff and students could gain more practice experience. (Caudell et al., 2003) Our study population, third year pharmacy students, had not started bedside learning. They did not have hands-on experience of reading case notes, taking patients history, or counselling patients. The AR exercises offered students the chance to practise and polish their skills before they entered clinical year and internship.

Despite the theoretical benefits that AR exercises can bring to medical education, studies have identified the limitations and problems in actual practice (Uruthiralingam and Rea, 2020). A systematic review by Gerup et al. analysed 26 studies involving AR or mixed reality in healthcare education. (Gerup et al., 2020) Gerup et al. pointed out the weaknesses of the studies, as well as the common difficulties with using AR as reported by the studies. (Gerup et al., 2020) One major problem identified was the inadequate evidence for improving learning. Studies were often designed as single group user studies, (Ma et al., 2016; Wang et al., 2016; Solbiati et al., 2018; Mewes et al., 2019) and many presented descriptive findings from self-reported evaluations without statistical analysis. (Sutherland et al., 2013; Bifulco et al., 2014; Ma et al., 2016; Wang et al., 2016; Kugelmann et al., 2018; Solbiati et al., 2018; Zhu et al., 2018; Mewes et al., 2019) This limited the generalisability of study results. Moreover, a portion of the studies reported no significant impact of AR on enhancing student's learning outcomes. (Moult et al., 2013; Moro et al., 2017; Noll et al., 2017; Rochlen et al., 2017; Siebert et al., 2017; Wang et al., 2017; Huang et al., 2018) Technological limitations were the common challenge reported among the studies. (Gerup et al., 2020)

In view of the conflicting results, there is a need to conduct a thorough assessment on how AR technology can facilitate student's learning, as well as evaluate student's perspectives on the new pedagogy. Our results echoed that reported in literature. Technical issues were the major problem that teachers and students encountered. Extra effort was needed to play an AR or VR video in usual classroom settings, as compared to a plain video. (Caudell et al., 2003; Samaniego Villarroel, 2016) For example, it took longer time for teachers to set up the devices in the classroom and for students to download the videos in their laptops. If the classrooms were not covered with stable network, it would take much more time for downloading the videos and graphics in class. In addition, playing AR or VR videos drained away the battery in the laptops quickly. It would be un-user-friendly if hardware supports were inadequate. As a result, student's learning experience was not positive. On the other hand, there was no significant difference in student's perceived knowledge and confidence with the topics. It might be because the AR exercises mainly simulated the patient interview and data collection process. Students evaluated their performance mainly through in-class discussion with peers and by listening to teacher's comments after class. Instant feedback from the AR exercises was limited. Thus, some students thought the learning objectives could be achieved by using conventional paper cases, which requires less preparation time and manpower.

With e-learning being more and more dominant in education, the prevalence of using AR in teaching is expected to grow. (Bacca et al., 2014; Lilly et al., 2019) Under the continued influence of Covid-19 pandemics, a lot of teaching activities such as practicum, clerkship, and clinical attachment had been called off. (Ahmed et al., 2020; Newman and Lattouf, 2020; Rajab et al., 2020; Singh et al., 2020) AR cases could provide alternative channels for students to learn. As technology advances, AR are getting more common in medical practice. (Li et al., 2017) It is expected that students will come across AR in their future careers. It would be beneficial for students to adapt to the technology during university study. Thus, the role of AR in the pharmacy curriculum should be further explored. Still, to ensure that AR technology can really add values to medical education, it is essential to define the learning objectives clearly and conduct structured evaluation on student's learning outcomes. Given that the time and financial cost required to produce an AR video are much longer than that of a plain video, it is crucial to select suitable topics when designing the teaching materials. Otherwise, AR exercises may not be cost-effective if the knowledge can be conveyed in a more straightforward way.

There are a few limitations in the study. Firstly, the impact of AR micro modules on student's learning was evaluated based on self-assessment. The cases were discussed in class to make sure students knew the right answers, but there was no specific quiz to formally assess the gain in knowledge among students. A more concrete relationship between the use of AR and student's performance could be established if their examination results were compared. Secondly, the sample size of this study was limited by the class size of pharmacy department. Student's opinions and suggestions had been collected in the study. The tools should first be modified, then the survey can be repeated in the subsequent years to increase the sample size.

CONCLUSION

There was no significant difference in pharmacy students perceived clinical knowledge and confidence on patient's counselling after completing the AR modules. Technical issues were the major hurdles that hindered student's learning experience with AR.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Survey and Behavioural Research Ethics Committee of the Chinese University of Hong Kong. Reference number: 14610518. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. JL analysed data and wrote the article, EN arranged the logistics and prepared teaching materials, VL contributed to the study design and supervised the study.

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REVIEW
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Eye-Tracking in Immersive Virtual Reality for Education: A Review of the Current Progress and Applications

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The concept of using eye-tracking in virtual reality for education has been researched in various fields over the past years. With this review, we aim to discuss the recent advancements and applications in this area, explain the technological aspects, highlight the advantages of this approach and inspire interest in the field. Eye-tracking has already been used in science for many decades and now has been substantially reinforced by the addition of virtual and augmented reality technologies. The first part of the review is a general overview of eye-tracking concepts, technical parts, and their applications. In the second part, the focus shifted toward the application of eye-tracking in virtual reality. The third part, first the description of the recently emerged concept of eye-tracking in virtual reality is given, followed by the current applications to education and studying, which has not been thoroughly described before. We describe the main findings, technological aspects, and advantages of this approach.

Keywords: eye-tracking, virtual reality, education and VR, eye-tracking in VR, education

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INTRODUCTION

Eye-tracking is a technology that has for a long time been used in the humanitarian, language (Kaushanskaya and Marian, 2007; Suvorov, 2015; Aryadoust and Ang, 2019), medical research (Pernice et al., 2014; Rigby et al., 2020), and quite recently it has found its way into the field of user experience design. One of the most well-known and cited examples of the use of eye-tracking is given in a study from Nielsen (2006), where people were browsing the internet and looking at the search engine results, while their gaze was tracked. It has been shown that their attention is scattered on the page in the shape of a triangle or letter F. This research has then been followed up and proved later in other studies (Brunyé et al., 2019). Active use of eye-tracking technology over recent years has facilitated the delivery of information to the consumer through the media. Eye-tracking has been also applied to biomedical research and showed good results in the rehabilitation measures after ischemic brain damage (Krupinski et al., 2006; Cameirão et al., 2016; Faria et al., 2016; Peshkovskaya et al., 2017; Maggio et al., 2019a,c,d).

The successful use of eye-tracking technology in medical treatment has influenced the research to turn toward the use of eye-tracking with healthy patients. Thus, when studying the decision-making process of an individual related to the need for social interactions in a virtual environment, it was demonstrated that eye-tracking technologies can be used as a forecasting tool. The frequency and duration of fixation, the peak velocity, and amplitude of saccades can be used to identify and eliminate transient states of uncertainty when making perceptual decisions (Maggio et al., 2019b), as well as to assess the complexity of a problem when it becomes too complicated due to many details (Brunyé and Gardony, 2017). In predicting decision making, gaze fixation, fixation duration, and the number and duration of visits are of great importance. Sustainable combinations of these parameters form various starring strategies (Spinks and Mortimer, 2016).

Moreover, with the help of eye-tracking, it is possible to identify higher nervous functions such as emotions, regret, and disappointment (Nakhaeizadeh et al., 2020), as well as memorization processes (Bault et al., 2016). It has also been shown that eye-tracking technologies can be used to control decision-making (Helbing et al., 2020) for example by increasing its value (Fridman et al., 2018). A recent study (Smith and Krajbich, 2019) showed the importance of the multiplicative model, which states that greater attention to options when making a choice, has higher influences on choices. Another important study has demonstrated (Pärnamets et al., 2015) that the number of eye movements between informationally important objects in the context of the current task can be used as an indicator, which has an inverse relationship to the quality of solving a cognitive task.

Research in the field of eye movements and eye trajectories analyses in the context of virtual three-dimensional space are fairly new. Some works are aimed at studying the emotional behavior of a person interacting with objects in a virtual space, in particular studies (Rosa et al., 2017; Reichenberger et al., 2020), implicit eye movements and their significance were analyzed with regards to the influence of attention on the emotional learning processes. Some researchers are studying the possibility of forming interactive interfaces for influencing the virtual environment by changing the trajectory of the gaze (Paletta et al., 2020). Research in the field of education is also beginning to appear, for example, in Piotrowski and Nowosielski (2020), the possibility of constructing a predictive system for students' skill level was studied by analyzing their trajectory of gaze in a virtual environment. Part of the research is also aimed at analyzing the usability of virtual reality (VR) interfaces by studying the gaze trajectory fixed in virtual three-dimensional space (Orlosky et al., 2019). Thus, over the past 5 years, sufficient experience has been gained in using eye-tracking as a technology for predicting, evaluating, and managing the solution of emotional and cognitive tasks.

The concept and applications of eye-tracking in education has already been described in several review papers. Rappa et al. (2019) have investigated different ways in which eye tracking can be implemented into the learning process by providing a detailed scoping review with measures and emerging patterns of eye tracking in learning environments. A recent review on applications of eye tracking into the digital learning environment (Gorbunovs, 2021) summarized the concept of eye tracking and current challenges in the field that have to be considered when applying eye tracking into the learning environment, such as the cultural background, gender, age, and literacy of the prospective users. Another new interesting work published in the special issue dedicated to the Research of Visual Perception in Educational Science (Kaakinen, 2021) indicates issues of the eye tracking research related to the operationalization of the theoretical constructs. More specifically, the paper explores the basic concepts of eye tracking, the measure of students' engagement as well as the measure of teachers' expertise. Moreover, the paper goes on to explore eye-movement as an indicator of student-teacher interaction. The second major point raised in the paper, is the analyses of eye tracking data.

Although there has been extensive research and many review papers on the topic of eye-tracking technology in various education areas, the concept of eye-tracking in virtual reality for educational purposes is a rather new direction that has only appeared in the last few years. Compared to previous review papers (Lai et al., 2013; Brunyé et al., 2014; Tien et al., 2014; Asan and Yang, 2015; Alemdag and Cagiltay, 2018; Weiss et al., 2018; Aryadoust and Ang, 2019; Rappa et al., 2019; Radianti et al., 2020), the current review combines both eye-tracking descriptions in various fields, focusing on education, and virtual reality, as well as their combination, which allows a novel perception of the existing techniques and technologies aimed at the improvement of the education process. With the existing knowledge, it is important to highlight the current progress in the area of eye-tracking in virtual reality for educational purposes. The study focuses on the existing applications in various fields of education as well as on proposing new ones. Over the past years, the most reported area of education with regards to eye tracking is medical education, many examples of which are mentioned in the current review. However, one of the aims of the article is to highlight the importance of research and implementation of technology in other areas of natural sciences education.

The article consists of three parts: a brief overview of eye-tracking techniques and application fields with the highlights of major developments, the implementation of eye-tracking in virtual reality in different fields of science, and the description of ongoing new research in the field of eye-tracking in virtual reality and education.

Literature Review

For the current review, the Scopus Electronic Library had been used to conduct the literature analysis. Various search queries were used, which included combinations of keywords in the Title, Abstract, and Keywords fields. For searching the articles that are related to various aspects of eye-tracking technology these combinations of keywords have been used:

"eye tracking," "eye movement," "eye tracking" AND "behavioral science," "eye tracking" AND "education," "eye tracking" AND "medicine," "eye tracking" AND "design," "eye tracking" AND "virtual reality," "eye tracking" AND "virtual reality" AND "education," "eye tracking" AND "virtual reality" AND "studying," "eye tracking" AND "virtual reality" AND "teaching," "eye tracking" AND "virtual reality" AND "learning."

For the 4th section of the current review, the initial search query included "eye tracking" AND "virtual reality" and resulted in a total of 1,632 papers. Out of them, 644 were obtained by limiting the presence of the word "learning." There were 409–64% articles of Computer Science subject area, 204–32% of

Engineering, 129–20% of Medicine, 105–16% of Mathematics, and 99–15% of Neuroscience. Further filtering of the 1,632 articles by the word "training" gave 527 documents, where the ratio of subject areas was: Computer Science – 302 (55%) articles, Engineering – 179 (32%), Medicine – 138 (24%), Mathematics – 82 (14%), and Neuroscience – 62 (10%). The first search that included the word "teaching" resulted in 124 documents within the following subject areas: 62–48% articles of Computer Science, 38–29% of Medicine, 37–28% of Engineering, 26–19% of Social Sciences, and 17–12% of Mathematics. Also, 93 articles were discovered by including the word "studying" into the search query within these 1,632 documents: 64% of them were dedicated to Computer Science (61 articles), 21% to Engineering (21 articles), 18% to Medicine (19 articles), 15% to Neuroscience (16 articles), and 10% to Mathematics (11 articles). By including the word "education" into the search within initial 1,632 articles, 307 papers had been identified. The priority areas covered by these documents were: Computer Science (59% – 188 articles), Engineering (30% – 97 articles), Medicine (23% – 78 articles), Mathematics (13% – 47 articles), and Social Sciences (11% – 40 articles). A more detailed overview of the papers used in the current review, organized by sections of the review, is given in **Table 1**.

EYE-TRACKING CONCEPTS AND APPLICATIONS

When it comes to human cognition, eye-tracking is a tool that has extensively been used for various research (Rappa et al., 2019). The first eye tracker device came about in the early 20th century, and it consisted of special contact lenses that were used with a pointer attached to them. This technique was then changed and optimized by using light beams and recording their reflection on film instead (Huey, 1968; Duchowski, 2003). In the 1960's modern eye-tracking approach had been developed, since then it has been further studied and improved (Buswell, 1937; Tatler et al., 2010). It is safe to say that the methods used for detecting eye movements have become significantly more accurate in recent years. At the moment, the most used methods involve video systems with computer vision techniques usage (Yarbus, 1967). Recent technological advances such as high-quality cameras have facilitated the use of eye-tracking devices of small size. These small devices can now be combined with portable "smart" glasses or a VR headset to provide accurate measures of eye movement and large data sets. Eye-tracking methods have been described in a variety of different experimental works (Hansen and Ji, 2010). Due to technological advances, eye-tracking is now widely and efficiently used in human cognition research.

Technological Aspects

The modern eye tracking devices can track the gaze by using an array of infrared or near-infrared light sources and cameras (Deubel and Schneider, 1996). The concept behind the majority of currently used system is based on an array of light sources illuminating the eye, which then produces a corneal reflection. The relationship between the produced reflection and the center of the eye pupil is then recorded, so that the vectors linking the eye position to the location in the perceived world can be calculated (Yarbus, 1967). The calculated viewpoint in space moves with the movement of eyes. Several hardware configurations of eye trackers are available on the market at the moment. These include systems that provide head stabilization, the so called «chin up» systems, as well as the remote ones that can only account for a limited amount of head movement. Moreover, there are also mobile eye-wear-based systems, which are the most modern of all. All of these hardware types have different advantages and disadvantages that are related to spatial (i.e., tracking) accuracy, tracking speed, mobility, portability, availability, and cost (Holmqvist et al., 2012; Funke et al., 2016).

Several indicators of visual behavior play an important role in understanding the interpretive processes behind gaze. Such indicators are, for example, position, motion, numeracy, and latency indicators (Deubel and Schneider, 1996). The fixations are the instantaneous pauses of the eyes that are measured in milliseconds. Saccades are the movements of the eye between successive fixations (Deubel and Schneider, 1996). Since the eye is constantly moving between fixation points, eye trackers are able to collect large amounts of data. Motion measurements provide quantitative analyses of the eye movement patterns in space during saccades. Examples of such measurements include the distance between successive saccades and saccade speed. Cartesian coordinate space is used to measure position of the gaze. The frequency of fixations and saccades is identified by the numerical measures of the eyes during scene perception. It is for example recorded, how these numerical values changes the position of the subject changes. The latency measures are then used to estimate the temporal dynamics of fixations and saccades, the example of these measures can include the duration of fixations and of saccades.

Once the fixations and sequential saccades have been recorded, the analysis is then carried out. The factors that are taken into consideration when analyzing are the internal and external states. The first includes states like frustration, uncertainty, anxiety, etc., while the latter is, for example, the organization of the stimulus. After explaining the technical side of the eye-tracking process, it is important to consider the areas of science and research where this technology has been most successfully applied in recent years.

Eye-Tracking in Behavioral Science

One of the fields where eye-tracking has been extensively used and studied over the last decade is without a doubt behavioral and cognitive science. There have been many studies that present eye-trackers for tracking changes in cognition (Lai et al., 2013; Holmqvist and Andersson, 2017). In one such study, it has been shown that the total viewing time and fixation time in areas corresponding to non-cooperative solutions are associated with the general level of participants' cooperation. The increase in the total viewing time and fixation time on the areas that correspond to non-cooperative solutions happens due to the preference for non-cooperation by participants and a decrease in the overall level of cooperation. Therefore, the viewing

TABLE 1 | Overview of the articles used for each section of the review by topic, virtual reality (VR) content, educational content, and educational method.

Section	Number of articles	Years	Topics covered (with the number of articles in brackets)	VR content (for articles included the educational part)	Educational content (for articles included the educational part)	Evaluation method
Introduction	36	2006–2021	Medicine (11) Social sciences (9) Psychology (6) Computer science (6) Neuroscience (6) Arts and humanities (4) Nursing (3) Agricultural and biological sciences (3) Biochemistry, genetics, and molecular biology (3) Engineering (3) Business, management and accounting (1) Decision sciences (1) Mathematics (1) Health professions (1)	Augmented reality, Immersive virtual reality, and 3D interfaces	Theoretical descriptions of the use of eye tracking technology in school, Experiments during the educational process	Outcomes-based
Eye-tracking concepts and applications: Technological aspects	10	1937–2019	Computer science (5) Social sciences (5) Mathematics (1) Neuroscience (4) Psychology (3) Medicine (2)	-	-	Process-based Outcomes-based
Eye-tracking concepts and applications: Eye-tracking in behavioral science	10	2011–2019	Psychology (5) Neuroscience (4) Medicine (3) Social sciences (2) Arts and humanities (1) Biochemistry, genetics, and molecular biology (1)	-	Discussion of the validity of eye tracking technology used in education due to the results of measurements showing the behavior in learning	Process-based Outcomes-based
Eye-tracking concepts and applications: Eye-tracking in education	7	2009–2021	Computer science (3) Social sciences (2) Psychology (2) Medicine (2) Decision sciences (1) Neuroscience (1)	Augmented reality, 3D interfaces	Experiments during the educational process, Discussions about the opportunities of implementation eye tracking for both students and teachers	Goal-based, Process-based
Eye-tracking concepts and applications: Eye-tracking in medicine	32	1995–2020	Medicine (16) Social sciences (10) Psychology (4) Neuroscience (3) Biochemistry, genetics, and molecular biology (3) Computer science (3) Engineering (2) Arts and humanities (2) Agricultural and biological sciences (2) Health professions (1) Nursing (1)	Non-immersive virtual reality and Desktop virtual reality	Experiments not confined directly to the educational process, Implementation in the classroom	Goal-based, Outcome-based
Eye-tracking concepts and applications: Eye-tracking in design	18	1996–2020	Earth and planetary sciences (5) Environmental science (4) Social sciences (4) Psychology (3) Arts and humanities (2) Medicine (2) Agricultural and biological sciences (1) Computer science (1) Neuroscience (1) Mathematics (1)	-	-	Process-based, Outcomes-based
Eye-tracking in VR	16	1960–2020	Computer science (5) Medicine (4) Neuroscience (4) Social sciences (4) Psychology (3)	Non-and Immersive virtual reality, Desktop virtual reality, Augmented reality, and 3D interfaces	Describing the integration into the educational process	Process-based
Eye-tracking in VR for education	12	2006–2020	Medicine (2) (Aggarwal and Darzi, 2006; Litchfield et al., 2010)	Immersive virtual reality simulator; Desktop virtual reality and pictures of x-ray	Theoretical benefits of virtual operating suites as a part of educational environment; Experiment with double checking the x-ray using the eye tracking	The success of the virtual operation and the motor skills acquisition are able to be measured by the experiments; Tracking eye movement trajectories during the operation; Comparison of the results of separate groups.

(Continued)

TABLE 2 | (Continued)

Section	Number of articles	Years	Topics covered (with the number of articles in brackets)	VR content (for articles included the educational part)	Educational content (for articles included the educational part)	Evaluation method
			Psychology, Social sciences (4) (Jarodzka et al., 2010; Mason et al., 2015; Pilgrim and Pilgrim, 2016; Schlechtinger, 2020)	Desktop virtual reality, pictures of the text with illustrations; Feedforward training displays; 3D glasses; HTC Vive Pro (immersive)	Experiment of reading using eye tracking in secondary school; Showing the VR instruments to engage students' enhance in literacy classroom	Tracking eye movement trajectories during the experiment; Analyzing time and gaze fixation characteristics; Evaluation the effects of feedforward training displays on novice visual search performance
			Engineering (3) (Khokhar et al., 2019; Yoshimura et al., 2019; Kang et al., 2020)	Immersive virtual reality; VR pedagogical agent responsive to shifts in user attention monitored by eye tracking; Virtual oil rig	Modeling the verification of monitoring the real-time drilling logs to find the possible anomalies as well as monitoring situation awareness; Helping students with paying their attention to the most important parts of the oil rig	Tracking eye movement trajectories during the experiment; Analyzing visual scan path cluster of the participants having different levels of situation awareness: Analyzing level of distraction; Analyzing time and gaze fixation characteristics
			Chemistry, Social Sciences (3) (Muna and Bahit, 2020; Maksimenko et al., 2021; Vandenplas et al., 2021)	Immersive virtual reality; Desktop virtual reality: text, images with audio, images; The special Simulations in web source PhET Atomic Interactions simulation	The experiment of implementation of the VR into classroom; The theoretical explaining of relationship between eye tracking data with metacognitive skills during chemistry lessons	Measuring the quality of the acquired knowledge by pre- and post-tests; Analysis of eye-tracking data by the following characteristics: (i) the proportion of time spent on each area of interest (AOI), (ii) average fixation duration, fixation count on each AOI, (iii) gaze duration mean on each AOI, and (iv) fixation rate (count/s)
Overall	102	1937–2021	18 priority areas	Seven types of VR	Theoretical and practical implementation of eye tracking into classes	All three types of evaluation methods

time clearly correlates with the decision-making process. The number of fixations on group attributes is associated with group identity, but it does not immediately lead to cooperative behavior (Maggio et al., 2019d).

Eye-tracking technology has been a useful tool in research that is related to social attention. For example, it has been shown that results from certain experimental studies correlate with measures of social impairment and with autism symptom severity. It has been found that reduced attention to social stimuli or increased attention to non-social stimuli is correlated with behavioral measures of autism (Bird et al., 2011; Chawarska et al., 2012; Eckstein et al., 2017). Face processing, as well as language skills, are also significantly correlated with measures of social attention. A strong association between face processing skills and attention to faces has been reported for children (Shic et al., 2011), more studies suggested that attention to a speaker's mouth and eyes could be a predictive measure of how fast the words are recognized among children with ASD (Parish-Morris et al., 2013). Moreover, when the processing of such social information as eye and mouth movement is atypical, it is correlated with difficulties in language learning or social impairment. An increase in attention toward the mouth has been associated with increased social adaptation (Tenenbaum et al., 2014) and communicative competence (Klin et al., 2002). These results suggest that eye-tracking methods are promising for studying social attention in ASD and can be successfully used in studies with children.

Eye-Tracking in Education

A major application and focus of this review is the use of eye-tracking in education (Norbury et al., 2009; Jarodzka et al., 2017, 2021; Strohmaier et al., 2020). Over the past decades, there has been substantial research on the fundamental concepts and applications of eye tracking in education. There are numerous great review papers on the topic some of which will be mentioned in this subsection.

In the work by Sun et al. (2018), it is argued that the application of the newest information technologies to traditional teaching methods can not only increase the value of technologies but also improve the progress in learning and effectively integrate various areas of education. A special educational software package has been developed based on eye-tracking technology. By analyzing data on the movement of students' eyes, teachers can improve the quality of teaching by adapting the teaching structure, while students can focus more on their interests and develop personalized education strategies. The study, Lai et al. (2013) aims to show how eye-tracking technology has been applied to learning research. A total of 81 articles, including 113 studies, were selected from the Social Sciences Citation Index database from 2000 to 2012. The tendencies of eye-tracking technology in the educational process are studied under several specific topics, e.g., patterns of information processing and patterns of decision-making. This study concludes that the eye-tracking method provides a promising channel for researchers to link learning outcomes with cognitive processes.

A work by Alemdag and Cagiltay (2018) is a systematic review that is dedicated to the cognitive processes in multimedia learning studying with relevant variables through eye-tracking technology. In the review, 52 articles with 58 studies were analyzed. The results showed that there is a growing interest in the use of eye-tracking technology in multimedia learning research. Eye movement measurements allowed the two authors to conclude the cognitive processes of choice, organization, and integration. Also, one of the results was that the multimedia content itself, individual differences, and emotions were potential factors that could affect eye movement measurements. Eye-tracking has proved itself to be an important tool that provides specific spatial and temporal measures to monitor, measure, analyze, and evaluate educational processes (McNamara and Jain, 2019). The topic of eye tracking in education is further developed with specific application to medicine as the next subsection.

Eye Tracking in Medicine

Eye-tracking has for a number of years been widely implemented in medical research, which has been reported and reviewed in many papers over the past decade (Krupinski, 2005; Krupinski et al., 2013; Bond et al., 2014; Tien et al., 2014; Asan and Yang, 2015; Rigby et al., 2020). For example, eye-trackers have been used alongside machine learning to improve the diagnostics, and also to predict diagnostics errors before they can even occur. With the use of eye trackers, automatic cueing or feedback can be provided to learners during image examination (Voisin et al., 2013). Such automatic feedback is realized by parsing medical images into diagnostically relevant and non-relevant regions (ROIs), while using expert annotation or automated machine vision techniques (Brunyé et al., 2014; Mercan et al., 2016; Nagarkar et al., 2016). Once these regions are known to the system that is used for eye tracking, fixations on the important regions are recorded. The recordings are then used to study the spatial distribution of attention over a digital image and the time of fixations. Once there is enough data available, it can be fed into the machine learning algorithm to provide automated diagnostics. Another example of the use of eye-tracking is demonstrated in the work by Tien et al. (2014), the review includes studies describing the use of eye-tracking when performing, learning, or evaluating completion of a task or acquiring skills for surgeons. The reviewed literature demonstrates the ability of vision tracking to provide reliable quantitative data as an objective assessment tool with potential application in surgical training to improve performance. Vision tracking remains a promising area of research with the possibility of further implementation in the assessment of surgical skills.

Another significant area of medical research that is associated with the use of eye-tracking devices is related to rehabilitation. It has been shown that the combination of virtual reality technology and eye-tracking, improves rehabilitation of such brain functions as attention, memory, motor and visual-spatial abilities, and speech when compared to traditional therapy methods (Rigby et al., 2020). Moreover, it has been reported that virtual reality training was able to stimulate the patients' motivation. The universal ability, which is not tied to the nature and specifics of the disease, to increase motivation and demonstrate better results in the rehabilitation of lost cognitive functions has been reported. This universal property was demonstrated for brain injuries (Barlinn et al., 2016) and neurodegenerative diseases (Krupinski et al., 2006; Maggio et al., 2019a,c). This finding allowed to reduce the total hospitalization time of patients while increasing the duration of rehabilitation training (Maggio et al., 2019a). These few examples demonstrate the importance of this technology in the medical field and the applications to medical education will be discussed further.

Research in the field of medical education suggests that the pattern of eye movement of students changes with regard to diagnostics as they progress in their studies. More specifically, the eye movements become more rapid and move toward the importance for diagnostic regions (Jarodzka et al., 2010). Hence, the eye movement of students becomes more and more like that of an expert, this process can be time and analyzed. It has also been suggested that this process can be accelerated by showing students video material of the expert's eye movement, this method is called eye-movement modeling examples (EMMEs) (Frank and Danoff, 2007).

The technology and application of EMMEs has been rapidly developing and many interesting studies have already been produced. EMMEs include video of expert eye movement as well as audio description of the action by the expert (van Gog et al., 2009; Jarodzka et al., 2013). The scientific basis behind this method lies in neuroscience, where it has been shown that the brain can mirror actions, when another person's action is observed. Such a response is known as a "mirror system" and can be integrated into the learning process (Calvo-Merino et al., 2005, 2006). This technology provides students with the unique opportunity to learn from the experts in the field without them being physically available, this brings the home- or distant education to a new level of quality, which is particularly relevant during the pandemic outbreak (Jarodzka et al., 2010). EMMEs method had been used outside the medical education field, one of the studies reported that the use of EMMEs improved the ability of notice aircraft inspectors to detect aircraft faults (Sadasivan et al., 2005). The same has been observed for circuit board inspectors (Stein and Brennan, 2004; Nalanagula et al., 2006). Moreover, EMMEs accelerated the speed of debugging for the software engineers (Mason et al., 2015). Reports show that with the use of EMMEs students can become better readers and solve logical tasks such as puzzles faster (Velichkovsky, 1995).

When the gaze is analyzed with the use of eye-trackers, in the medical diagnostic field it is seen that a sequence of saccades and fixation over a medical image appears. In one study, radiographers viewed the eye movements of either fellow novices or experts during the learning process and then interpreted a chest X-ray (Litchfield et al., 2010). Interestingly, it has been shown that the ability to notice and locate pulmonary conditions has improved in comparison to "free-search" not only from observing the experts but also from observing novices.

In a recent study, medical students observed a video of child epilepsy cases. The video was played in three different settings, in the first one the expert was narrating the video with voice, this was a control video sample. In the second, the eye-movement of the expert was traced onto the video by a small circle on the images. In the third video, the eye movements of the expert were also presented, but the area of the image, which the expert didn't focus on, was blurred out. The results of this study showed an increase in the diagnostic of students after viewing the third video and no change for the first or the second. Therefore, specific viewing conditions can facilitate the use of a "mirror" system in the brain and enhance the learning process (Jarodzka et al., 2012).

Alongside applications in medical education and research, eye tracking and VR can also play a part in assessing the standards of teaching in the medical field. New frameworks for those studying and working in healthcare are being developed by the international accreditation establishment to ensure the highest level of professionals. An example of such a framework is Competency-based medical education (CBME), which is aimed at ensuring that healthcare workers have high expertise that isn't just certified on paper but also proven by practice (Aggarwal and Darzi, 2006). In recent years CBME is already being implemented by including new standards of teaching, assessment, and curriculum into medical education and practice (Simpson et al., 2002; Frank and Danoff, 2007; Swing, 2007; Nasca et al., 2012; Holmboe et al., 2016). Due to these changes, we need new technology to facilitate the assessment procedure and eye-tracking in VR can surely become one of the major tools in this process.

Eye Tracking in Design

Variety of studies reported the use of eye tracking in design, for example in graphic design and other computer-based visual evaluation methods, which are used to measure the distribution of visual attention (Poole and Ball, 2005; Hollander et al., 2019). In a study from 2016, eye-tracking was used to assess computer-based visual tools, which help decision-making to investigate ecosystem services (Klein et al., 2016). It has been suggested that the ability of users to understand ecosystem services can be improved through the use of such decision support systems. Other studies have analyzed the how people can perceive landscapes, using the data from eye trackers such as fixation time, saccade amplitude, etc. (De Lucio et al., 1996; Dupont et al., 2013; Potocka, 2013). The opportunities, as well as challenges for the use of eye-tracking in the fields of cartography, geographic information science, spatial cognitions, etc., have recently been reported in a broad review (Kiefer et al., 2017). Eye-tracking has also been investigated in the built environment, for example, a study of a contextual guidance model with a Bayesian framework was used to predict regions of gaze fixation of people while they search for objects in space (e.g., pedestrian paintings on the street) (Torralba et al., 2006). Similar work has been done by Ehinger et al. (2009) with an addition of the pedestrians being present or absent in the picture. Eye-tracking in the built environment has also been used to find out about visual preferences that people have with regard to the general objects in public spaces (Noland et al., 2017). The effectiveness of GIS software was studied with eye-tracking when the subjects performed orientation tasks with the help of GIS (Kudelka and Dobesova, 2015). This study provided a useful insight into the way people were orientated, and the subjects that were successful in the self-localization task were found to spend more visual attention on objects that provided helpful clues. Recently, real-time eye-tracking systems have been implemented to increase the efficiency and quality of interactive graphics applications as well as large-scale display systems (Cheng and Pulo, 2003; Bergeron et al., 2015; Saxena et al., 2016; Celine et al., 2018; Weiss et al., 2018; Merali et al., 2019; Pottle, 2019; Rutkowski et al., 2019; Ustun et al., 2020).

EYE-TRACKING IN VIRTUAL REALITY

The natural development of technology and research in the field of eye-tracking had led to the combination of eye tracking with a virtual reality tool (McNamara and Jain, 2019). VR is a powerful tool that can change the way we work and relax; it can also transform learning techniques in the near future. New applications of VR are invented every day, so it is safe to say that it could be present in our daily life in a relatively short time. The extent of VR research is rather large and recently many virtual reality systems with eye-tracking have emerged. A vast part of VR research is aimed at improving user experience and reducing usability issues, and it is believed that eye-tracking technology can be of assistance in this task (Clay et al., 2019).

Essentially, eye-tracking gives the ability to identify what the user's gaze is focusing on in the virtual reality environment (VRe). Moreover, VR can be used to change the focus of attention if it will increase the positive outcome of the task. There are techniques to draw attention to certain things in the VRe, which can be used if needed. The success of these techniques can be constantly checked since the gaze of the user is tracked in real-time. The use of eye-tracking in VR can be a helpful asset, not only improving the work of various applications but also identifying the disadvantages of some VRe. In VR, full-body motion tracking can be used, so the environment can react to the user's movement, action, and gaze.

In comparison to real-world eye-tracking, the one in VR has the advantage of the easier definition of the regions that the user had looked at. These regions of interest can also be identified in time and reconstructed. The experimental setup with eye-tracking in virtual reality is much more flexible and promising for many fields of science since it can be thoroughly controlled. One can control the data collection, environmental settings, and make the stimuli more natural for the user, therefore enhancing the possibilities of research. It is especially useful in research that focuses on human cognition and behavior. It has been reported that such eye-movement signals as pupil diameter can be used for emotional recognition, and therefore there is a correlation between various emotions and pupil size (Hess and Polt, 1960). Research has provided a comparison between eye-tracking in VRe emotional recognition and the classic EEG approach. This research suggests that although the eye-tracking classification method was not as efficient as EEG, it still had statistically good enough results to be considered a useful tool for this task (Zheng et al., 2020).

Various implementations of VR and eye-tracking have been numerously reported in the field of computer science. Some research includes very detailed technical reports of VR and eye-tracking implementations. For example, a review paper by Clay et al. (2019) gives a step-by-step explanation of the available hardware and techniques used to implement eye tracking into the VR set. Other studies have been dedicated to the development of VR devices and the improvement of existing hardware. There is a particularly interesting study, which assesses what technical requirements a VR set needs to have in order to generate a well-known immersive effect of being "in reality," or as researchers refer to it, in "presence" (Radianti et al., 2020).

A lot of recent VR research is being conducted in the area of computer gaming. The ability to use eye-gaze in the play has for a long time been a question of investigation and a desired feature for the gaming industry. This topic was given further rise with the launch of VR headsets with built-in eye-tracking, such as Vive, FOVE, and other devices available on the consumer market (Fove Inc, 2017; High Tech Computer Corporation HTC Vive Pro Eye, 2019). Apart from using gaze as an instrument of gameplay, eye-tracking can also collect data on where the attention of the gamer is scattered in 3D VRe, therefore, an adaptive game mechanism can create reactive content in the gameplay. One of the papers has shown that the use of gaze to interact with remote objects in the VRe is much faster than the use of hands (Tanriverdi and Jacob, 2000), which could be used as a great advantage for shooting or racing games or any other applications where special attention is paid to speed and aiming quality.

Gaze can also be used as means of non-verbal communication, especially useful in collaborative VR environments. There has been research showing that the use of VR can regulate the interaction between people in this process (Gergle et al., 2013). The integration of eye movement in avatar interactions is actively researched with the use of eye-tracking (Hußmann and Oechsner, 2017).

In the area of medical research, VR technology has been studied and integrated into the educational process. An example of this would be the study of nurse education in a collaborative immersive system (Weiss et al., 2018), or another research on the medical training in a virtual hospital and medical professional training (Saxena et al., 2016; Pottle, 2019). VR technology has been reported and researched in dental medicine, such as simulated cavities removal exercise for dental students in VR (Celine et al., 2018) or a surgical education system where finger tracking is used to show the students the location of the fingers and the exact movements of the expert's fingers during surgery (Merali et al., 2019). Another use of VR in medicine is rehabilitation, where the technology is used on patients. Many papers regarding rehabilitation have been reported so far, an example is a VR-based therapy for vestibular problems (Bergeron et al., 2015), VR breathing exercises for people with Chronic Obstructive Pulmonary Disease (Rutkowski et al., 2019). VR has been used to visualize the body and actually move through the neural tissue; this feature has been used in medical research (Ustun et al., 2020). In recent years VR with eye-tracking has been appearing in the medical field. It has proven itself especially useful in the area of medical education and will be described below.

Here we have described the major areas of eye-tracking in VR research which has been rapidly developing in the last years. With the development of this scientific area, more and more research emerge on the advantages, and importance of VR in educational programs. This will be discussed in more detail in the next section.

EYE-TRACKING IN VIRTUAL REALITY FOR EDUCATION

A concept that has been the major interest of this review is eye-tracking in VR, which can be used in education to enhance the learning process and to assess the knowledge of students. This idea has been reported in some literature over the past decade, especially with regards to medical education, however, the field is still evolving and the wide use in the other fields is yet to be seen (Aggarwal and Darzi, 2006). Here, we describe the findings of the aforementioned papers and suggest ways in which the technology can be applied to the assessment of knowledge in the classroom. An immersive education environment has the functionality to carry out assessment procedures with minimal distraction. The knowledge level of the taken course as well as individual aspects of the student, such as cognitive abilities, and achievements can be taken into account. Therefore the learning trajectories of the students can be personalized to enable the best possible result. A particular planned study with a focus on eye-tracking in a virtual learning environment is described in a paper by Schlechtinger (2020), where the author argues that the literature has provided enough initial evidence for the use of eye-tracking in the context of learning. This planned study will evaluate how well eye-tracking works when it comes to detecting objects that cause excessive cognitive load in virtual reality conditions.

Some research has recently been conducted in the area of knowledge assessments, for example, students were asked to read a text or a fragment of text being in the virtual reality environment (Pilgrim and Pilgrim, 2016). It has been stated that their knowledge in a particular field can be judged by data collected from eye-trackers, more specifically, the concentration on specific words and expressions during the task (Mason et al., 2015).

While eye-tracking has already been used for years in medical education and training, it is argued that eye-tracking in VR will provide even more opportunities to enhance the learning process. One of the main findings in this field shows that there is a difference in the way experts and novices move their eyes (Jarodzka et al., 2010). It has been mentioned that the use of eye-tracking in medical education can perhaps decrease the time it takes a novice to become an expert by accessing gaze patterns.

The available research suggests that vision tracking in desktop VR in LCD display can be a useful tool for developing diagnostic skills in medical students (Litchfield et al., 2010). It is well known that the process of medical education and training is a long multi-step process, therefore, using eye-tracking in VR alongside conventional teaching techniques might be able to increase the efficiency and accelerate the training.

With the successful and effective implementation of eye-tracking in virtual reality into medical education and training, it makes sense to interpolate these findings into other fields of education. There is also the potential of implementing eye-tracking technologies in virtual reality to engineering education (Khokhar et al., 2019). Kang et al. (2020) describe the so-called Deepwater Horizon operation, where VR allows the assessment of the awareness of trainees and operators in a non-dangerous environment. One of the unobtrusive and viable methods for assessing situation awareness can be the use of eye movements, in particular, time-ordered visual scanning trajectories. Based on the presented data, it can be argued that a field of science education, which usually involves a lot of lab work, would greatly benefit from the novelty of eye-tracking in virtual reality. The personalization of learning trajectories in chemistry education can be achieved in a variety of ways.

The implementation of virtual reality can create an environment where students learn each topic at their own pace. For example, a recent technology report has shown how chemistry education can be enhanced with the use of VR (Maksimenko et al., 2021). Furthermore, eye-tracking could be used to collect data regarding the progress of a student on a chemical topic (Muna and Bahit, 2020; Vandenplas et al., 2021). It can be anticipated that the better knowledge students have, the less time they will spend looking at incorrect answers and the quicker they will concentrate their gaze on the correct one in tests. The same assessment can be done with regards to chemical exercises. Naturally, some students will learn faster than others, and eye-tracking could be a good measure of this process. The educational process can then be personalized, more on this will be specified in the outlook. The attention of the students can be measured as described by Yoshimura et al. (2019) where the study shows the development of attention-restoring visual signals for displaying when gaze tracking detects that students' attention is shifting from important objects since in educational virtual reality it is important to solve the problems of students' inattention to the presented content (Yoshimura et al., 2019). Experiments to compare different signals and their parameters to assess the effectiveness and trade-offs, as well as to assess the impact of eye tracking are proposed. Eye-tracking is used both to detect inattention and to control the appearance and location of signals.

OUTLOOK FOR EYE-TRACKING IN VIRTUAL REALITY FOR EDUCATION

As eye trackers are becoming cheaper, more portable, easier to use, and generally more available to the consumers, research on principled methods for using eye-tracking for competency assessment is expected to increase (Al-Moteri et al., 2017). However, the implementation of eye-tracking in VR into the educational setting is a new concept of educational science, therefore, there are many directions for future research that we would like to point out.

First of all, more experiments in the educational environment are to be conducted with the use of eye-tracking in VR, not only in the aforementioned areas of medical education, but also other natural sciences. A major advantage of VR in the educational field is the ability to combine classic laboratory experience while eliminating dangers that are associated with it for school and university students. Therefore, the experimental work is necessary in order to establish the extent to which the learning process is inhibited in such an environment.

The wider use of the technology will provide more data sets that are crucial for understanding the effectiveness of such educational approaches. Moreover, large data sets can be analyzed to optimize the experience. They are also needed in order to establish a stronger correlation between cognition and education, and therefore ensure qualitative assessment for students when using eye-tracking. Thus, analyzing the data from the eye-trackers is another vital direction of the research.

However, the methods to be used when analyzing the data are not established. Thus, a major research direction is the development of techniques to evaluate the effectiveness of eye-tracking in education. This should be done by using both quantitative and qualitative research methods and assessing the knowledge of students, increased level of skill, overall learning experience as well as the downsides of the approach. For example, a possible method for assessment of engagement can be done by the implementation of a machine-based algorithm, as suggested for eye-tracking in education (Goldberg et al., 2021).

Eye-tracking can facilitate the transition to personalized education, where eye-trackers in VR education applications are to measure cognitive load, fatigue, tiredness, and concentration level of individual students. The development of methods that will be used in order to effectively convert data from eye-tracking devices into the quantitative assessment of students' involvement is to be a major part of the research. Further research can potentially show how personalized education will effect cheating in tests and exams while in the classroom, as well as anxiety and peer pressure that motivate students to avoid extra questions on the topic.

It is important to investigate the drawbacks and limitations of the approach with respect to education but also the technical drawbacks. For example, one drawback can be that eye-trackers need to be individually calibrated, which is tedious and time-consuming in an experimental lab environment. Another is the movement of the headset which would lead to inaccurate data produced by the eye-tracker. Therefore, the position of the headset needs to be fixed before the activity, sharp and fast movements need to be avoided. Some of the problems related to physical discomfort can be solved by making a series of short experiments and having periods of rest or providing students with an active and engaging task to distract from physical discomfort. However, further research needs to be conducted with respect to the aforementioned limitations, motion sickness, and others that arise in the process of technology implementation.

Another fascinating research direction is the use of a multi-method approach, where eye-tracking can be combined with others by which eye-tracking is combined with other physical and cognitive measures in order to provide a more detailed insight into the learning process. An example of such a measure can be a head pose (Ballenghein et al., 2020; Goldberg et al., 2021).

It has already been described that eye-tracking in VR can be used to also test the expertise of teachers (Seidel et al., 2021) or increase it, as well as to assess student-teacher engagement (Haataja et al., 2021). We suggest that more detailed research should be done in these directions.

Together with many exciting ideas and advances, eye-tracking in VR also has a fair number of drawbacks. However, we suggest that exploring these technologies alongside each other, will facilitate and perhaps accelerate the overcoming of these problems. And inevitably it will bring these technological advances to many classrooms across the globe.

CONCLUSION

In conclusion, the current review has provided firstly an overview of the areas where eye-tracking technology has been researched and implemented over the past decades. A specific focus has been dedicated to eye-tracking in education and the areas of application. Secondly, it shows that VR technology has been widely applied in many fields of scientific research over the past years and the interest in it continues to grow. It can be observed that both these technologies are sophisticated and well researched, moreover, we argue that now they can be used together and more extensively applied to the area of education.

Implementation of eye-tracking in VR provides new interesting approaches for studying the attention and motivation of students, possibly accelerating and making the education more efficient as well as a tool for assessment. The ability to use VR with different environments, model and control every aspect of the process, makes it an indispensable educational tool. In this review, we provide a possible trajectory for the development and application of these technologies in the classroom.

It is worth noting that the development of new methods for using eye-tracking in VR for education is especially relevant in the current situation, with many countries worldwide switching to distant teaching and the educational system trying to adapt to the changes. The methods of eye-tracking in VR implementation with regards to hardware and software have been numerously reported, therefore this technology can soon become available in day-to-day life.

However, there are certain disadvantages to this technology, a major one of which being motion sickness and visual discomfort which appears while using VR for a longer time. It can prevent students from using the technology to its full potential or even using it at all. Nonetheless, these obstacles will be surpassed with the help of further research in the area.

Overall, we believe that eye-tracking in combination with VR presents a powerful tool that can change the way we perceive education and greatly expand the potential of modern educational programs. This combination has already been successfully applied in the field of medical education, therefore we suggest that more people from different fields should pay attention to this technology and consider the possibility of its implementation into the educational process.

AUTHOR CONTRIBUTIONS

MK, NM, and MM conducted conceptualization and contributed to writing—review and editing. MK contributed to project administration and validation. MM contributed to writing—original draft. MM and NM contributed to later drafts of the manuscript.

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Signaling in 360° Desktop Virtual Reality Influences Learning Outcome and Cognitive Load

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Learning with desktop virtual reality learning environments (DVR) can be highly visual and present many visual stimuli simultaneously. This can be distracting and require instructional support to help learners in their learning processes. The signaling principle could be a promising approach to support these processes, as signals can guide learners' attention to the relevant information (Mayer, 2005). The present study investigated the effects of signals in a 360° DVR on learning outcomes and cognitive load. In our between-subjects design, we examined a total of N = 96 participants who were randomly assigned to the signaling or non-signaling group. We hypothesized that the signaling group would achieve higher recall, comprehension, and transfer performance than the non-signaling group. We also expected that the signaling group would experience less extraneous cognitive load and higher germane cognitive load than the non-signaling group. The results show that learners who received signals in a DVR achieved significantly higher recall and comprehension scores than learners who did not receive signals. Transfer performance did not differ between groups. Participants in the signals group also experienced significantly lower extraneous cognitive load than participants in the non-signaling group. However, no differences in germane cognitive load were found between groups. These results suggest that learners in a DVR can be supported by signals in their learning processes while simultaneously helping to reduce unnecessary cognitive load.

Keywords: virtual reality, signaling, desktop virtual reality, cognitive load, instructional design, learning outcome, media in education

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INTRODUCTION AND THEORETICAL BACKGROUND

In recent years, virtual reality learning environments (VRLE) have become increasingly popular. They are also increasingly used as a learning medium in educational institutions to enhance learning (Radianti et al., 2020; Wu et al., 2020). VRLE makes it possible for learners to be immersed in a wide variety of scenarios while feeling as if they are actually present in that environment. With VRLE, learning scenarios can be created that would be difficult or impossible to implement in the real world. But what exactly is virtual reality (VR)? VR is defined as a realistic computer-generated environment that can engage multiple human senses (Burdea and Coiffet, 2003), leading to the immersive and sensory illusion of actually being present in the VR environment (Biocca and Delaney, 1995). One of the most important features that distinguishes classical learning environments from VR environments is immersion. On one hand, immersion can be defined as a psychological state of how much learners feel mentally involved in the learning environment (Li et al., 2020). While, this definition is also often used for presence, in this article we will limit ourselves to this definition of immersion. On the other hand, immersion can be defined as objectively measurable by the characteristics of the technology used, such as its degrees of freedom, which relate to the user's freedom of movement in a three-dimensional space (Slater and Wilbur, 1997). Depending on the VR technology, the extent of immersion may differ (Radianti et al., 2020). According to both definitions, so-called head-mounted displays (HMD) usually lead to a high degree of immersion (Radianti et al., 2020). These are displays worn in front of the eyes, the display of which adapts according to the movement of the head and thus enables a view of the virtual environment of up to 360° (Rolland and Hua, 2005). However, in a learning scenario, the drawbacks of HMD technology include its high acquisition cost and difficult scalability in real learning environments (Richards and Taylor, 2015; Radianti et al., 2020).

A widely used alternative to HMDs is a desktop virtual reality. These are virtual environments that run on inexpensive computer systems and can be operated with a mouse, keyboard or touchscreen (Lee and Wong, 2014). They can even be used in an online classroom setting (Dodd and Antonenko, 2012). While, desktop virtual reality learning environments (DVR) are technically classified as low immersive, they still contain certain immersive aspects to it (Robertson et al., 1997; Radianti et al., 2020). The learner is in control by determining the temporal and visual sequence of the learning environment, which allows the learner to be drawn into the virtual environment (Robertson et al., 1997). There is also a form of navigation and search through the operation of the 360° field of view, as textual coherent learning information, depending on the learner's point of view, can be discovered in the virtual space. The main advantage over HMDs is the lower acquisition cost, since only an Internet-enabled device with a browser is needed to present the VRLE. This is also associated with greater scalability in difficult learning settings.

In theory, VRLE seem to bring great opportunities for learning. However, the empirical evidence on whether VRLE lead to better learning outcomes is heterogeneous. Some studies indicate that learning in VR improves learning outcomes (Dalgarno and Lee, 2010; Tüysüz, 2010). In contrast, other studies have shown that learners learn less in a VRLE, regardless of the level of immersion (Parong and Mayer, 2018; Makransky et al., 2019b). However, there are also studies that find no differences regarding learning outcomes (Stepan et al., 2017). Recent meta-analyses show that learners using VRLE can show higher learning outcomes than learners in control groups, but further empirical research is needed to investigate the levels of processing in more detail (Radianti et al., 2020; Wu et al., 2020). A common classification for these levels of processing is described in Bloom's (1956) Taxonomy. The first three levels are recall, comprehension, and transfer. While, recall tasks only aim at reproducing memorized information, comprehension questions test a deeper understanding of the content, e.g., by asking for explanations or relations. The transfer level describes how the acquired knowledge can be transferred to new situations. The majority of the presented studies only examine recall performance for learning outcomes in VR, with some study results suggesting an advantage in retention performance (Pulijala et al., 2018). Other studies find a lower recall performance in VR compared to a less immersive presentation of the learning material (Parong and Mayer, 2018; Makransky et al., 2019b). A few studies also measure transfer performance and also show heterogeneous results for learning in VR (Chittaro et al., 2018; Makransky et al., 2019b). In summary, it is important to consider the learning outcome in a DVR in a differentiated way, otherwise possible effects can be overlooked or overestimated.

Challenges of Learning With DVR

Although we examine a 360° DVR in this study, the challenges presented below are also relevant to VRLE. The learning material was developed to be presented in both DVR and a VRLE. That is why we also draw conclusions from and for VRLE. Characteristic of immersive DVR is the particularly large number of 3D models, which are often displayed with high resolution and a high level of detail. With realistic textures and sounds, a DVR can look convincingly real and thus promote immersion (Jensen and Konradsen, 2018). However, when so much visual information is presented graphically at the same time, learners can easily become overwhelmed in filtering out the relevant learning content (Mayer, 2005; Jensen and Konradsen, 2018). In the Cognitive Theory of Multimedia Learning (CTML) this process is called selection (Mayer, 2005). An impaired selection process can result in either important information being missed or irrelevant information being selected for further processing. Since the selection process is the basis for further processes of learning, all subsequent levels of learning outcomes can be impaired (Moreno and Mayer, 2000). If information is incompletely selected, then only incomplete connections can be made between the information in the working memory. When irrelevant information is selected, not only is it more difficult to make correct connections between relevant stimuli, but unnecessary prior knowledge may be activated, requiring additional working memory capacity (Moreno and Mayer, 2000). In addition, the visual complexity in a DVR can also actively distract the learner from the actual learning subject (Jensen and Konradsen, 2018). In this complex representation, there are often stimuli that are not related to the actual learning content. These so-called seductive details are stimuli that are not relevant for the understanding of the learning material and can distract from what is actually important (Sundararajan and Adesope, 2020). In a DVR, this would mean that anything that is not coherent with the learning objective can be counted as seductive details. de Koning et al. (2009) have shown that in a dynamic and transient learning environment, salient but not learning-relevant information is more likely to be selected and processed, and therefore the capacity of working memory may not be sufficient to cognitively process the learning-relevant information (de Koning et al., 2009). Due to the many visual stimuli and thus possible seductive details, learners in a DVR may experience increased cognitive load by placing additional demands on working memory capacity simply by presenting the information in DVR (Parong and Mayer, 2018; Frederiksen et al., 2019). This unnecessary load for learning is called extraneous cognitive load (ECL) in the Cognitive Load Theory (CLT; Sweller, 2005).

Another challenge in the selection of information in a DVR is that the relevant information is not always placed directly in front of the learner, but only becomes visible when the learner actively looks around in the learning environment. This additional navigation effort must also be invested by the learner and takes up capacity in limited working memory, which can lead to higher ECL (Parong and Mayer, 2018; Frederiksen et al., 2019).

When the actual learning content, distractions and navigation effort must be processed simultaneously in working memory, there may not be enough capacity left for the germane cognitive load (Sweller, 2005). The germane cognitive load results from the effort a learner must invest in the learning task and thus contributes directly to learning outcomes (Sweller, 2005).

The cognitive process of organization involves making connections between selected elements of the learning material. If irrelevant information is selected for learning, further processing of that information would not be useful for learning and could result in irrelevant or incorrect connections being made, leading to impaired comprehension performance. In order to select relevant information for better comprehension performance, it might be necessary for the learner to return to an earlier processing step. Another challenge in the process of organization can occur when auditory information is presented in addition to visual information. In a DVR, the learner must then independently search for the matching visual information to the auditory information and determine whether the information belongs together. If the information does not match, the visual search continues. However, a narrated audio track will continue regardless of whether the learner has already formed enough connections, which can affect comprehension performance. Therefore, it is important to assist the learner by means of instructional design in how to focus attention on what is relevant, be less distracted, and reduce navigation effort in a DVR.

Guiding Attention by Using Signals

To help leaners avoid getting distracted by seductive details and focus their attention on the relevant parts of the learning material, highlighting these sections could be beneficial for learning in DVR. A multimedia design principle that derived from the CTML and particularly addresses this problem is the signaling principle. The signaling principle refers to the idea that learners can process the learning material more deeply when learning-relevant information is highlighted. The learner's attention is thus directed to the relevant parts of the learning material (Mayer, 2005; Van Gog, 2014). In classical multimedia learning environments, signaling has already proven to be an effective instructional aid to support selection processes (Van Gog, 2014; Alpizar et al., 2020). To understand whether signals can also support deeper learning processes, a differentiated view of learning outcomes is necessary (Xie et al., 2017). In Xie et al.'s (2017) meta-analysis, they distinguished between three types of learning outcomes according to the levels of Bloom mentioned above (Bloom, 1956). They found that signaling not only increased learning outcome for recall and comprehension but also for transfer scores. Schneider et al. (2018) found in their meta-analyses that signaling can improve recall and transfer performance, when compared to non-signaling groups. Another meta-analysis by Richter et al. (2016) also found effects for comprehension and transfer when signaling was used in the multimedia learning environment. This effect was moderated by prior knowledge, making it even more pronounced for learners with low prior knowledge (Richter et al., 2016). Overall, it can be assumed that signals can be used as an effective instructional aid in a DVR, just as in classical multimedia environments. This is because signals directing attention to relevant learning material, making it salient to the learner, so that it can stand out from irrelevant material (Lorch, 1989). This so-called guiding attention hypothesis was supported by Ozcelik et al. (2010) in an eye tracking study in which learners in a signaling group outperformed the non-signaling group in transfer and matching tests.

Directing the learner's attention with signals in a visually complex DVR can reduce unnecessary search and orientation processes, which can lead to less seductive details being selected, ultimately reducing extraneous cognitive load (Dodd and Antonenko, 2012; Alpizar et al., 2020). The freed-up capacity in the limited working memory, could then be used for germane processes (de Koning et al., 2009). In a DVR, the learning material may have relevant information outside the current field of view. To navigate to the relevant information, the learner must decide what might be relevant to the learning (Neumann, 1996). Especially for learners without prior knowledge, signals could help to reduce this navigation effort (Richter et al., 2016).

In conclusion, signaling in a DVR could help to focus on relevant information, help to not be distracted by seductive details and help to orientate in the learning environment. Therefore, signaling represents a promising approach to support the visually and cognitively demanding learning processes in a DVR, thus enhancing the user's learning performance and helping them manage the different types of cognitive load.

Recent Studies

While, different types of signals in DVR have been explored, there are still research gaps on how these may affect learning (Horst et al., 2019). Initial research investigating the effects of signals on learning outcomes and cognitive load in a VR context appears promising. Albus et al. (2021) revealed that signaling in the form of textual annotations can improve learning outcomes in a VRLE compared to a group without signaling on recall performance. In addition, they also found that the use of signaling in VR can also increase germane cognitive load (Albus et al., 2021). Another study that looked at signals in a VRLE showed an interaction effect on learning outcome with motivation as a moderator. They found that less motivated learners supported by signals achieved a similar learning outcome as intrinsically motivated learners (Vogt et al., 2021a). Chin et al. (2015) found similar results in VR lab safety training. They showed that the signaling group achieved better learning outcomes than the group without signals when prior knowledge was taken into account as a covariate (Chin et al., 2015).

Research Question and Hypothesis

In this study, we will examine the effects of signals in a 360° DVR on the topic of the German forest and its animals on learning outcomes and cognitive load. In order to examine learning outcome and the underlying levels of processing in a DVR more precisely, the learning outcome were differentiated into recall, comprehension and transfer according to Bloom's (1956) Taxonomy. We also measured cognitive load differentiated into extraneous cognitive load and germane cognitive load (Sweller, 2005). In addition, variables relevant to the learning process are considered in the data analysis, including motivation (Goodman et al., 2011) and prior knowledge of the subjects (Seufert, 2003) to shed more light on their influence of signaling when learning with DVR.

We hypothesize, that the use of signals in a DVR can lead to better recall (H1), comprehension (H2), and transfer (H3) outcomes, than learning without signals. Concerning cognitive load, we hypothesize that extraneous cognitive load should be significantly lower in the signals condition than in the non-signaling condition (H4). We also hypothesize that germane cognitive load should be significantly higher in the signal condition than in the non-signaling condition (H5).

MATERIALS AND METHODS

A priori Power Analysis

For the estimation of the required sample size for this study, an *a priori* power analysis was performed. Mayer's (2017) review concerning the effect size of signaling on learning outcomes was considered as reference of the effect size. Applying $\alpha = 0.05$, a power level of $(1–\beta) = 0.95$ and reference effect size of $d = 0.46$, the required sample size for our study was estimated to be approximately $N = 64$ [G*Power 3.1; Faul et al. (2009)]. In total, we collected more participants than we initially calculated. We decided to collect additional subjects in order to counteract the expected drop out of an online study. We could not identify which subjects had to be excluded due to technical problems or early termination of the study until the end of the data collection.

Participants and Study Design

A total of 113 participants completed the study, of which 17 were excluded from the study due to technical problems with the learning environment. The analyses presented therefore refer to a total sample of $N = 96$ subjects (72.9% female). The age of the participants varied from 18 to 64 years ($M = 28.29$; $SD = 12.48$). The study was conducted as an online survey with the DVR built in. Participation was 95.8% via desktop devices and 4.2% via tablets or smartphones. In our one-factorial between-subjects design with two groups participants were randomly assigned to either the signaling group ($n = 48$) or the non-signaling group ($n = 48$). Informed consent was obtained from participants prior to participation in the study. The study was conducted as a browser-based online study. Within the survey, the subjects were redirected to an external website where the integrated 360° DVR started automatically. As dependent variables, we measured learning outcomes (recall, comprehension, and transfer) and cognitive load (ECL and GCL). As potential covariates we assessed prior knowledge, motivation, previous contact with VR and immersion.

Materials and Instruments

The learning material in the 360° DVR was about native animals in German forests. While, learners could click and drag their way around the visually rich environment, additional auditive information about the animals was played. In total, there were 14 interactive segments that were presented to the learners in a linear progression. In the first segment, the use and navigation of the learning environment was explained to the learners. At this point, they were instructed to work through the learning environment conscientiously and to listen to each audio track once. They were able to move on to the next learning content in a self-paced manner, but could not return to the previous content. Also, the audio track could be activated in each segment by clicking on the corresponding icon. The audio tracks were on average about 60 s long and could not be paused once activated. Only the signaling group contained static signals in the form of light green circles around learning relevant information (e.g., the feet of the deer are highlighted when it is explained that they belong to the cloven-hoofed genus; see **Figure 1**). Both groups spent the same amount of time in the DVR, approximately 14 min. The questionnaires and constructs measured in the present study can be found below. In addition, basic demographic data such as age, gender, student status and previous contact with VR of participants were collected.

Prior Knowledge

At the beginning of the study, the participants' prior knowledge was determined with a total of 15 questions. Domain-specific knowledge about the German forest and its native animals was assessed. These questions were created with experts on the topic to ensure content validity. The test consisted of five open questions (e.g., "Name five animal species that live in our forests.") and ten closed multiple-choice questions that had between three and five possible answers. The maximum score achievable was 18 points, and participants could earn half points for partially correct answers. No points were deducted for incorrect answers. Two independent raters scored the answers using a coding scheme and achieved very high inter rater reliability ($ICC = 0.98$, 95% CI [0.95–0,98] $p < 0.001$).

Motivation

The Questionnaire on Current Motivation (QCM; Rheinberg et al., 2001) was used to measure motivation. The 18 items of the questionnaire (e.g., " I would also work on such a task in my spare time.") are rated on a 7-point Likert scale (1 "strongly disagree" to 7 "strongly agree"). For further analyses, a mean was calculated across all items. Internal consistency was Cronbach's $\alpha = 0.72$ (95% CI [0.63–0.79]) indicating acceptable reliability (Cohen, 1988).

Cognitive Load

Cognitive load was assessed differentiated by ECL and GCL using the Cognitive Load Questionnaire (Klepsch et al., 2017).

FIGURE 1 | Desktop virtual learning environment with signals and without signals in comparison. The learning environment was displayed in full screen and the participants could turn 360° in any direction.

Two items each for ECL (e.g., "During this task, it was difficult to recognize and link the crucial information.") and GCL (e.g., "For this task, I had to think intensively about what things meant.") were rated using a 7-point Likert scale (1 "absolutely not true" to 7 "completely true"). Internal consistency for ECL was Cronbach's $\alpha = 0.65$, 95% *CI* [0.48–0.77] and for GCL $\alpha = 0.70$, 95% *CI* [0.58–0.79].

Learning Outcomes

To measure the participants' learning outcome, a knowledge test was conducted that was related to the content of the 360° learning unit. The posttest consisted of 13 open-ended questions that were differentiated into recall, comprehension, and transfer according to Bloom's taxonomy (Bloom, 1956). With five recall questions (e.g., " Name the two most important body parts of the fox, which are used to detect prey and enemies."), four comprehension questions (e.g., "Explain why there is only one male deer in a rutting pack."), and four transfer questions (e.g., "Briefly justify whether these molars belong to a younger or older deer."), a maximum total score of 16.5 could be achieved. The maximum score for recall was six points, five points for comprehension, and 5.5 points for transfer. Partial points were awarded for partially correct answers and no points were deducted. Interrater reliability between two independent raters was very high for all learning outcomes (recall: *ICC* = 0.86, 95% *CI* [0.79–0.91], $p < 0.001$; comprehension: *ICC* = 0.90, 95% *CI* [0.85–0.93], $p < 0.001$; transfer: *ICC* = 0.97, 95% *CI* [0.96–0.98], $p < 0.001$).

Immersion

Immersion was assessed using a subscale of the Technology Usage Inventory (TUI; Kothgassner et al., 2013). A total of four items (e.g., "During the virtual simulation, I completely forgot about the world around me.") were rated on a 7-point Likert scale (1 "I disagree" to 7 "I agree").

RESULTS

All data analysis was performed with IBM SPSS (Version 28) with an α-error = 0.05 for all calculations. The interpretation of partial η^2 as a measure of effect size, was appropriately categorized according to Cohen (1988) as $\eta^2 = 0.01$ (small), $\eta^2 = 0.06$ (medium), and $\eta^2 = 0.14$ (large).

Descriptive Analysis

Descriptive analysis revealed no significant differences between the signaling and non-signaling groups in terms of gender [$\chi^2_{(1, N = 96)} = 0.21$, $p = 0.646$], age [$t_{(94)} = 1.86$, $p = 0.067$], motivation [$t_{(94)} = 0.65$, $p = 0.519$], prior exposure contact to VR [$t_{(94)} = 0.20$, $p = 0.846$], immersion [$t_{(94)} = 0.84$, $p = 0.403$], and time-on-task [$t_{(86)} = -1.10$, $p = 0.273$]. However, there was a significant difference in prior knowledge between the signaling and non-signaling groups [$t_{(94)} = 2.34$, $p = 0.022$]. Since prior knowledge was also significantly correlated with recall ($r = 0.29$, $p = 0.004$) and comprehension ($r = 0.45$, $p > 0.001$), it was included as a covariate in subsequent analyses.

To identify other potential control variables, we tested whether motivation, prior contact to VR, immersion, or time spent in the learning unit had an influence on learning outcomes or cognitive load. There was a significant correlation between motivation and GCL ($r = 0.45$, $p < 0.001$). Motivation was therefore included as a covariate in the analyses of GCL. Beyond that, there were no other correlations between control variables and dependent variables. Descriptive statistics of demographic and other relevant variables, separately for the signaling and non-signaling conditions, are presented in **Table 1**.

The descriptive statistics of the results for learning outcomes and cognitive load can be found in **Table 2**.

Learning Outcomes

The ANCOVAs with prior knowledge as covariate for all three learning outcomes revealed significant differences between the signaling and non-signaling groups for recall [H1: $F_{(1,93)} = 9.58$, $p = 0.002$, $\eta^2 = 0.093$] with a medium to high effect size. Participants in the signaling group achieved higher recall scores than participants in the non-signaling group.

In addition, there was a significant between-group difference for comprehension [H2: $F_{(1,93)} = 3.06$, $p = 0.042$, $\eta^2 = 0.032$] with a medium effect size. Participants in the signaling group scored again higher on comprehension than participants in the non-signaling group.

Regarding transfer, the data showed no significant difference between groups [H3: $F_{(1,93)} = 0.58$, $p = 0.405$, $\eta^2 = 0.001$]. These results are visualized in **Figure 2**.

Cognitive Load

Results of the ANCOVA with prior knowledge as a covariate showed a significant difference in ECL between the signaling and non-signaling group [H4: $F_{(1,93)} = 5.97$, $p = 0.008$, $\eta^2 = 0.060$] with a medium effect size. Participants in the signaling group experienced less ECL than those in the non-signaling group. However, contrary to our hypothesis, there was no significant difference between groups on GCL when controlling for motivation and prior knowledge [H5: $F_{(1,92)} = 0.62$, $p = 0.217$, $\eta^2 = 0.007$]. The graphical representation of these results can be seen in **Figure 3**.

DISCUSSION

The aim of this study was to investigate the effects of signaling in a 360° DVR on learning outcome differentiated by recall, comprehension, and transfer, as well as on cognitive load differentiated by ECL and GCL.

Effects of Signaling on Learning Outcomes

In line with our hypotheses, learning with signaling led to significantly higher learning outcomes for both recall (H1) and comprehension (H2) than learning without signaling in a DVR. However, we found no differences between the groups in terms of their transfer performance (H3). These results indicate that signals in a DVR can be used to support learners in their selection and organization processes.

We infer that learners were supported by signals in a DVR in their selection process by directing their attention to the relevant information (Ozcelik et al., 2010; Dodd and Antonenko, 2012). Other studies on signals in classical multimedia settings have also shown that the selection process can be supported, which is reflected in a higher recall performance of the highlighted information (Lorch, 1989; Mautone and Mayer, 2001). We were thus able to show that the effects of signals in classical learning environments can be transferred to DVR, since the underlying learning processes involved remain identical. Our results are also partially supported by the findings of previous research in a VRLE. Albus et al. (2021) who examined signals in a VRLE in the form of textual annotations also found higher recall scores for the signaling group compared to the non-signaling group, but no effects for comprehension or transfer. This is an indication that textual annotations can support the selection processes, but not the deeper organization or integration processes (Albus et al., 2021). However, in this study we were able to show that signals in a DVR could promote comprehension performance. This could be an indicator that the signals also supported the learners in their organizational processes. The signals might have enabled the learners to process the relevant visual and auditory information simultaneously in working memory. This allows logical mental connections to be made between the information, which has translated into higher comprehension performance. When the auditory information is processed, the learner searches

TABLE 1 | Descriptive data of relevant variables, separately for the signaling and non-signaling conditions.

Variables	Signaling group (*n* = 48)		Non-signaling group (*n* = 48)		Full sample (*N* = 96)	
Gender (female): *N* (%)	34	(70.80)	36	(75.50)	70	(72.90)
Age (years): *M* (SD)	30.63	(14.41)	25.96	(9.80)	28.29	(12.48)
University student: *N* (%)	31	(64.60)	41	(85.40)	72	(75.00)
Prior knowledge (%): *M* (SD)	71.47	(12.69)	65.57	(12.07)	68.5	(12.66)
Motivation: *M* (SD)	4.15	(0.65)	4.07	(0.55)	4.11	(0.60)
Contact to VR: *M* (SD)	2.73	(1.59)	2.67	(1.55)	2.70	(1.56)
Immersion: *M* (SD)	3.37	(1.53)	3.13	(1.32)	3.25	(1.43)
Time-on-task (min): *M* (SD)	13.39	(3.19)	14.39	(5.13)	13.89	(4.28)

n, sample size; N, number of participants; M, mean value; SD, standard deviation.

TABLE 2 | Means, standard deviations, and ANOVA/ANCOVA results, separately for the signaling and non-signaling condition.

	Signaling group (*n* = 48)		Non-signaling group (*n* = 48)	
	***M* (%)**	**SD (%)**	***M* (%)**	**SD (%)**
Learning outcome				
Recall	4.43 (63.29%)	0.96 (13.71%)	3.65 (52.14%)	1.14 (16.29%)
Comprehension	3.83 (54.71%)	1.04 (14.86%)	3.32 (47.43%)	1.14 (16.29%)
Transfer	2.91 (41.57%)	1.22 (17.43%)	2.87 (41%)	1.24 (17.71%)
Cognitive load				
ECL	2.02 (28.86%)	0.99 (14.14%)	2.75 (39.29%)	1.39 (19.86%)
GCL	5.56 (79.43%)	0.96 (13.71%)	5.3 (75.71%)	1.1 (15.71%)

M, mean value; SD, standard deviation; ECL, extraneous cognitive load; GCL, germane cognitive load.

for the corresponding matching visual information in the DVR. The signals make it clear that it belongs together with the auditory information. They help learners identify matching information in working memory as being related and encourage them to want to comprehend how this information fits together. Auditory information is also transient and learners need to associate the information together in working memory in time for understanding processes to happen. The signals help reduce the visual search time for the relevant information within the DVR (Xie et al., 2017). Signals help learners to be less distracted by seductive details, allowing more time to be spent on comprehension processes.

However, we did not measure visual search time in this study, but it could be measured by eye movements in future studies. Furthermore, it is not only relevant to link auditory and visual information, but also several visual information among each other. Although the signals were only simple outlines of the objects, they seem to be able to help highlight the connections between the individual visual information that learners would have to conclude themselves without signals (Lorch, 1989; Mautone and Mayer, 2001).

Contrary to our hypothesis (H3), we did not find a significant effect of the signals in a DVR on the transfer performance. A possible explanation for this could be that our signals were solely visual in the form of green outlines. While, these could draw the learner's attention to the relevant information and even possibly reduce visual search time, they did not help to stimulate learners to deeper processing at the transfer level. Here, for example, prompts could be helpful in the future to get the learner to invest in deeper processing of the information (Vogt et al., 2021b). Signals also do not seem to have had an effect on immersion. The signals used here are visually coherently integrated into the DVR and therefore should not interfere with the learners' experience of immersion. However, it would be interesting to find out which features of the signals, such as size relative to the image or animations could influence the feeling of immersion.

Effects of Signaling on Cognitive Load

Our hypotheses on cognitive load could only be partially confirmed. We could show that signals in a DVR can significantly reduce ECL compared to when learners are not supported by signals (H4). DVR are often visually complex and can contain many seductive details. While, on the one hand these are important for immersion, on the other hand they can also be distracting and occupy cognitive resources (Van Merrienboer and Sweller, 2005). Our results suggest that these non-relevant visual stimuli in a DVR can be perceived as distracting to learners and occupy working memory capacity important for learning (Parong and Mayer, 2020). Signals, on the other hand, could make the essential elements salient to learners through their attention-guiding function, which reduces unnecessary visual search time (Mayer and Fiorella, 2014). Thus, fewer seductive details are also processed cognitively, which can reduce the associated ECL (Sweller, 2005; Noetel et al., 2021). If less seductive details are cognitively processed, the selection process can also be supported (Parong and Mayer, 2020).

If the ECL can be reduced by signals, there should be more cognitive capacity left in working memory for germane processes (Sweller, 2005). Our hypothesis about GCL could not be supported by the results we found (H5). Learners in the signaling group reported no significant difference in terms of their invested GCL compared to the non-signaling group. One possible explanation for why the signals in the DVR did not encourage learners to invest more GCL is that we measured high GCL values in both groups. Learners thus already invested high levels of GCL regardless of the signals. This may be due to our DVR, because learners may have been motivated by the interesting topic or the visually appealing learning environment to invest enough cognitive capacity for it. For many learners, DVR are still a new technological experience. This may be a factor that can motivate learners to learn in a DVR (Huang et al., 2021). In studies that compared classical learning environments with VRLE, it was found that learners showed higher motivation and interest when learning in with VRLE (Makransky et al., 2019a; Parong and Mayer, 2020). Since we also identified motivation as a covariate for GCL, this could be an indicator of why a possible effect of signals on GCL does not become sufficiently pronounced.

Strengths and Limitations

The present study used a controlled randomized trial design investigated the effects of signaling in a DVR, differentially on learning outcomes and cognitive load. The DVR used in this study was chosen to reflect realistic educational settings. This is primarily due to its accessibility and low-cost implementation, as learners only need an Internet-enabled device to immerse themselves in the DVR. Another strength of this study is the differentiated perspective on learning outcomes on different levels of processing as well as on cognitive load. In doing so, we also meet the demands of recent meta-analyses and articles on learning in VRLE that criticized the lack of theory-driven research and application development in VRLE (Radianti et al., 2020; Makransky and Petersen, 2021). However, there are also limitations that need to be considered. Despite proper randomization to both groups, there was a significant difference in prior knowledge. To avoid a possible bias in the results, we statistically controlled for prior knowledge in the analysis of the hypothesis. There were also limitations

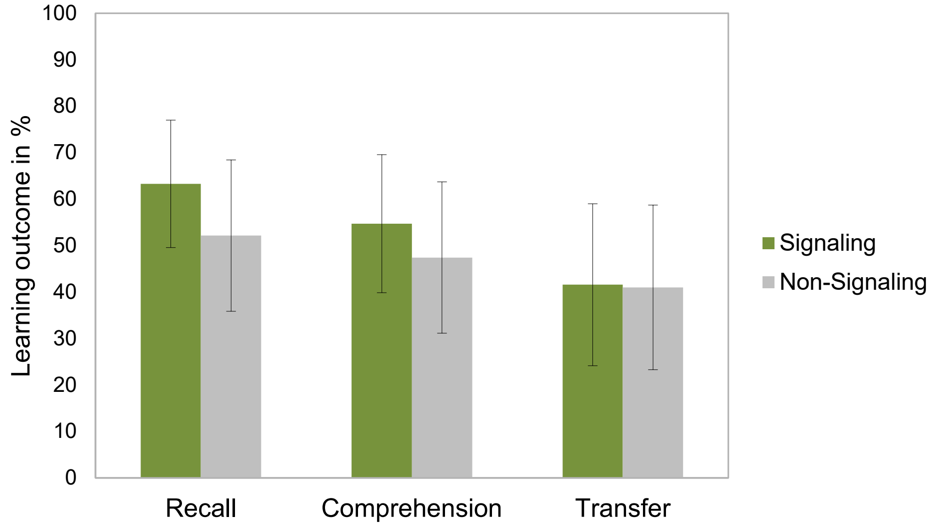

FIGURE 2 | Mean values (in percent) for the learning outcomes recall, comprehension and transfer, separately for the signaling and non-signaling group. The vertical error bars indicate the standard error of the mean.

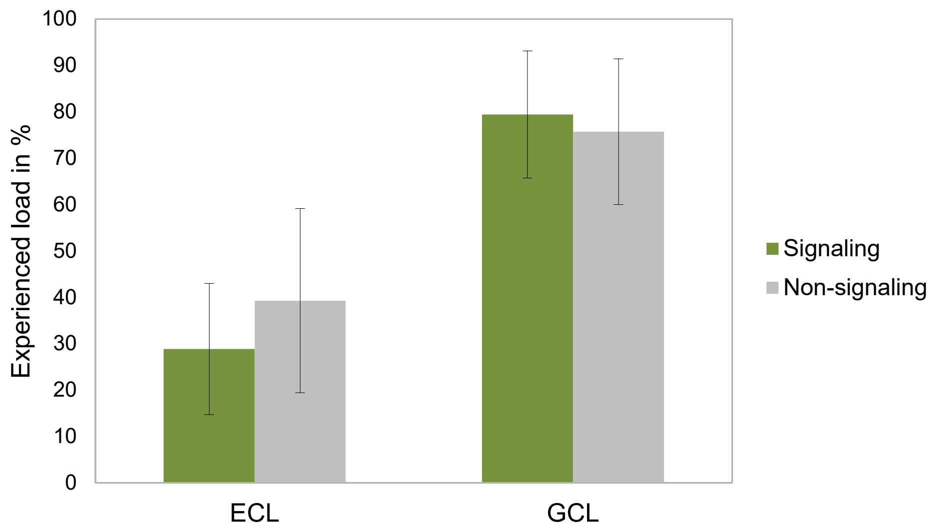

FIGURE 3 | Mean values (in percent) for ECL, and GCL, separately for the signaling and non-signaling group. The vertical error bars indicate the standard error of the mean; ECL, extraneous cognitive load; GCL, germane cognitive load.

within the DVR. Learners could look around independently and start the audio track to the image in a self-directed manner. However, we do not have objective data on whether subjects listened to each audio track in its entirety. It could also be that learners, against instruction, listened to the audio track multiple times. Nevertheless, we measured how much time learners spent in total in the DVR. Since both groups spent on average the same amount of time in the DVR, any possible influence on the results should be negligible. Furthermore, learners were also able to self-navigate to the next content, but not jump back to the previous one. It could be possible that participants jumped to the next topic by mistake or too fast, which could possibly influence the post-test results. However, participants were able to indicate in the post-test if they experienced any problems while completing the learning environment. That said, participants who experienced problems were excluded from the analysis, as explained in the methods section.

Since the participants could look around 360° in the learning unit at any time, it is possible that the relevant learning content that the audio track is currently talking about is not in the field of view of the learners at this time. This might have affected the integration of text and pictures, leading to poorer learning outcome performance (Seufert, 2003). To further empirically investigate the attention-guiding function of signals, future eye tracking studies in DVR would be highly desirable and informative.

CONCLUSION

Our study was able to show that signaling can improve learners' recall and comprehension performance in a DVR. At the same time, signaling can also reduce unnecessary load in working memory. Our results also demonstrated that established theories from multimedia research, such as the CTML or the CLT can be well-suited as a foundation for studies in a DVR (Mayer, 2005; Sweller, 2005). Although DVR can often be more visually complex and also involve a higher degree of immersion, it is these features that can be perceived as distracting. Nevertheless, the learning processes are the same in both classical and immersive learning environments and can benefit from instructional aids (Parisi, 2015).

It is also interesting to consider that even quite simple visual signals can have positive effects on learning outcomes and the cognitive load. However, such simple signals do not seem to be sufficient to stimulate deeper levels of processing. Here, future studies would be interesting to investigate signals specifically aimed at supporting deeper levels of processing or how signals work in combination with prompts (Vogt et al., 2021b). While, different types of signals have been studied in DVR, their effectiveness in learning environments has not yet been investigated (Horst et al., 2019). It would also be desirable to investigate different types of signals (e.g., auditory signals, adaptive or dynamic signals) to find out how they can affect different levels of processes in learning. In addition, it is also important to investigate further instructional aids in DVR. A possible starting point could be further multimedia design principles originating from the CTML.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

PA contributed to the conception and design of the study, developed the used questionnaires, led data collection, performed the statistical analysis, and interpreted the data. PA wrote the first draft of the manuscript with support from TS. TS supervised this manuscript. Both authors contributed to the final version of the manuscript.

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Reflecting on the Creation of Virtual Laboratory Experiences for Biology Students

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The COVID-19 pandemic challenged the *status quo* of higher education practices. With the transition to remote learning, students and faculty faced several challenges while making great strides in equalizing education access. Although theoretical aspects can be easily taught online, practical experiences are difficult to convey without dedicated laboratories and equipment. This is especially true in biological studies, where practical laboratory training significantly impacts the Student's professional development. Presented here is an overview of some of the available resources that faculty can implement in their remote teaching curricula, a discussion on a possible approach toward creating *in silico* practicums, and potential challenges that could be experienced in creating such virtual laboratories (VL). To prevent another interruption in academic training, higher education institutions (HEIs) should focus on designing, developing, and implementing practical educational material. We propose that these resources be free and open-source, allowing for a global effort to create a standardized practical curriculum for basic biological technical skills.

Keywords: Unity3D, gamification, remote higher education, online laboratory, laboratory skills

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INTRODUCTION

During the last 2 years, higher education institutions (HEIs) had to completely reimagine their curricula, mainly due to the global coronavirus disease of 2019 (COVID-19) pandemic. Efforts to curb the spread of this viral threat included the implementation of various public health measures. These actions included mainly the closure of borders, placing restrictions on intracountry movements, and closing facilities with a high aggregation of people in confined spaces, including schools, HEIs and other training facilities (Hale et al., 2020). Although such closures occurred with little prior notice, many institutions were agile enough to take their academic activities online; thus, enabling students to receive an education while the pandemic raged. The shift to online learning was relatively seamless in many countries with a high gross domestic product and high levels of computer literacy. However, economies with limited resources had to implement innovative solutions to ensure a high standard of academic activities. Indian HEIs implemented various online solutions, ranging from dedicated web-based radio and television stations to virtual laboratories (VL), as Jena (2020) reviewed. Learning also changed to a mainly online format in countries such as Egypt, Indonesia, Nigeria, Nepal, and the United Arab Emirates, among others (Crawford et al., 2020; Paudel, 2021), using various platforms ranging from social media (WhatsApp, YouTube, Facebook, and Twitter among other networks) to dedicated online teaching platforms (Google Classroom, Moodle, Blackboard, Zoom among others).

However, the COVID-19 pandemic was not the sole driving force in the shift toward online learning. HEIs saw the potential to take academia online prior to the pandemic, driven in part by an intensification for a continuously developed workforce adapting to ever-evolving digital economies and the global adoption of the Internet (Palvia et al., 2018), as well as the increasing popularity of online education (Dumford and Miller, 2018). e-Learning holds many benefits for students: giving them the ability to learn remotely while working to create an income; developing themselves regardless of geographical barriers; and investigating and developing new career prospects (Nguyen, 2015). Online learning is also not a lesser pedagogy compared to "traditional" face-to-face teaching. Whether classroom time can be reduced and replaced with an online learning environment without compromising learning outcomes was the focus of a meta-analysis conducted by Müller and Mildenberger (2021). They report that blended learning is on par with traditional classroom learning, despite a reduction in classroom time of up to 79% in some reports. Although the COVID-19 pandemic may have expedited the process of moving higher education online, predictions before the pandemic were that online education would become the main delivery method by 2025 (Palvia et al., 2018; World Economic Forum, 2020). There are many benefits to learning online; however, online learning also has challenges to overcome for students and faculty.

The shift to online learning occurred so quickly that many students and faculty felt inadequately prepared at the beginning of the pandemic. In Jordan, 40% of the faculty surveyed had no prior online teaching experience, while 66% reported receiving some form of online pedagogy training (Almahasees et al., 2021). Egyptian tertiary educators listed poor Internet connectivity, inadequate access to computers, and technical problems as the highest barriers to e-learning (Zalat et al., 2021). These barriers have also been reported in other countries, including South Africa (Mhlanga and Moloi, 2020; Mpungose, 2020), the Republic of Ireland (Cullinan et al., 2021), and the Philippines (Joaquin et al., 2020). There is evidence of ingenious approaches to overcome these challenges. For example, in South Africa, a country known for the high costs of mobile data, several universities banded together to bargain for reduced pricing on data from mobile operators, offering students access to 30 Gb of free monthly data to attend online video-based live classes. Many educational websites were also zero-rated (i.e., browsing these websites did not incur any cost for the browser). However, the most widely used online teaching service, Blackboard, could not be zero-rated at the beginning of the pandemic in South Africa (Hedding et al., 2020), thus requiring HEIs to subsidize mobile data. The University of Johannesburg, the University of Cape Town, and the University of the Witwatersrand (among others) implemented computer loan schemes to ensure that deserving students had access to the computing hardware required to complete their online studies.

Teaching theoretical aspects is quite easily done using online lecturing through live classes or in asynchronous modules when students are adequately equipped with the necessary support (technical, hardware, and access to broadband Internet) to access such learning opportunities. However, education is based not only on theoretical learning, but also on the practical implementation of techniques in practice, especially in the sciences. In an early review on how HEIs responded to the COVID-19 pandemic, Crawford et al. (2020) examined HEI strategies in 20 countries. Although providing a detailed examination of the pedagogical approaches implemented in these countries, the only mention of practical training was a singular notion that Hong Kong HEIs suspended practical training until further notice (Crawford et al., 2020). From this early report, it would seem that HEIs did not highly prioritize practical training, as was the case for theoretical learning. Students without such practical experience are likely to graduate with inadequate laboratory skills, a major long-term disadvantage compared to previous students who were able to study "normally" (Gamage et al., 2020). However, current technological advances have allowed virtual laboratory (VL) experiences to be created. VLs can be defined as "technology-mediated experiences in two or three dimensions that situate the student as being in an emulation of the physical laboratory with the capacity to manipulate virtual equipment and materials" through input devices (Reeves and Crippen, 2020).

In their extensive review of published VLs, Reeves and Crippen (Reeves and Crippen) describe that the majority of VLs before the COVID-19 pandemic were 2D desktop-based (92%) and acquired from external sources rather than developed for specific courses (75%). Udin et al. (2020) reviewed published VLs that improved Students' understanding of abstract biology concepts and laboratory skills, with a total of 47 reports of 19 VLs dedicated to the topic. The students found the use of VLs to be mostly positive (Udin et al., 2020). The reported small number of self-developed VLs motivated the author's investigation of whether the creation of VLs is feasible for an academic in their regular line of work. Here an approach toward creating two VL experiences is presented. One focused on creating a 3D laboratory environment where students could learn to perform a streak plate, a microbiological technique used to isolate colonies of a single strain of bacteria. The other aimed to educate students on micropipetting skills.

This paper investigates two aspects of the instructional design processes followed to create the VLs mentioned above.

(1) To provide an example, using mainly freely available software tools, of an approach toward developing different online laboratory learning methods.

(2) To report on the challenges we faced in creating an online laboratory training session and how these challenges were overcome.

This reflective paper is structured as follows. In section "An Approach to Virtual Laboratories," the approach to creating VLs is described. In section "Challenges Experienced During the Creation of Virtual Laboratories During a Pandemic," there is a discussion of challenges experienced in this endeavor to create VLs, and how these challenges were overcome. Lastly, in section "The Future of Virtual Laboratories and Conclusions," we introduce the idea of creating an open access online repository where open-source applications can be shared for use by anyone. This report avoids being a technical report of creating a VL, as each VL will require a unique solution (i.e., creation of specific 3D models, programming of interactions, creation of assessment opportunities). The created VLs will soon be shared on a newly developed online repository (amakhono.org) Interested readers are welcome to contact the author for access to the source code and the VLs.

AN APPROACH TO VIRTUAL LABORATORIES

The approach described below was developed based on the following self-formulated challenge: *Create a teaching experience in which students can learn how to use a micropipette and how to perform a microbiological streak plate. The experiences should be available in various formats, including video, mobile applications, and virtual reality. The solution should be cost-effective and developed as far as possible without third-party payments.*

Development Platform

At the beginning of this challenge, the author investigated several potential approaches for creating such VL experiences. The platforms are listed in **Table 1**, including the perceived benefits and caveats for using these platforms.

Game engines held the most promise in creating VLs in an agile manner, with the additional benefit of being able to export the content in various formats (i.e., PC, Linux, iOS, Android, WebGL). Several freemium game engines, including Unity3D,[1] Unreal Engine[2] and CryEngine[3] offer 3D spatial representations and increasingly higher levels of immersion (Keil et al., 2021). Each one of these game engines offers different benefits to the programmer, and each has merits for using in the creation of VLs. Based on the author's previous experience in programming in the C# language, Unity was chosen as the preferred game engine for development.

Various educational tools used Unity3D, a Unity Technologies-developed game engine, as a preferred development tool. The Open University OpenScience Laboratory implemented Unity3D to create different experiences, including a geology field trip based on Skiddaw in the Lake District (Minocha and Burden, 2013). High-level safety demonstrations in chemistry (Dholakiya et al., 2019), augmented reality of traditional foods for nutrition education (Yulia et al., 2018), fire safety training (Zhang and Shi, 2019), and virtual practice platforms for chemical engineering (Ouyang et al., 2018) are among a few examples of how HEIs have implemented this software in the creation of dedicated training software.

Unity3D offers the option to export to various platforms, including Apple iOS, Android, Windows, Linux, and WebGL. The ability to export to these formats enables educators to develop their VL once and make them available to a broader range of devices that students can access. Although Unity3D has a range of 2D tools, its approach to 3D helps developers create immersive environments.

Creating a 3D Laboratory Environment

Unity3D supports standard 3D file formats (.fbx, .dae, .dxf, and .obj), and although not recommended for production builds, Unity can also import proprietary file formats (Autodesk Maya, Blender, Modo, and Cheetah3D), which are internally converted to the .fbx format (Unity Technologies, 2021a). Generating a 3D world within Unity3D is done by placing 3D objects in a three-dimensional coordinate system. Each 3D object can be programmed to interact with other objects by adding the necessary physics objects, including object colliders and "rigid body" components, allowing objects to react in a simulated manner and expected physics.

When creating VLs, the developer should have a clear priority list, ensuring that his efforts are implemented optimally. In this presented case, the focus was on generating VLs as quickly as possible while ensuring that a high level of immersion was managed. Therefore, we opted to use the Unity Asset Store for some 3D models. The Unity Asset Store links potential buyers with sellers of Unity3D optimized add-ons and production elements. We found a modeled chemistry laboratory[4] in this online store for the backdrop for our VLs. At the time of purchase, this model was on sale for US $5 (**Figure 1**).

Unity3D renders at various quality levels, depending on the render pipeline used. Since our range of devices had varying graphical outputs, we opted to use the Universal Render Pipeline (URP). This rendering pipeline is optimized for use on mobile platforms and works exceptionally well on high-end consoles. The 3D laboratory model was created for Unity's High-Definition Render Pipeline (HDRP). The model conversion from HDRP to URP was done in Unity3D, by reassigning textures to the relevant materials in and with the appropriate shaders.

The purchased 3D laboratory model provided only the basic essential equipment and environment for a VL (table, blackboard, and aesthetic objects). All the additional equipment required for these applications needed to be sourced elsewhere. Various online marketplaces selling 3D models exist, including Turbosquid,[5] CG Trader,[6] Shapeways[7] and Free3D,[8] among other domains. When searching for 3D models of required laboratory equipment, we found that prices ranged between $2 US and $1,699 US per item on the various platforms (June 2021). As an example, the price of a micropipette varied between $9 US and $59 US on these markets, resulting in an increasing cost estimate in creating a whole laboratory experience. Instead of buying these 3D models,

[1] https://unity.com
[2] https://www.unrealengine.com/
[3] https://www.cryengine.com/
[4] https://assetstore.unity.com/packages/3d/environments/industrial/chemistry-laboratory-188274
[5] https://www.turbosquid.com/
[6] https://www.cgtrader.com/
[7] https://www.shapeways.com/
[8] https://free3d.com

TABLE 1 | Pros and cons list of potential software applications that could be used to create VLs.

Modality	Arguments for use	Arguments against use
Adobe Animate CC (or similar Adobe Flash based programs)	Relatively easy to learn animation package. Extensive repository of online video tutorials on the use of Adobe Animate CC.	Limited to two-dimensional animations. Expensive monthly subscription. Various computing platforms no longer support Adobe Flash.
Adobe captivate	The built-in quiz functionalities can be used for evaluation.	Limited functions for creating novel experiences. Requires footage captured external to the software. Requires a license.
Blender 3D	Free software. Capable of creating 3D and 2D animations. Exportable to a wide range of formats, including video and 3D objects. Thousands of video tutorials are freely available to learn how to use the software.	Lacks the ability to program user input (linear style of experiences). It is time consuming to learn.
Visual coding (JAVA or other programming languages)	Excellent potential to create extensive experiences rich in user input.	Lacks a built-in physics engine. Requires extensive programming to generate physics and input from different devices.
Game engines	The built-in physics engines result in more accurate simulations and less programming required. Large support networks for developers. Free, until profit threshold reached. Exportable to various formats and devices.	Requires some initial learning. Knowledge of programming languages is required for some interactions.

FIGURE 1 | 3D model of a chemistry laboratory used in our experience.

the author decided to design and develop the 3D models required for laboratory experiences in-house.

Creating a 3D Laboratory Equipment

On the basis of this decision, 3D modeling software was required. Many such packages exist in the market, ranging from high-end to extremely basic and carrying varying price tags from relatively expensive to free. One 3D modeling software package that stood out was Blender[9] based on the high level of community support in the form of tutorials and open discussion forums, as well as the capabilities of the software to generate 3D models that range from comical to photo realistic. Blender is also available for free for any use. Creating 3D models of laboratory equipment in Blender was first described over a

[9] https://www.blender.org/

decade ago (Dere et al., 2010). With Project OSCAR (Open-Source Courseware Animations Repository), Dere and their colleagues created the first online repository of Blender-generated 3D models of laboratory equipment, licensed under a Creative Commons—Attribution-Non-Commercial ShareAlike 2.5 India license. Project OSCAR hosts 19 chemistry and 26 physics-related models. However, and perhaps better phrased, unfortunately, the project has not added many new models apart from the initial "more than 40" reported (Dere et al., 2010).

The author used Blender to generate 3D models of standard laboratory equipment, including an incubator, micropipette, Petri dishes, Bunsen burner, and inoculation loop. After completing a basic Blender tutorial on YouTube to learn how to use the software, the 3D laboratory equipment models were quickly created (averaging approximately 30 min per item). A demonstration of how to make a low-polygon Bunsen burner is presented in **Supplementary Video 1**. Other low-polygon 3D models were created in a similar fashion. It should be noted that the author has no formal training in 3D modeling prior to this endeavor, apart from watching free video tutorials on-line. The author is classically trained in environmental microbiology and genetics.[10]

Creating custom-made 3D objects for use in VLs has the benefit that it can be modeled to be similar to the equipment that students will most likely have used in a real laboratory, making asynchronous learning a feasible addition to the current practical curriculum. The main caveat is that it takes time to develop these 3D models and to learn how to use 3D modeling software such as Blender. However, the software has become much more user-intuitive with recent upgrades to the Blender user interface. The created models were easily imported into Unity3D and arranged in a 3D space to mimic a traditional practical training session (**Figure 2**). Once the models have been correctly placed in the 3D space, user interactions could be scripted.

Animating, Scripting, and Interactions

Both Blender and Unity3D provide the developer with tools to animate 3D models, based on incremental movements or changes made to selected parts of the 3D object on a linear timeframe. Where possible, it is advised to animate objects rather than coding complex behaviors. For example, we decided to animate the Bunsen burner collar that adjusts the amount of oxygen entering the gas mix, as well as the gas tap that opens the flow of gas and the movement of the lighter to ignite the Bunsen burner and the opening/closing of the incubator door. These animations were done in Blender, and the exported 3D objects and animations were easily imported into Unity3D by a simple drag and drop.

However, to generate a sense of realism, not all objects can be animated to react in a predetermined fashion. Scripting is required for some objects to ensure that their behavior is as expected in a real-life laboratory. Some of the objects that we scripted to have additional behaviors included the flame of the Bunsen burner, the incubator temperature controls and light settings, and the pipette volume changer. Animating these objects would have been a momentous task, while scripting allowed for a far less laborious effort. An example is VR-based micropipette training, where the volume setting was scripted to be changed based on the number of turns on the volume setting dial. Animating this would have resulted in generating animation for each of the 9,999 possible volume settings on a 1,000 μL micropipette. For this solution, we used a Unity3D text object, overlain on the position where the text should be displayed, that could be changed from a C# script. The assigned script checks whether the volume changer is turned left or right and then adds or subtracts an arbitrary amount from the displayed volume of the pipette, updating the text value in each frame of the application.

In scripting, one is going to run into some conundrums as to how best to move forward. An example of one such problem that we faced was in modeling liquids in containers. Although game engines are competent in handling everyday objects' physics, liquids (and, by extension, gases) remain a challenging physical state to model. Generally, two-dimensional modeling of these states of nature is done relatively easily by software such as Unity3D, but with an added dimension, it becomes more complicated. Since Unity3D does not support fluid handling in its standard format, the use of an additional package from the Unity Asset Store was investigated. Currently, there is only one fluid simulation package (called Obi Fluid)[11] that mimics particles to generate accurate fluid simulations. The package retails for $60 US. However, one warning is that such fluid simulations are extremely demanding on computing resources, resulting in us opting rather for a shader-based solution for our application, as these applications were required to run on a wide variety of Students' hardware. Various shader-based options are available in the Unity Asset Store; however, we opted for a solution reported by the Unity Community member—specifically "Binary Lunar" on YouTube.[12] This free solution resulted in a primitive liquid that would take the shape of a container. Scripting the behavior of the liquid, based on the status of the pipette, resulted in a "virtual" fluid that could be manipulated at a fraction of the computing requirements. This enabled us to export the final applications to PC, Android (including Oculus), and WebGL.

The intended platform of the developed application is an important choice that needs to be well defined at the start of any similar projects. Although the export is relatively easy (a switch done by Unity3D), the interaction programming requires that the platform be kept in mind. For instance, input on a personal computer will require a different input framework compared to VR or mobile. In interaction coding, platform-specific alterations were incorporated to ensure an optimum user experience. These included changing the orientation of the camera (for mobile users with a gyroscope and VR devices, we incorporated the movement of the device to change the view in the game; mouse center button could be used to direct the camera for PC users, etc.) as well as the advancement methods of the tutorial steps, all to improve interactivity and ensure an engaging educational experience.

[10]https://orcid.org/0000-0001-8280-6718

[11]https://assetstore.unity.com/packages/tools/physics/obi-fluid-63067

[12]https://www.youtube.com/watch?v=eIZgPAZx56s

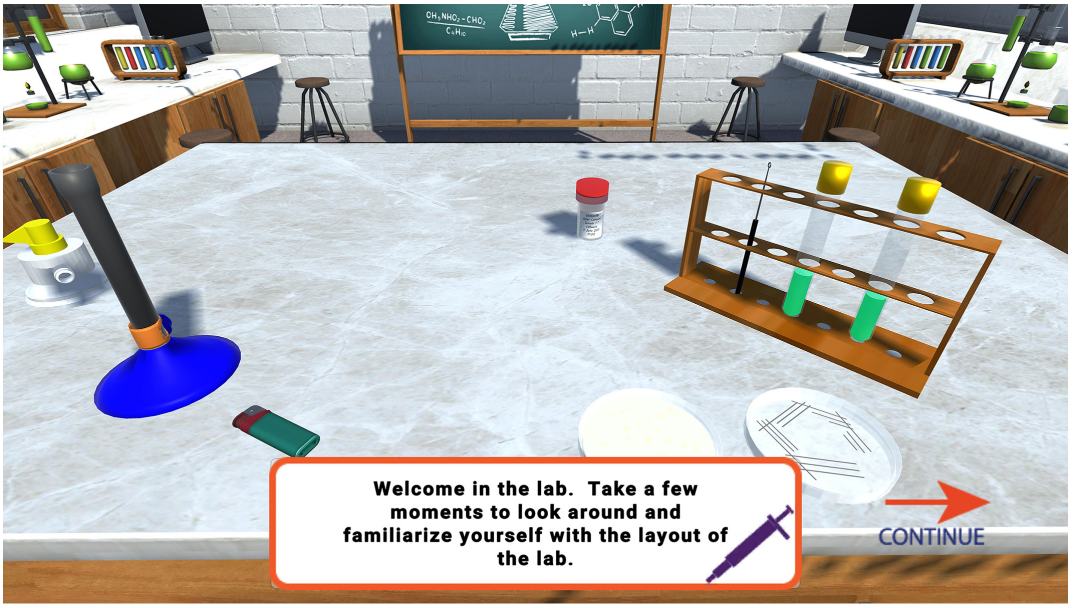

FIGURE 2 | 3D Models placed in Unity3D. Several 3D models were generated in Blender, including the Bunsen burner, Petri dishes with agar, inoculation loop, green fluid test tubes, and the gas tap.

Tutorial and Guiding Student Through Experience

An important aspect of the created experiences is the tutorial, a guidance given to students to ensure that they achieve the targets of the VL experiment. There are two methods, both warranting further investigation as to which method aids students more. The first method is to provide step-by-step guidance and allow students to follow the tutorial in a specific order. Using this guided approach, students can focus on the steps in question. Second, students can be shown a video before the start of their virtual experiment, followed by a "free play" in the laboratory. We opted to investigate both styles to experience first-hand the implementation of these two guidance techniques in our VLs.

Practical Aspects of Implementing a Tutorial

By comparing students in three different tutorial scenarios, those who watched a video tutorial were better equipped to deal with a specific scenario compared to those who underwent static text-based instructions (Craig and Friehs, 2013). Interactive tutorials did not necessarily improve learning compared to static web-based tutorials (Craig and Friehs, 2013). However, Generation Z students are more inclined to innovative teaching styles, including visual and audience participation through simulation, case studies, and engaged learning (Hampton et al., 2020).

Practical Aspects of Implementing a Tutorial

In retrospect, the focus of this endeavor at the beginning of the development process was wrongly placed upon creating the experiences, without considering the implementation of a tutorial to guide students as an integral part of the experience. This resulted in an extended period required to create guided tutorials, including programming pauses in the experience where the user first needed to complete a specific task before advancing the tutorial to the next step. In the planning of any VL, special attention should be given to addressing how students will be guided, a valuable lesson that was learned from our experience.

Our implemented tutorial mechanism used the concept of "slides," similar to PowerPoint or other slide presentation software. We programmed a tutorial manager to project images on the screen, play an audio voiceover (.mp3), and display the transcript (to include deaf and hard-of-hearing individuals). The tutorial manager would not allow advancement to the next phase until a set of criteria has been achieved. Therefore, it guides the student through their experience in a step-by-step manner. This method has the advantage of providing the student with short bursts of information, avoiding information overload, and ensuring that the student follows the tutorial exactly. The disadvantage of this tutorial method, at least for the programmer, is that it requires extensive programming to ensure that each step is coded correctly.

Audio quality is also an essential factor to include in the design of learning experiences. Here, the creator has three choices. First, they can record audio on their own devices and edit the audio to be of high quality. Various audio editing applications exist that can aid the developer in generating quality audio files, including open-source software packages, such as Audacity,[13] which provides a robust workflow for editing audio files. However, recording requires a high-quality microphone to ensure that audio quality does not distract students. Furthermore, in many cases where recordings are made outside of a professional studio, background noise may be recorded as well. The highest quality audio content will be

[13]https://www.audacityteam.org/

generated by recording audio in a dedicated studio, yet this increases production costs and may also result in an increase in the project development time. Additional recording or editing may further increase the cost of outsourcing audio.

The author believes that the most cost- and time-effective solution is to use an artificially intelligent text-to-speech generator to record audio. This allows the producer the opportunity to edit tutorial text and regenerate the audio files by merely pressing a button. Various text-to-speech services exist with varying price tags. Some free options include Amazon Polly[14] and Balabolka.[15] However, the free services that were evaluated were deemed monotonous by a small focus group (results not shown). Therefore, it was decided to investigate more advanced text-to-speech options. These include paid services such as murf.ai, nuance.com, and many others. Following a free trial of murf.ai, it was found that this platform provided for the immediate needs (although this is by no means supportive of murf.ai being the best platform for text-to-speech). Utilizing the paid-for service ($19 US per month, cancelation when no longer needed) allowed unlimited downloads of generated voiceovers, with 24 h worth of voice generation per year and commercial usage rights. Furthermore, it provided access to 60 different voices, allowing multiple "virtual" instructors to facilitate online tutorials. Unfortunately, one caveat of using text-to-speech generators is the absence of many languages and a lack of diversity in the ethnicity of the AI "voiceover artist". An example of the realism achieved with AI text-to-speech generators is presented in **Supplementary Audio 1** (Abstract of this article, narrated by "Edward"—a United Kingdom English voice on murf.ai).

Video and Free-Play Tutorial

Although the guided tutorial was created first, we found that the video tutorial was faster to produce, especially in Unity3D. One of the benefits of using Unity3D is its ability to manipulate and code camera(s) to render 3D recreated environments. Using the Unity Recorder add-in allows the user to capture and save data from Unity during play mode—including animations, videos (2D and 360 degrees), images, audio, and more (Unity Technologies, 2021b). Any editing required for the videos was done using Davinci Resolve 17,[16] a free-to-use video editing software package. Such tutorials can then be uploaded to the educational content management system of choice or disseminated via online social platforms.

CHALLENGES EXPERIENCED DURING THE CREATION OF VIRTUAL LABORATORIES DURING A PANDEMIC

In section "An Approach to Virtual Laboratories" we reported on our experience in creating a VL, which was done in a game engine and using as many freely available software packages and resources as possible. The monetary cost involved in the creation of the said VLs was $24 US ($5 US for the laboratory environment and $19 US for access to the murf.ai AI-generated text-to-speech service). However, in addition to monetary input, several other factors need to be taken into account in creating VLs as part of the normal daily activities of an academic at an HEI.

Time

The amount of time that it takes to develop depends on the prior knowledge that the developer has in using the software to create training opportunities. In our presented case study, the author was well experienced in the C# programming language and had some prior experience in creating and editing video, although neither of these experiences was the result of formal training. However, completing one VL took more than a 100 h despite prior knowledge of the software used. Academics wanting to explore VLs as a viable alternative to physical laboratory training should consider this in their planning.

However, although the creation of VLs requires an initial investment in time, the experience can be used in subsequent training sessions. VLs are also an excellent asynchronous training method, where students will be allowed to experiment without the need for supervision in a physical laboratory. Shifting some practical to an asynchronous delivery method frees up time in the academic schedule—potentially allowing for additional training modules that would be difficult to model *in silico* to be included in the curriculum.

Technical Skills

Above, we mentioned that the author had limited experience with some packages implemented in the VL creation process. Although the production of such experiences does not require formal training, it does help speed up the creation process. In our approach toward choosing appropriate tools for creating specific sections of the VL, we searched social media platforms and ensured that the investigated software had an active community of users. As students are turning toward social platforms to enrich their learning experience, so should academics. In doing so, faculty members develop their skillsets, which could then be transferred to new academics and thus transform the academic milieu into a complement of educators who are well versed in various technological solutions.

Working Remotely

When creating virtual laboratories while working remotely, one needs to ensure that communication between collaborators is in place. In this report, a single educator created the different VLs, based on his personal experience teaching the two laboratory techniques to students. This was due to a change in the working environment, where the researcher transferred to a new host institution and had yet to develop collaborative networks at the new host facility. However, the VL creation process can be substantially improved when working in a team environment. Furthermore, by splitting tasks and focusing on the strengths of a collective, VLs can be produced much faster than the mentioned 100 h.

[14]https://aws.amazon.com/polly/
[15]http://www.cross-plus-a.com/balabolka.htm
[16]https://www.blackmagicdesign.com/hk/products/davinciresolve/

Version control, as well as add-ons facilitating collaborative work for software packages such as Unity3D, will result in teams being agile in their creation of VLs for students. Therefore, although an educator can create their own VLs, the demanding nature of academic life makes it a rather heinous task to achieve while ensuring that all other demands on time are met. As the African saying goes: "If you want to go fast, go alone. If you want to go far, go together."

THE FUTURE OF VIRTUAL LABORATORIES AND CONCLUSION

Millions of biological sciences students are trained in basic laboratory skills, ranging from handling a micropipette to dissecting organisms. From recent events that transpired (and are pretty much still in play) during the global COVID-19 pandemic, access to laboratories for training students is not a given, as was the case a few years ago. With increasing student numbers, and poor access to equipment in resource-limited regions, now is an opportune time to develop an open-source, free-to-use set of virtual laboratories.

In the following months, the author's team will be launching amakhono.org, intending to host and create free and open-access resources for VL creators. The platform, which is currently in development, will host 3D models of laboratory equipment under Creative Commons licensing; it will also provide practical guidelines on creating VLs and a community resource for hosting VLs for students and other educators to access. Having a free resource, in our opinion, will drive science education into the fourth industrial revolution while allowing students from all walks of life the opportunity to receive a high standard of practical training. Similar to how theoretical education has shifted its trajectory—from face-to-face to online teaching, so too will new technologies, such as extended reality devices, become the VL of tomorrow. However, to reach tomorrow, we need to start building today.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.796840/full#supplementary-material

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A Bibliometric Analysis of Virtual Reality in Anatomy Teaching Between 1999 and 2022

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Human anatomy is an important medical subject that includes abstract content and strong operability. The lack of specimens required for anatomical experimental teaching and unclear observation of fine structures of specimens lead to difficulties for students in learning. As a new technology in the field of computers, virtual reality (VR) has been widely used in the medical field and has great development potential and application value. Its use in the teaching of human anatomy has received increasing attention. This technology increases the sense of reality of medical students in learning and improves the learning effect, including initiative and enthusiasm of students. Publications were obtained from the Web of Science (WoS) Core Collection on April 30, 2022, with the following retrieval strategy: [(TS = VR) OR (TS = virtual reality)] AND (TS = anatomy) AND [(TS = education) OR (TS = train*) OR (TS = teach*) OR (TS = learn*) OR (TS = study*)] NOT TS = (surgery), and the time frame was from 1999 to 2022. Then, VOSviewer software, Excel and GraphPad Prism 9 were used to analyze the data. The keywords included cocitations, countries/territories, publication numbers, institutions, authors and journals of publications. A series of scientometric and visualized analyses were conducted, and a table for a detailed analysis of the application of VR in anatomy teaching was created. This paper mainly analyses the application status and progress of VR technology in anatomy teaching, which is shown to improve the anatomical learning effect of medical students. In conclusion, the application of VR technology in human anatomy has great potential.

Keywords: model, neuroanatomy, dissection, technology, stereopsis

INTRODUCTION

Human anatomy basically studies the structure of the human body, and it's a subject that bridges basic medical courses with clinical medicine courses. In addition to theoretical courses, human anatomy experimental teaching is required content of medical colleges and universities. Experimental teaching is essential teaching content, and usually occupies a large number of teaching hours. In order to deepen students' understanding of the structure of the human body, as well as their mastery and memory of theoretical knowledge, anatomical experiment teaching is mostly carried out by autopsy, cadaver observation, and wall chart observation. However, this teaching method still has many defects. The current problems are the lack of medical specimens and the reduction of teaching hours (Moro et al., 2017). Despite the long history of cadavers in anatomy teaching, there are numerous financial, ethical and regulatory restrictions on their use. Currently, a greater emphasis on student autonomy has led to reductions in some basic science courses and a diminishing amount of time allocated to gross anatomy (Drake et al., 2002, 2009, 2014). As a result, many medical schools now use the teaching method of several students working together in groups to dissect specimens. In this case, a cadaver is usually shared by 10–12 students. This can lead to a lack of practical opportunities for each student. In addition, the availability of specimens, cost and time constraints greatly affect students' learning outcomes, especially for small and complex structures, such as nerves, lymph nodes, and blood vessels (McLachlan and Patten, 2006). Substances used for fixation and preservation also pose a risk of contamination and toxicity (Akbar-Khanzadeh et al., 1994; Demiryürek et al., 2002). Another option is to use plastic models to study anatomy. It is not restricted by cadaver studies and has the advantage of presenting structures in three dimensions. However, these models are poor at showing fine structures and are expensive, and their decline in production has exacerbated the price problem in recent years (Nicholson et al., 2006). Therefore, VR technology provides a solution to these problems.

VR is the use of computer technology to create a realistic virtual environment with a variety of sensory functions, such as touch, hearing and sight. Users can learn human anatomy in an immersive virtual environment by interacting with entities through devices, such as a wearable perception helmet, tracking ball and perception gloves (Matthews, 2018). Compared with traditional human anatomy experiments, VR technology has many advantages. First, VR has the characteristics of digitalization, virtualization and automation, which creates a vivid environment for students to learn anatomy. In such a learning environment, students change from passive learning to active learning. Participants often find VR models interesting and engaging, with their enthusiasm for learning fully aroused (Weyhe et al., 2018; Erolin et al., 2019; Gloy et al., 2022). Second, the VR system provides a clear picture, which is convenient for students to observe. Seeing the anatomical structures from different angles and at different anatomical levels is very useful for learning complex structures, such as the heart, knee joint, and nervous system (Nicholson et al., 2006; Silén et al., 2008). In addition, VR constructs an immersive learning environment, making it easier for students to concentrate and improve their learning efficiency. Fun is recognized as an important factor in case learning and one of the key factors for success of problem-based learning in medical education (Neville, 2009; Telner et al., 2010). The interaction between the body and the three-dimensional model is crucial to understanding its physical structure, while autopsy has difficulty achieving interactivity. It is worth emphasizing that an important feature of VR that cannot be ignored is how much the users enjoy it, which is crucial to its application potential, as subjects often believe they will learn more while playing (Chittaro and Ranon, 2007b; Maresky et al., 2019). Moreover, the system allows students to repeat dissection exercises, which solves the problem of insufficient cadaver specimens and is conducive to the consolidation of students' knowledge (Chittaro and Ranon, 2007a). Overall, the application of VR in anatomy teaching has great significance and broad prospects. Therefore, it is necessary to evaluate and analyze the current publications about VR in anatomy teaching. However, there is no precedent for a bibliometric analysis of this area.

Bibliometric analysis is a scientific method based on a large-scale literature database. It can be used to assess contributions to a field of research, including by countries, institutions, authors and journals. At present, it has gradually become a research hotspot in many fields (Ahmad and Slots, 2021; Bashir et al., 2021; Celik et al., 2021). In this study, VOSviewer (van Eck and Waltman, 2017), an important analytical tool, was used to perform a bibliometric analysis. The keywords, cocitations, countries/territories, publication numbers, institutions, authors, and journals of publications were analyzed. Finally, a series of scientometric and visualized analyses were done to provide a comprehensive knowledge map for the application of VR in anatomy teaching and to understand future research directions via bibliometric analysis.

MATERIALS AND METHODS

Data Source and Search Strategy

The Core Collection database of Web of Science (WoS) was chosen to collect publications, since it is widely regarded as the most authoritative database of scientific publications on a wide range of research areas. The data was obtained from the Web of Science (WoS) Core Collection on April 30, 2022, with the following retrieval strategy: [(TS = VR) OR (TS = virtual reality)] AND (TS = anatomy) AND [(TS = education) OR (TS = train*) OR (TS = teach*) OR (TS = learn*) OR (TS = study*)] NOT TS = (surgery), and the time frame was from 1999 to 2022. Then, 646 publications were obtained. Afterward, 646 publications (**Figure 1**) were read and screened, and 287 of them were included in the final data analysis. The inclusion and exclusion criteria were as follows:

Inclusion Criteria:

(1) The publication year of the literature was from January 1, 1999, to April 30, 2022;
(2) The language of the literature was English;
(3) The type of literature was review or article;
(4) The research topic of the literature was the application of virtual reality to anatomy teaching.

Exclusion Criteria:

(1) The types of documents were conferences, reports and letters;
(2) The documents did not use VR as the research topic;
(3) The documents did not use anatomy teaching as the research topic;
(4) Non-English documents.

Statistical Analysis

VOSviewer software (Leiden, Netherlands), Excel and GraphPad Prism 9 were used to analyze the data. A comprehensive

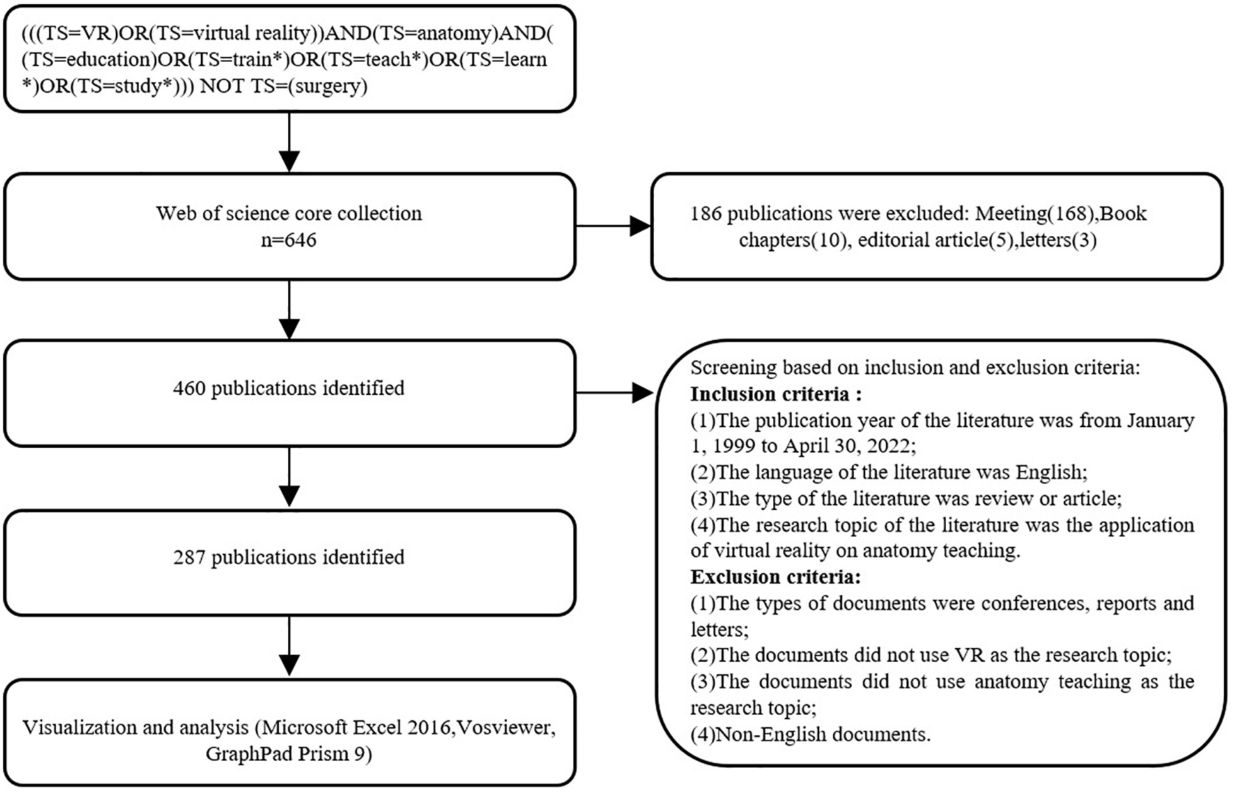

FIGURE 1 | Flow chart for the analysis of virtual reality in anatomy teaching.

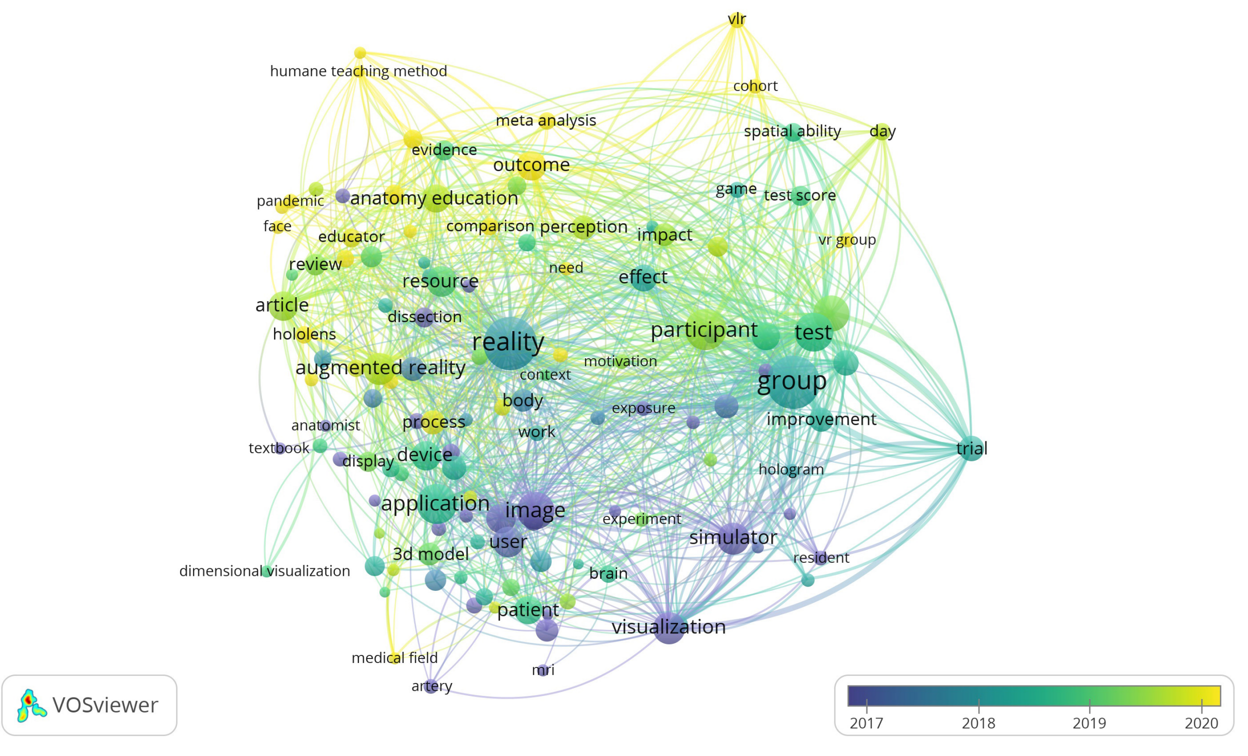

FIGURE 2 | The co-occurrence network of keywords.

description of various publishing characteristics was provided, including keywords, cocitations, countries/territories, publication numbers, institutions, authors, and journals.

RESULTS

Key Words Analysis

As shown in **Figure 2**, VOSviewer was used to analyze keywords in 287 papers. Among all the keywords, reality, group, participant, application, and test, have higher frequencies. This shows that an increasing number of articles about the application of VR in anatomy teaching have been published. In addition, the emergence of the keyword "brain" was noted, which may indicate that the brain is a hot spot in VR applications due to its complex anatomical structure.

Cocitation Analysis

Then, an author cocitation analysis was conducted. The size of the nodes in the figure represents the author's citation frequency, the thickness of the line represents the cocitation frequency, and different colors represent different clusters of clusters. Three distinct classes are seen, as shown in **Figure 3**. Among them, Moro, C, Yammine K. Nowinski, WL's, articles were cited the most frequently. In addition, a cocitation analysis of the references was also carried out, as shown in **Figure 4**. There are four distinct classes. Among them, the paper published by Moro C (Moro et al., 2017) in 2006 is the most frequently cited, which is the classic literature in the application of VR in anatomy education.

Publication Distribution of Countries/Territories

As shown in **Figure 5**, the most published countries are the United States, Australia, and China. For further research, VOSviewer software was used to conduct visual analysis on cooperation relations between countries and territories, and the results are shown in **Figure 6**. Each country or region is represented by a circle, the size of which depends on the number of publications produced in that country. The curve connecting the two circles represents the cooperative relationship between the two connected countries. The thicker the curve is, the stronger the cooperation between the two countries. In general, there is less cooperation between countries. As seen from **Figure 6**, the cooperation between countries is not close. Among them, the United States has more cooperative relations with 10 countries or territories. Britain, China and Australia also have cooperation with a small number of countries. There is not much cooperation between other countries, so countries can strengthen cooperation in this field and jointly promote its development.

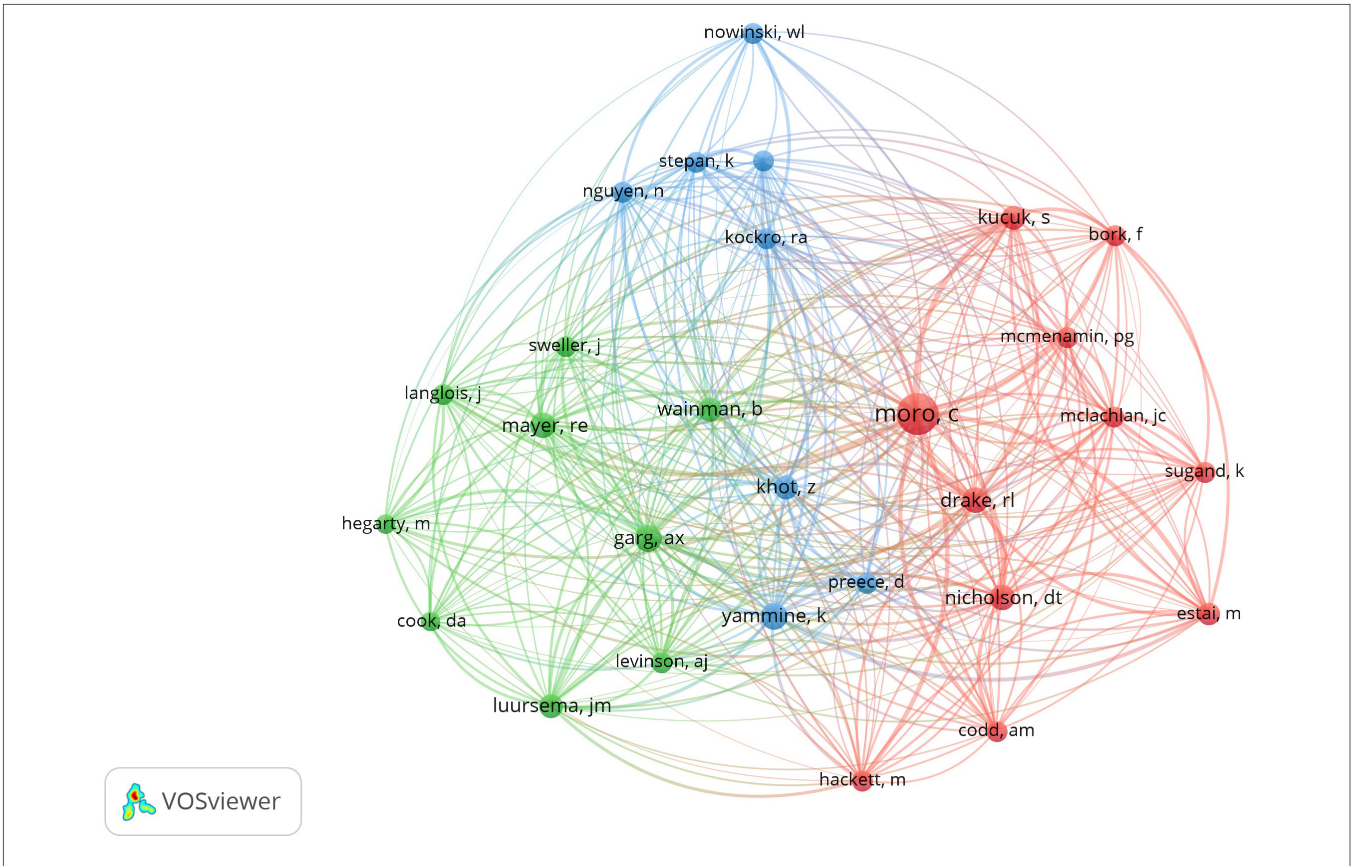

FIGURE 3 | A visualization of author co-citation analysis.

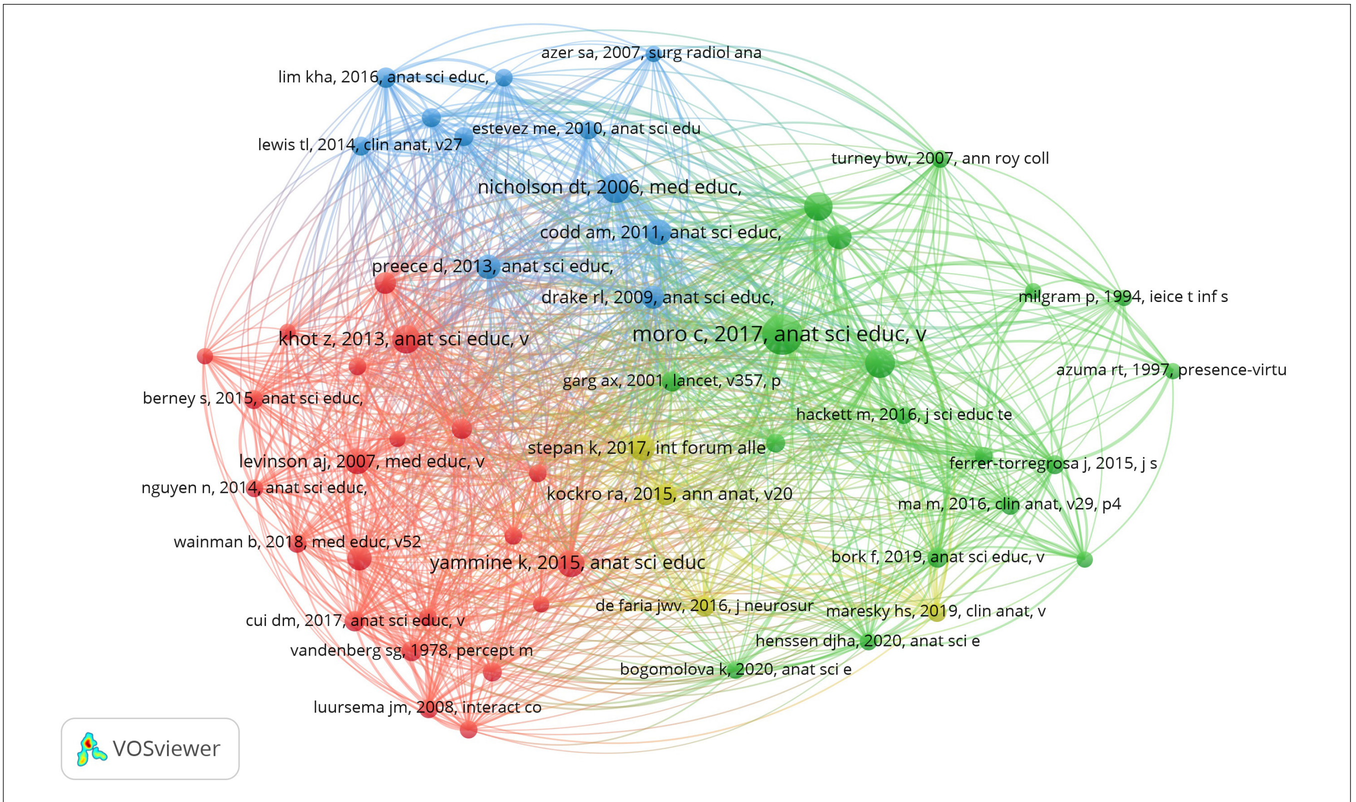

FIGURE 4 | A visualization of co-citation analysis of reference.

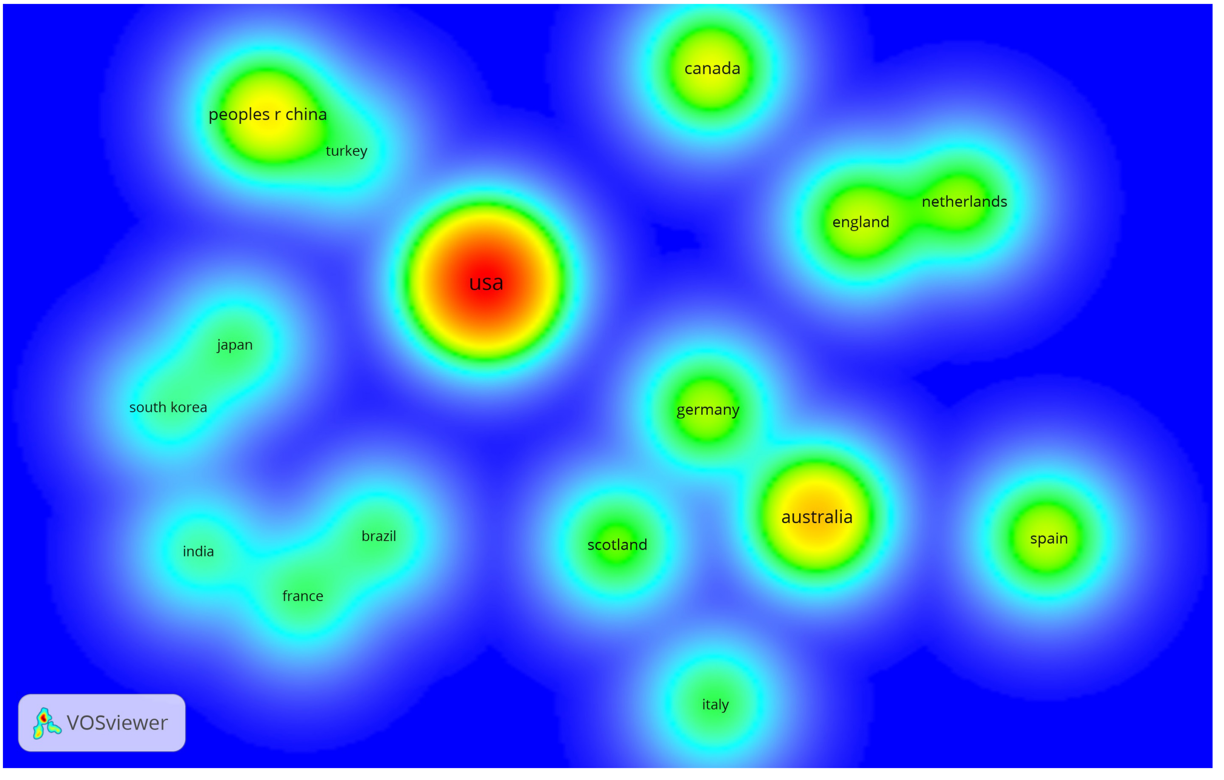

FIGURE 5 | The co-author relationship of countries.

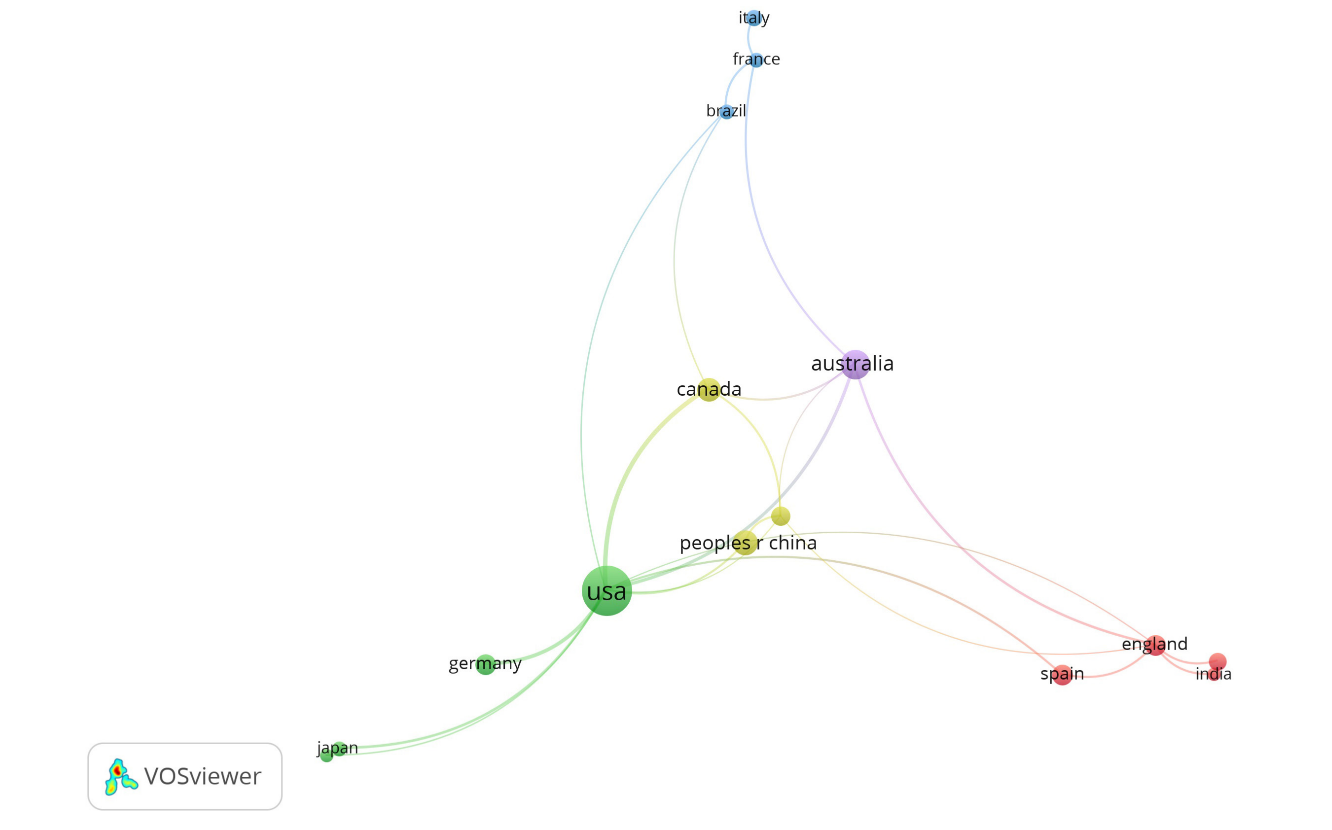

FIGURE 6 | Country distribution for the articles.

Growth of Publications

The number of publications per year reflects the level and development of a field to some extent. We analyzed the number of published articles on the application of VR in anatomy teaching in the past decade (**Figure 7**). This indicates that the publications between 2011 and 2015 show an increasing trend year by year. After we fit the curve of the number of posts, we found that the number of posts in this field approaches an exponential relationship, which means that great breakthroughs of VR in anatomy education have been made in recent years.

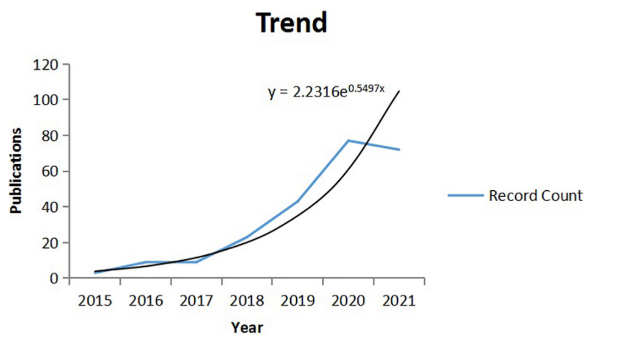

FIGURE 7 | Year distribution of the articles between 2015 and 2021.

Publication Distribution of Institutions, Authors and Journals

Figure 8 shows the top 10 organizations with the number of publications. Universities, such as McMaster University, Bond University, and Radboud University Nijmegen, have made outstanding contributions to the application of VR in anatomy. Similarly, **Figure 9** shows the top 10 authors with the number of publications. Among them, Moro Christian, Stromberga Zane, and Wainman Bruce are the top three. In **Figure 10**, according to the average citation rate, the published journals in this field are ranked in descending order, and a total of 20 journals are included. This picture summarizes the journals with high academic profiles, the number of published journals from 2010 to 2022 in this field, and the impact factors of these journals. Among the 20 journals, the journal *Brit J Anaesth* has the highest impact factor (IF = 9.17), and the journal *Anat Sci Educ* has the highest number of publications in this field (Publication = 43).

DISCUSSION

Human anatomy is the foundation for new medical students and an indispensable part of understanding other clinical disciplines, as it is closely related to other medical disciplines. Only on the basis of understanding the normal structure of the human body can one distinguish between pathological and physiological

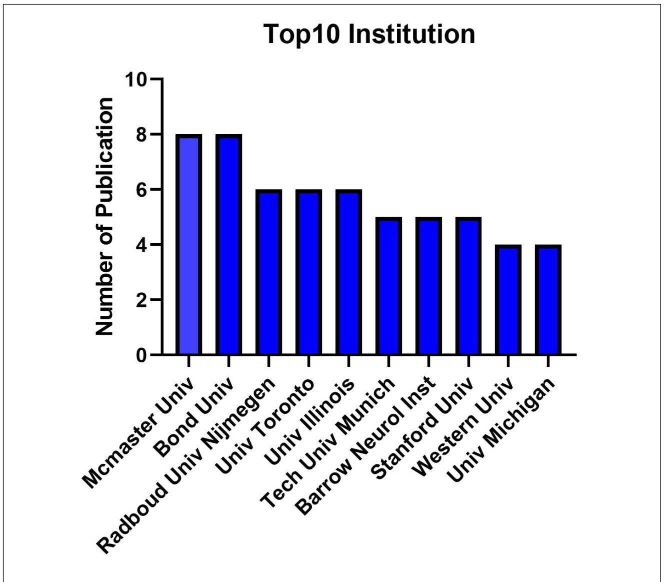

FIGURE 8 | The contribution of the top 10 institutions.

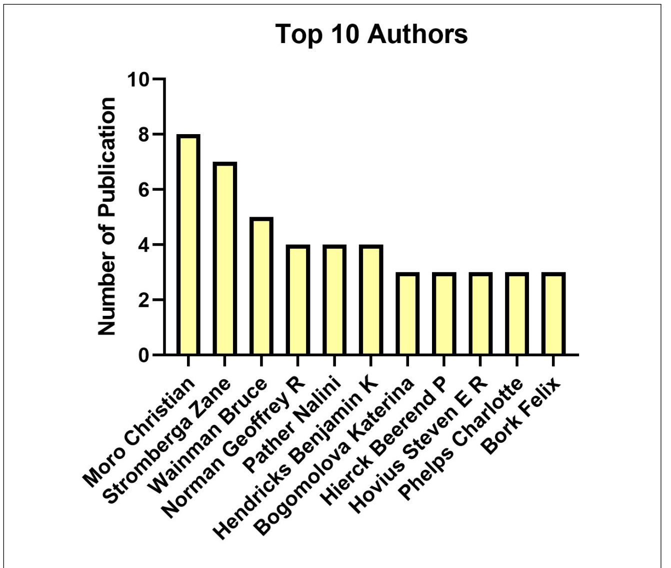

FIGURE 9 | The publication of top 10 authors.

processes. Furthermore, the clinical operation and treatment of diseases are inseparable from human body structure and pathophysiological processes. However, due to the complexity of the course content and the limitation of traditional teaching methods, the teaching of anatomy is very difficult. Moreover, the lack of human specimens further increases challenges of anatomy teaching (George and De, 2010). Overall, there are many factors that hinder the application of traditional anatomy teaching, and new technologies are urgently needed to improve teaching methods in this area.

Fortunately, the application of VR has solved these problems. Virtual scenes of the real world significantly improve the intuition, accuracy, and real-time nature of the user's sensory world (Shi et al., 2020). Therefore, the emergence of VR has an important influence on the development of medicine, especially the application of anatomy teaching. VR is a helpful tool for learning human anatomy and a useful adjunct to teaching

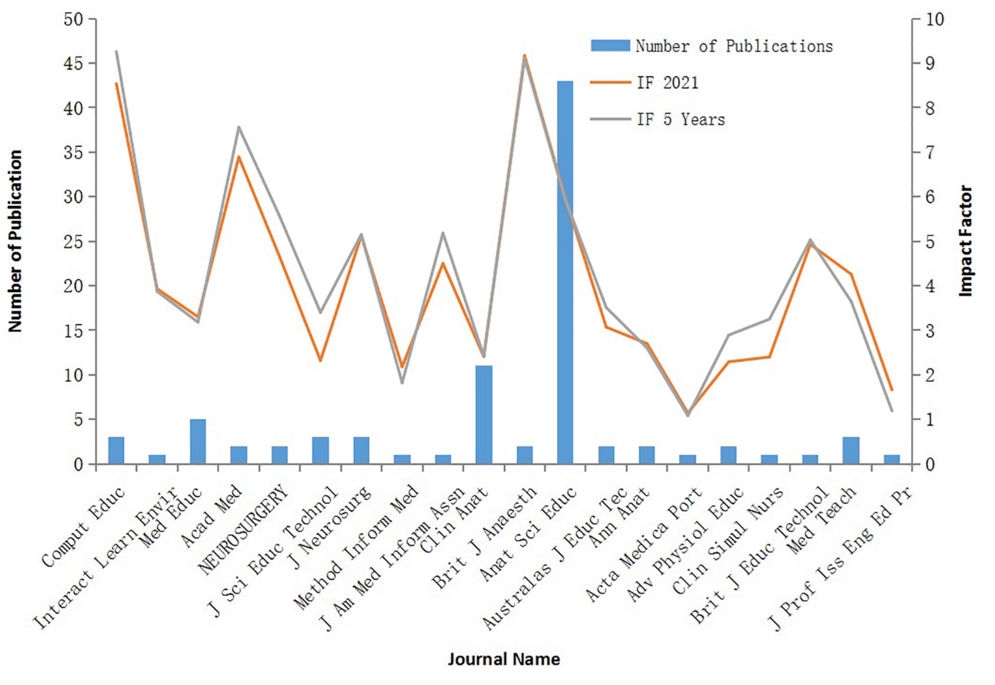

FIGURE 10 | The impact factor and contribution of journal.

(Fairen et al., 2020). To further understand what advantages VR has in anatomy teaching, the following 9 articles were analyzed (**Table 1**), which highlight the advantages of VR in anatomy teaching. The total citations of 287 articles were ranked and screened according to the following inclusion criteria: (1) the paper discusses the application of VR in anatomy teaching; (2) the paper compares the difference between VR teaching and anatomy teaching; (3) there are clear evaluation criteria for teaching effects; (4) participants have clear grouping criteria; and (5) the total citations were more than 50 times. Finally, the nine most cited articles were selected that met the criteria for analysis. Nicholson et al. (2006) conducted a study in 2006 to test the educational

TABLE 1 | Summary table of published studies applying virtual reality in anatomy education.

References	Citation	Year	Application	Participants	Methods	Assessments	Results
Moro et al. (2017)	242	2017	Learning the anatomy of skull	59 Participants from biomedical and health sciences (n = 50), medicine (n = 5) and other faculties (n = 4)	Randomized into one of the three learning modes: VR, (augmented reality) AR, or (tablet-based) TB and completed a lesson on skull anatomy	An anatomical knowledge assessment	No significant differences were found between mean assessment scores in VR (a mean score of 64.5%), AR (62.5%), or TB (66.5%).
Nicholson et al. (2006)	239	2006	Learning the anatomy of the middle and inner ear	57 Medical students	29 In the control group and 28 in experimental group; Students in the control group took the tutorial without exposure to the model and in experimental group completed a Web-based tutorial that included the interactive model	15 Quiz questions	The experimental group scored higher than the control group
Jang et al. (2017)	123	2017	Learning the anatomy of the inner ear	76 Medical students at a medical school	Randomized into two conditions: manipulation and viewing. Manipulation: directly manipulated a virtual anatomical structure (inner ear). Viewing: passively viewed an interaction in a stereoscopic, 3-D environment.	A test on ear anatomy knowledge	Participants from the manipulation condition achieved significantly higher scores than their yoked partners in the viewing condition
Khot et al. (2013)	122	2013	Learning the anatomy of the pelvis	60 Students at McMaster University	Randomized into one of three groups: model, key views (KV), and VR	A 25-item test	No significant differences were found between mean assessment scores in VR, AR, or TB
Levinson et al. (2007)	110	2007	Teaching brain anatomy	240 1st-year psychology students (phase 1, n = 120; phase 2, n = 120)	Randomized into each groups. Phase 1: (1) learner control/multiple views (LMV); (2) learner control/key views (LKV); (3) program control/multiple views (PMV); (4) program control /key views (PKV); Phase 2: 2 conditions: low learner control /key views (PKV) vs. no learner control /key views (SKV)	A 30-item post-test	In phase 1:The PKV group attained the best post-test score and the PMV group received the worst; In phase 2:The SKV group performed similarly to those students in the PKV group
Codd and Choudhury (2011)	102	2011	Learning human compartment musculoskeletal anatomy	39 Students in the Faculty of Life Sciences, University of Manchester	Randomized into one of the three groups: traditional group, control group and model group	A knowledge test	The model group mean test score to be higher than the control group and not significantly different to the traditional methods group
Maresky et al. (2019)	63	2019	Learning cardiac anatomy	42 First year undergraduate medical students	Randomized into control and variable groups	A ten-question quiz	The students exposed to VR scored 23.9% higher overall ($p < 0.001$.)
Kockro et al. (2015)	53	2015	Learning neuroanatomy	169 Second-year medical students	Randomized into two groups: a two-dimensional (2D) PowerPoint presentation (n = 80) and a 3D animated tour of the third ventricle with the DextroBeam	A 10-question multiple-choice exam	Students in the 2D group achieved a mean score of 5.19 (± 2.12) compared to 5.45 (± 2.16) in the 3D group, with the results in the 3D group statistically non-inferior to those of the 2D group
de Faria et al. (2016)	51	2016	Learning neuroanatomy	84 Graduate medical students	Divided into three groups: 1 (conventional method), 2 (interactive non-stereoscopic), and 3 (interactive and stereoscopic)	A written theory test and a lab practicum	Groups 2 and 3 showed the highest mean scores in pedagogic evaluations and differed significantly from Group 1. Group 2 did not differ statistically from Group 3.

effectiveness of computer-generated three-dimensional models of the middle and inner ears. The subjects were divided into two groups, 29 in the control group and 28 in the experimental group. Students in the control group took the tutorial without exposure to the model, and students in the experimental group completed a Web-based tutorial that included the interactive model. However, there were some limitations to the study. For example, students in the experimental group took more time to complete the lessons and quizzes, which might indicate that the experimental group and the control group had different levels of effort, on average. A study on cardiac anatomy teaching conducted by Maresky et al. (2019) also suggested that VR could significantly improve learning effects and students' interest in learning compared with traditional teaching methods. In 2015, Kockro et al. (2015) conducted an experiment on 169 second-year medical students. They were randomized into 2 groups. In the control group, they were taught by a standardized prerecorded audio lecture detailing the anatomy of the third ventricle, complete with a two-dimensional (2D) PowerPoint presentation. DextroBeam was used to visit the third ventricle. Immediately after class, students completed a 10-question multiple-choice exam based on what they learned and their subjective evaluation of the teaching methods. The results of this research showed that the students in the 2D group achieved a mean score of 5.19 ($\pm$ 2.12) compared to 5.45 ($\pm$ 2.16) in the 3D group, with the results in the 3D group being statistically non-inferior to those of the 2D group ($p < 0.0001$). The students rated the 3D method higher than 2D teaching in four domains. According to this research, stereoscopic enhanced 3D lectures are an effective way to learn anatomy, and students benefited greatly from the lectures. However, some studies suggested that VR teaching did not significantly improve students' learning. Khot et al. (2013) showed that there was no significant difference in the teaching effects of VR, AR, and TB, and participants in VR teaching were more likely to suffer from headache, dizziness, blurred vision, and other adverse reactions.

Through our analysis, VR plays a positive role in the learning process of anatomy, not only for students' learning of normal anatomical structure, but also for students' thinking and enthusiasm of anatomy learning. However, due to the small number of current studies, small sample size and variable control problems, the research results are also different, to some extent. Therefore, more research is needed to demonstrate the role of VR in anatomical learning. On the whole, there is great promise for the effective use of virtual as a means to supplement lesson content in anatomical education.

CONCLUSION

Through systematic analysis, one fully understands the advantages of VR in anatomy learning, especially during the epidemic. To avoid the risk of exposure, VR has become an excellent tool for students to learn anatomy, which is the basis of medical knowledge. VR enables medical students to understand the complex structures of the human body comprehensively and systematically. Generally, knowledge in textbooks and practical anatomy training is very practical for medical students, which is conducive to better understanding the structure of the human body, but VR enables them to understand knowledge from a new dimension. For example, in VR, students can take a muscle from the human body to understand the interaction and innervation of each muscle during exercise.

In addition, this research shows that VR has great potential in anatomy teaching in the future. In the past two decades, the overall number of publications has shown a significant upwards trend. Through literature research, it was found that VR has significant advantages in teaching results compared with traditional teaching modes. In recent years, VR has also been used in other fields, such as surgical teaching (Seymour et al., 2002; Sumdani et al., 2022), which reflects the broad development prospects of this technology.

However, little is known about how VR can be effectively used in medical education (Galvez et al., 2021). The reasons may include: First, VR equipment is expensive under the current conditions, which is a large expense for schools. Second, VR technology is not mature enough at present, and new theories are needed to break through the bottleneck to be more conducive to popularization. Third, VR-related technicians have not developed well in the medical field, which further hinders the popularization of VR in anatomy. Overall, the application of VR in anatomy still has considerable obstacles, and the efforts of relevant personnel are needed. According to **Figure 4**, which indicates that publications about VR in anatomy education show exponential growth, the field is at a rapid development stage, with new breakthroughs constantly. The future should focus more on establishing technological standards with high data quality and developing approved applications (Joda et al., 2019).

We have reason to believe that with the development of science and technology, VR will have a wider application in the field of anatomy and will also become a powerful modern teaching method in medical research institutions.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

ZSL and ZXL collected the literature and drafted the initial manuscript, and drawn the figures. ZSL drew the table. CP, MZ, and QH were the lead investigators. All authors approved the final manuscript as submitted and are accountable for all aspects of the work.

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The Metaverse and complex thinking: opportunities, experiences, and future lines of research

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Research trends about the Metaverse have increased in recent years due to its potential to create immersive realities, where complex thinking becomes relevant as an ability to promote emerging ways to understand and explain the different realities that comprise a digital society. Although some investigations allow us to know both topics' concepts and applications, scientific literature production about them is scarce. In this work, we conducted a systematic review of the literature (SLR), analyzing 234 publications from various databases, including Scopus and Web of Science, to understand how studies about the Metaverse overlap with the components of complex thought. The results showed that there has been extensive exploration of the Metaverse since 2022. The prevalence of the Metaverse aligns with the design of algorithms and retail sales, and it primarily correlates with virtual reality technology. Likewise, various reference frameworks and taxonomies have been designed to explain the operation of the Metaverse in different formative spaces. We concluded that examining the Metaverse from the perspective of critical, systemic, scientific, and innovative thinking can open lines of research that affect the knowledge of immersive technologies and the evolution of disruptive digital ecosystems.

KEYWORDS
higher education, Metaverse, complex thinking, educational innovation, education 4.0

1. Introduction

The use of digital technologies to strengthen the quality of education and provide innovative training experiences has been a continuous topic in educational systems (UNESCO, 2018; Cabero Almenara and Martínez Gimeno, 2019). In this sense, the Metaverse's potential to offer virtual environments that allow users to socialize, collaborate, and learn through developing high-quality immersive experiences has positioned it as an alternative content source for students (META, 2022).

The use of this technology gained importance in 2003 when the Second Life (SL) platform was released. SL can be considered the first virtual world in which teachers in different educational levels had the opportunity to build simulated work scenarios such as laboratories and classrooms without walls with avatar interactions in immersive realities (Carr, 2008; Brennen and Erika dela Cerna, 2010; Beaumont et al., 2014).

In the SL environment, disruptive learning strategies like problem-based learning, role-playing, gamification, and various training practices flourished (Ortiz et al., 2019). It made virtual reality an option to participate in alternate realities in which the virtually enhanced physical reality and the physically persistent virtual spaces converge, that is, digital mirrors in which interactions, communication, and information exchanges are generated in cyberspace (Collins, 2008).

Over the years, the Metaverse evolved into shared three-dimensional virtual spaces (Hackl, 2021), with a structure composed of seven layers that make its growth and implementation possible (Radoff, 2021), allowing teachers and students to access, use, and appropriate the immersive technologies on which virtual environments are based. Table 1 identifies and describes each of the seven layers.

Also, the Metaverse has been categorized into at least four models that coexist in the environment of a large Metaverse: (1) games and virtual realities, (2) mirror worlds, (3) augmented reality, and (4) digital recording systems that collect data from the environment (lifelogging; Márquez, 2011). These models have main characteristics of interactivity, corporeality through the design of an avatar, and persistence (meaning the ongoing functionality of the Metaverse, even when the avatars are not connected; Castronova, 2001).

In this regard, Kye et al. (2021) classify four types of Metaverses: (1) augmented reality, (2) lifelogging, (3) mirror world, and (4) virtual reality, also suggesting that the Metaverse has the potential to consolidate as a new educational environment since it generates a new space for social communication, a greater degree of freedom to create and share, the opportunity to create disruptive learning experiences, and a high immersion in alternative reality through virtualization. Table 2 shows the classification of the Metaverse and its possible contributions to education.

Therefore, in the educational context, the Metaverse concept is much broader than using virtual reality glasses and interacting with avatars because it involves training experiences with various tools. These include the HoloLens, with which anatomical models of diseases can be explored using augmented and virtual realities (Stromberga et al., 2021), virtual and augmented reality platforms to build molecular models (Cortés Rodríguez et al., 2022), and gamification experiences to motivate learning (Park and Kim, 2022).

In higher education, the Virtual Campus of Tecnologico de Monterrey is an environment specially designed for students to attend classes with their personalized avatars (TecReview, 2021). In this Metaverse space, both thematic sessions and an entire higher-level course (CONECTA, 2021) have been conducted, highlighting that in this simulated campus, not only interactive and dynamic learning experiences can be generated, but also skills such as digital transformation, the reasoning for complexity, social intelligence, and communication (Rocha et al., 2022).

Due to the above, the Metaverse and its strategic implementation to create disruptive learning scenarios are based on a paradigm shift that moves from training dynamics in face-to-face, hybrid, or digital modalities mediated by videoconferences and educational platforms to a fully immersive educational process requiring a change in content delivery formats. There are different approaches to analyzing the Metaverse structure and its impact on educational settings. Therefore, the objective of this document is to analyze the scientific production regarding the subject of the Metaverse in the field of education from the perspective of the sub-competences of complex thought, in order to elaborate a classification that allows identifying which lines of research can be emerge to continue with the study of the use of disruptive technologies.

1.1. Complex thought and the Metaverse

University education must respond to the challenges of emerging educational scenarios, which, as has been observed in the context of

TABLE 1 Layers of the Metaverse and their application in education.

Layer	Description
Infrastructure	Access to Metaverse technology, such as computers, digital tablets, and smartphones.
Human Interface	Access to hardware for an immersive experience in the Metaverse, such as virtual reality glasses and cardboard.
Decentralization	Democratize and offer freedom to interact in the Metaverse by designating spaces and avatars.
Spatial computation	Use virtual, augmented, and extended realities to design learning experiences.
Economy	Possible monetization of school services in the Metaverse.
Discovery	Virtual campuses tours and advisory service offerings from professors or experts.
Experience	Design accessible, diverse spaces for learning, such as classrooms, libraries, and conference rooms.

TABLE 2 Contributions of the Metaverse to education.

Metaverse types	Possible contributions to education
Augmented Reality	Learning with three-dimensional applications, access to virtual learning spaces that simulate high physical risk, and hologram teacher technology.
Lifelogging	Learning through data analytics, personalized learning, adaptive learning, and social intelligence. Strengthening of digital literacy skills.
Mirror World	Learning in multiple communication spaces such as videoconferences, learning management systems, social networks, real-time collaboration software, and video games.
Virtual Reality	Learning using virtual campuses, high-fidelity simulations, low-cost 3D devices such as cardboards, having a digital identity through an avatar, and acquiring knowledge through social interactions.

the pandemic, can be changing and not necessarily present in face-to-face formats (Sepulveda-Escobar and Morrison, 2020). It is imperative to seize the opportunities offered by technological trends to transform education through disruptive learning.

However, developing skills that allow the advancement of pedagogies based on the use of technologies such as the Metaverse should also be privileged. In addition, in university settings, improving complex thinking (CT) is a necessary enabler for more accurate academic decisions in many higher education disciplines (Vázquez et al., 2022).

Complex thinking is a mega-competency with four sub-competencies: scientific (ST), critical (CR), systemic (ST), and innovative (IT) thinking (Ramírez-Montoya et al., 2022) that allow students, through cognitive skills, to participate in the Knowledge Society, Industry 4.0, and Education 4.0. Figure 1 shows the components of complex thinking (Miranda et al., 2021; Ramírez-Montoya et al., 2022) and those of the Metaverse and their possibility of overlapping.

These sub-competencies can be intertwined with the essential Metaverse characteristics to offer added value to the training processes that use new digital-pedagogy experiences (Abdul et al., 2020) and knowledge dissemination in dynamic, hybrid learning ecologies (Vodovozov et al., 2021; Wasilah et al., 2021). The previous also contributes to recognizing complex skills that serve to develop classifications that answer the research question posed in this article: How can research on the Metaverse in the educational field be categorized within the framework of complex thinking, and what are the research lines they can promote?

There are different approaches to analyzing the structure of the Metaverse, as well as the impact it is having on educational settings. This article analyzes scientific production around Metaverse experiences in the educational field to contribute to a classification using the components of complex thinking to generate new lines of research. Thus, this article presents the results of a bibliometric investigation that focuses on identifying studies that consider the relationship between systemic, scientific, critical, and innovative thinking and the Metaverse. To this end, a systematic literature review (SRL) was prepared using various databases.

2. Method

To guide the development of this work, we formulated the following research question: How can research on the Metaverse be categorized within the framework of complex thinking, and what lines of knowledge generation can be promoted? Figure 2 shows the methodological approach implemented in this research.

The research aims to identify and categorize the scientific production of the Metaverse with the components of complex thought. The research is descriptive since it collects information to analyze the social phenomenon of the Metaverse and how it overlaps with complex thinking (Shields, 2020). The Systematic Literature Review (SLR) was selected as the method, applying the proposal of Kitchenham and Charters (2007), who proposed the identification, evaluation, and interpretation of all available and relevant research related to the subject.

Metaverse (MV) was a keyword used to search for scientific production, and Complex Thought (PC) was a contextual term. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Page et al., 2021) consists of two stages, planning, and action (Vázquez et al., 2022), which were applied as a

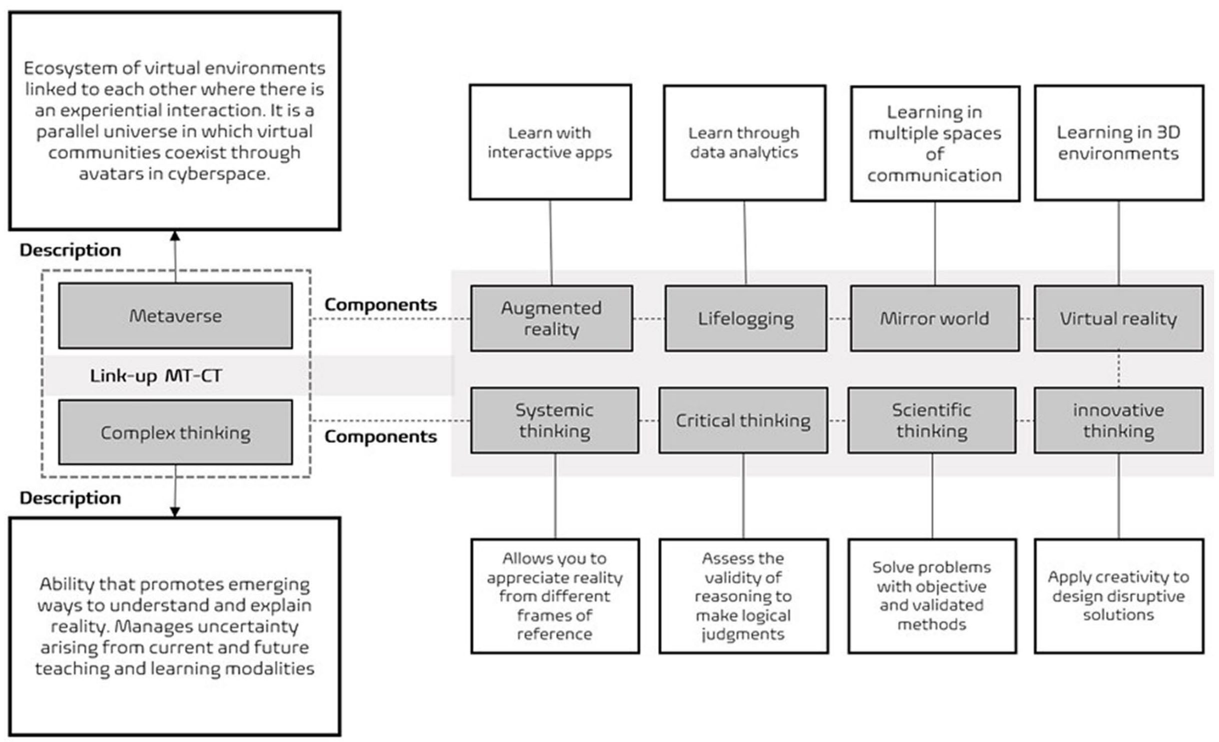

FIGURE 1
Approach to the components of the Metaverse and complex thought.

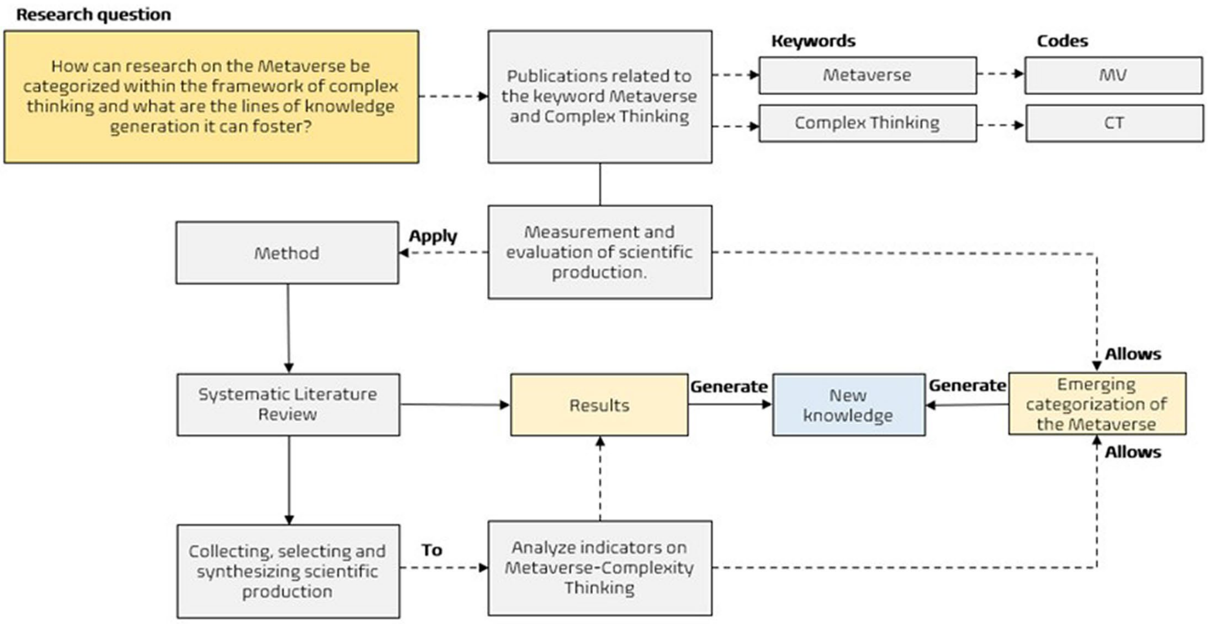

FIGURE 2
Systematic literature review methodology.

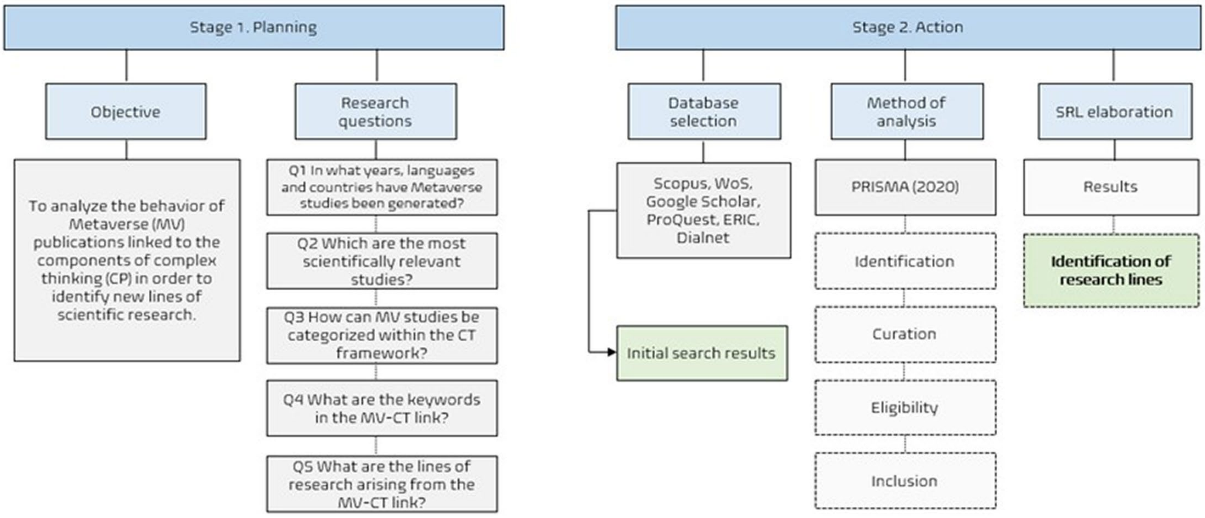

FIGURE 3
Systematic literature review process.

strategy to collect and select scientific production. Figure 3 shows the objective and the research questions, the selected databases, and other details of the applied strategy.

2.1. Search strategies and inclusion, exclusion, and quality criteria

Seven databases were used to identify and select the documents: Dialnet, ERIC, Google Scholar, ProQuest, Scielo, Scopus, and Web of Science (WoS). Emphasis was placed on using Scopus because it is considered one of the largest and most prestigious databases of citations and peer-reviewed literature (Ball, 2021). As a result, 518 articles were identified.

The method to analyze these articles was PRISMA (Page et al., 2021), which consists of identifying and selecting the scientific documents, carrying out their curation by eliminating duplicates, and applying the inclusion, exclusion, and quality criteria, then finally reading the abstracts of the articles to include those that are relevant and feasible for quantitative and qualitative analyses. To conduct the curation of the documents, we applied the following criteria:

Research, scientific dissemination, systematic literature review, methodological, and meta-analysis documents that

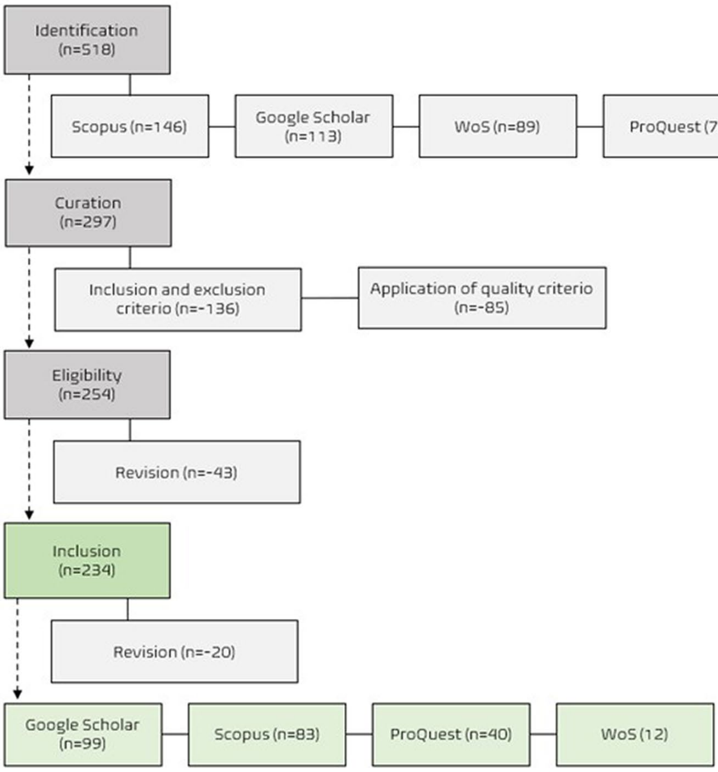

FIGURE 4
PRISMA flow to obtain the bibliography.

included the MV-PC codes in the title, abstract, or keywords were included.

Editorials, errata, and documents not closely related to the subject of study were excluded, as well as publications that did not show the MV-PC codes in the title, abstract, or keywords.

For quality criteria, we established that the articles must be published between and including 2010–2022, written in English or Spanish, focused on studying the Metaverse, and addressing some components of complex thought in its sections or results. The preceding generated 232 documents (link: https://bit.ly/42FXYcc) which a sequential numbering was assigned and with which a bibliographic database was created with the following fields: (a) author(s), (b) job title, (c) year, (d) type document, (e) journal or publisher, (f) country of authors, (g) institutions or organizations, (h) DOI, (i) reference in APA style, (j) abstract, (k) keywords, and (l) language. In Figure 4, the eligibility process can be seen.

3. Results

The first result presented is a general analysis of the coincidences of the scientific production found concerning the components of complex thought, the number of citations, and the keywords that appear most frequently. Figure 5 shows that the Metaverse has had a significant impact on the scientific production related to systemic thinking ($n = 70$), as well as innovative thinking ($N = 69$); however, the articles linked to scientific thinking had the highest number of citations ($n = 292$).

On the other hand, regarding the categories in which the Metaverse can be classified, mirror worlds ($n = 145$) correspond to the most used category referring to the experiences mediated by the Metaverse. The publications related to this classification are also the most cited ($n = 420$). In second place, virtual reality is a topic that has also been analyzed in scientific production ($n = 61$) and has the second-highest number of citations ($n = 286$). This indicates that knowledge about the Metaverse focuses on exploring technological trends that have been incorporated into education; however, it should be noted that an emerging line of research could be found in the analysis of augmented reality technology (six publications with 14 citations) from the perspective of some of the sub-competencies of complex thinking.

The results are presented below, based on the guiding questions defined in the Planning Stage:

> Q1: In what years, languages, and countries are studies of the Metaverse?

Figure 6 shows that the scientific production on the Metaverse increased notably in 2022, with 173 publications. This could be explained by the documentation of strategies employing disruptive technologies to face the challenges of the COVID-19 pandemic. Some were based on using the Metaverse (Rocha et al., 2022). Some resulted from the media effect of the announcement of the creation of Meta by Mark Zuckerberg (Fernandez, 2022), which boosted the use of virtual reality environments to position products and services in cyberspace and education (Akgül and Uymaz, 2022; Kraus et al., 2022).

On the other hand, Figure 7 shows the classification of scientific production from two aspects. Notably, the most significant number of works is related to systemic thinking; that is, with the design of reference frameworks and taxonomies to offer services and propose methodologies to apply the experiences based on the Metaverse, as well as application schemes to generate learning mediated by digital spaces. The second aspect relates to the preference for using mirror worlds to carry out learning, instructional, or customer service experiences, such as designing museums, laboratories, virtual campuses, and three-dimensional exhibition halls to enhance retail sales.

Regarding the languages in which the investigations were out, most of them were published in English (222), followed by Chinese (6), Korean and Spanish (2), and finally, Japanese and Portuguese (1). Regarding the contribution by country, Figure 8 shows that 59 countries contributed studies of the Metaverse. The most significant production came from the United States of America (66), followed by China (53), South Korea (41), Great Britain (36), and Japan (23). Spain (4) and Mexico (1) were the Ibero-American countries with the highest production.

Regarding the collaboration between authors from different countries, Figure 9 shows that the closest relationship is between researchers from the United States of America (316 citations and link strength of 276) and Korea (212 citations and link strength of 236). Collaboration ties have also been generated with Japan (112 citations and a link strength of 83). The studies carried out in the United Kingdom (126 citations and a link strength of 147) have less close links with the United States of America since the scientific

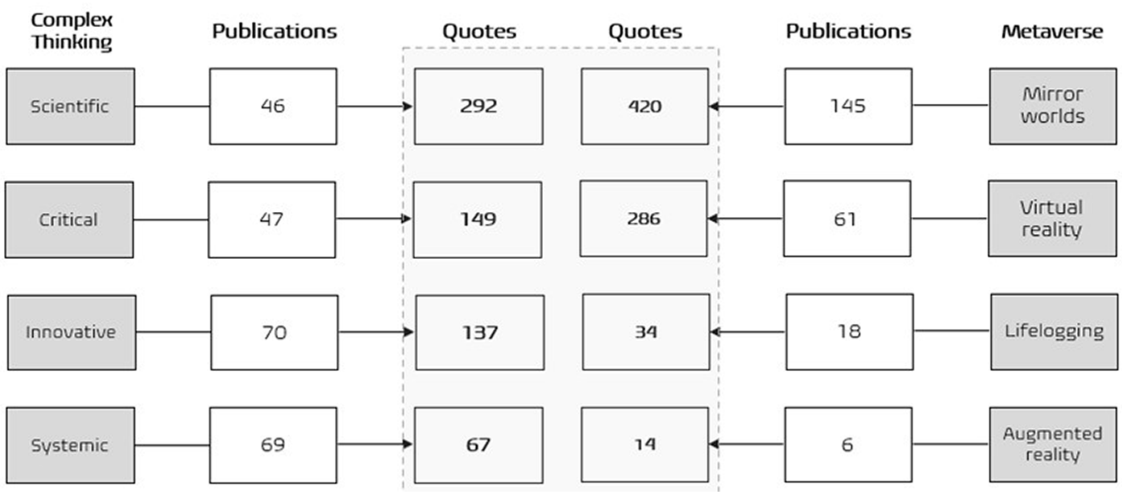

FIGURE 5
The general impact of scientific production.

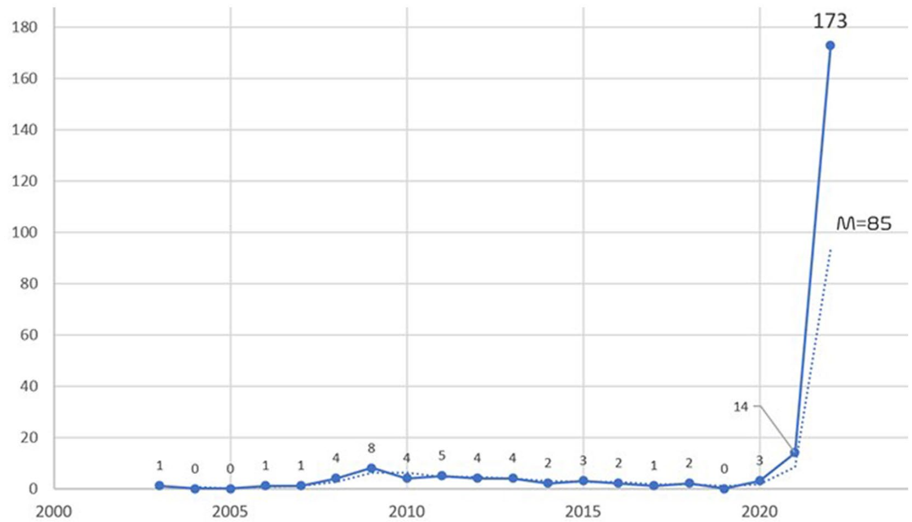

FIGURE 6
Scientific production by year of publication.

production is more related to Belgium, Iraq, Yemen, Malaysia, and Saudi Arabia.

Q2: What are the most scientifically relevant studies?

The most cited document ($n = 108$) is an article called 3D Virtual Worlds and the Metaverse: Current Status and Future Possibilities, which explores the definition and meaning of virtual worlds and classifies them into four areas of development: immersive realism, the ubiquity of access and identity, interoperability and scalability, as well as the factors that influence and limit the formation of a viable metaverse to develop both educational and commercial experiences. This study represents the systems thinking approach since it elaborates a historical classification of experiences based on the Metaverse, particularly those related to virtual reality. Table 3 shows that journal articles and conference papers have the highest citations. The information is classified according to the components of complex thought and metaverse classification.

Regarding the conference papers, the document A Metaverse: Taxonomy, Components, Applications, and Open Challenges, was cited 55 times in the same year of its appearance (2022), which indicates that it has had a high relevance in the scientific field since it addresses a redefinition of the Metaverse based on the evolution of digital infrastructure and the development of hardware, software, and content design for instruction and learning, and user interaction experiences.

Figure 10 shows an analysis of co-citation between researchers. The results show that three authors collaborated in the development of the conceptual foundations of the Metaverse. The document Decision Intelligence and Modeling, Multisensory Customer Experiences, and Socially Interconnected Virtual Services across the Metaverse Ecosystem (Nica et al., 2022) was consolidated as a base document for other works such as Multimedia research toward the Metaverse (Chen, 2022) and A survey on Metaverse: Fundamentals, security, and privacy (Wang et al., 2022).

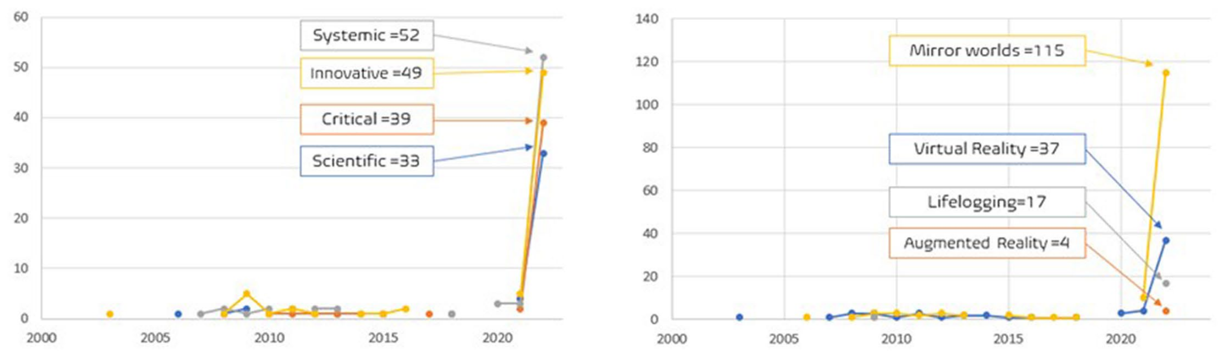

FIGURE 7
Scientific production by type of thought and Metaverse topic.

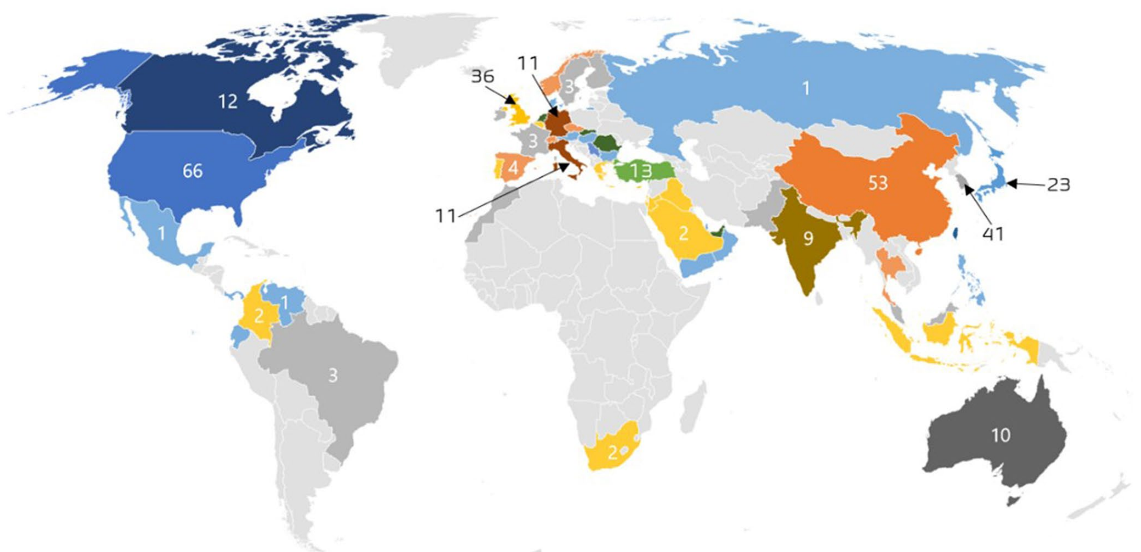

FIGURE 8
Scientific production by country.

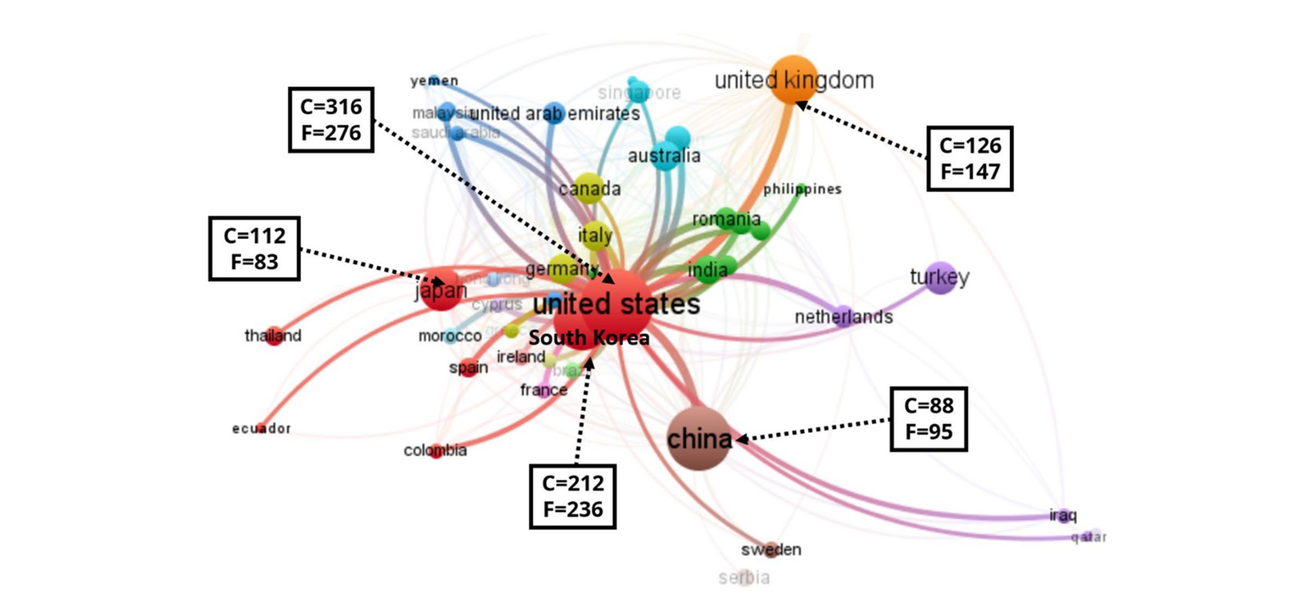

FIGURE 9
Scientific collaboration by country.

> Q3: How can studies be categorized within the framework of complex thinking?

Table 4 classifies according to the concepts related to the components of complex thought (refer to Figure 1). Regarding Scientific Thought (*CF*), the publications aimed to measure the impact of the Metaverse in different digital spaces, such as virtual campuses in universities and laboratories without walls in Industry. Studies that evaluate the digital security and privacy of users who interact in virtual socialization environments were included.

The primary studies analyzed from systemic thinking (ST) are those in which reference frameworks and taxonomies are elaborated to allow differentiating methods of applying the Metaverse in different environments, including marketing, education, and industry, highlighting those with parameters established to design virtual exhibitions either for museums or retail sales products.

Critical Thinking (CR) is explored in the selected documents regarding the challenges that designers of immersive experiences face to achieve greater user engagement and to understand what they want to show in three-dimensional worlds. One of these challenges was to have multidimensional communication channels for better decisions to conduct virtual practices; likewise, most studies analyzed the possibilities of always-on access to the Metaverse, connectivity with virtual currencies, and even the integration of neural networks.

Studies related to innovative thinking (IN) analyzed the experiences of viewing, using, and accepting participants in unconventional virtual interaction spaces in which new communication and collaboration models prevail. Most of the research categorized as IN relates to the evolution of retail sales and how the Metaverse influences its promotion. In this category, it is pointed out that although experiences based on extended reality and other novel forms of telepresence are favorably received by people and generate a positive impact, they are confined to small groups of users. It is also suggested that the Metaverse presents challenges, such as whether Augmented Reality (AR) and Virtual Reality (VR) technologies increase or decrease the difficulties of carrying out tasks in simulated situations.

> Q4: What are the keywords in the Metaverse and complex thinking link?

An analysis of the keywords was carried out, finding the emergence of three clusters (see Figure 11). That is, the publications were organized into three possible lines of research. In the first (Cluster A), note that the investigations articulated data analysis (frequency = 71) that emerged from applying the algorithms (frequency = 40) that define the interactions in the virtual worlds.

The second line (Cluster B) is related to teaching-learning experiences in formal and non-formal study environments (frequency = 70), emphasizing the perceptions of usability and acceptance of the Metaverse by students (frequency = 74) as a means to access content and enrich communicative VR interactions in an internet ecosystem (frequency = 74).

Finally, a third possibility of generating knowledge about the Metaverse (Cluster C) is found in generating reference frameworks and methodologies to design innovative experiences to favor the positive impact of user experiences (frequency = 41) and reconceptualizations (frequency = 44) that make statements about the various spaces of interventions in which the Metaverse can be used. Finally, some studies analyze how the design and use of avatars (frequency = 37) can motivate users to access virtual worlds.

> Q5: What lines of research could arise from the Metaverse and complex thinking link?

An analysis of the summaries of the publications was carried out to determine what lines of research could arise when the Metaverse and Complex Thinking topics overlap. Figure 12 shows that virtual reality (frequency = 456) was a recurring concept in the selected investigations,

TABLE 3 Documents with the greatest scientific relevance.

Title	PC	MV	Year	Journal/Conference	Citations	Type
3D virtual worlds and the Metaverse: current status and future possibilities	ST	RV	2013	ACM Computing Surveys	108	Article
A content service deployment plan for Metaverse museum exhibitions—Centering on the combination of beacons and HMDs	IN	ME	2017	International Journal of Information Management	51	Article
A Metaverse: taxonomy, components, applications, and open challenges	ST	ME	2022	IEEE Access	55	Conference Paper
Metaverse for social good: a university campus prototype	IN	ME	2021	MM 2021–Proceedings of the 29th ACM International Conference on Multimedia	45	Conference Paper
Retail spatial evolution: paving the way from traditional to Metaverse retailing	ST	ME	2009	Electronic Commerce Research	43	Article
The Metaverse–A networked collection of inexpensive, self-configuring, immersive environments	CR	RV	2003	Proceedings of the Workshop on Virtual Environments, EGVE'03	27	Conference Paper
The challenges of entering the Metaverse: an experiment on the effect of extended reality on workload	*CF*	ME	2022	Information Systems Frontiers	20	Article
The social metaverse: battle for Privacy	CR	ME	2018	IEEE Technology and Society Magazine	16	Article
Neuro-symbolic speech understanding in aircraft maintenance metaverse	CR	RV	2021	IEEE Acces	16	Article
Evaluation of students' learning manner using an eye blinking system in Metaverse	*CF*	ME	2015	Procedia Computer Science	15	Conference Paper

CF, scientific thinking; ST, systemic thinking; CR, critical thinking; IN, innovative thinking; ME, mirror world; RV, virtual reality.

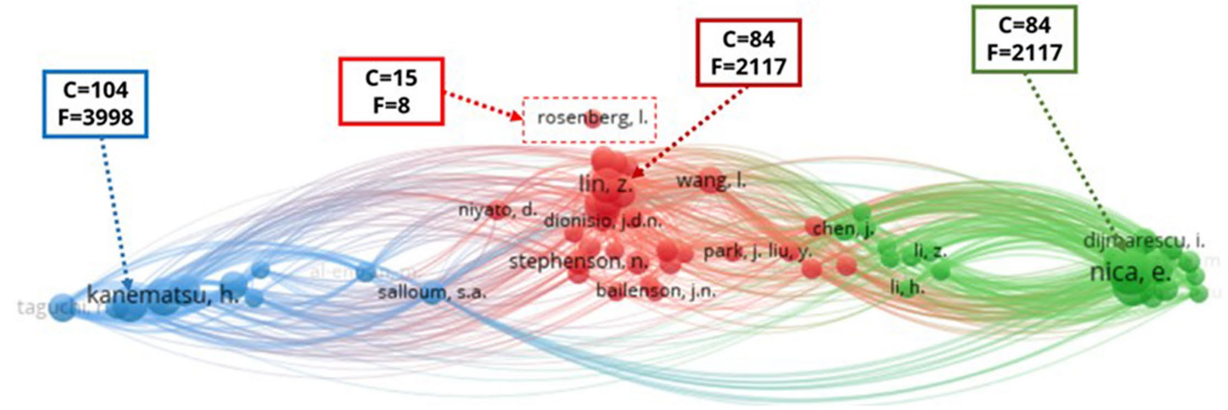

FIGURE 10
Scientific collaboration by author.

especially linked to analyses focused on behavior and the human-computer relationship. Augmented reality (frequency = 190) was also linked to the evolution of 5G communication systems and learning during the COVID-19 pandemic. A correlation between blockchain and internet privacy and security issues was present, which could generate future lines of research.

It was also observed that the Metaverse evolved from the first practices carried out in the Second Life environment, the design of the first accessible virtual spaces, and the creation of e-learning environments (frequency = 96). By 2020, the study of the Metaverse began to be linked to technologies such as immersive reality (frequency = 119). Other research explored topics related to deep learning, blockchain, machine learning, security, and privacy, as well as the design of algorithms for direct purchase offers and retail sales.

Analyzing the Metaverse and its link with the sub-competencies of complex thinking offers the possibility of formulating research proposals that address complex interaction, collaboration, management, and communication schemes in various alternative reality environments that can support learning. Thus, the MV-PC imbrication finds its space for inquiry in environments mediated by

TABLE 4 Categorization of metaverse studies into the components of complex thinking.

PC	MV	Lead author	Title	Journal/Conference	Citations
CF	ME	Duan, H.	Metaverse for social good: a university campus prototype	MM 2021–Proceedings of the 29th ACM International Conference on Multimedia	45
	ME	Falchuck, B.	The social metaverse: battle for privacy	IEEE Technology and Society Magazine	16
	ME	Kanematzu, H.	Nuclear energy safety project in Metaverse	Smart Innovation, Systems, and Technologies	15
ST	ME	Dionisio, J.	3D virtual worlds and the Metaverse: current status and future possibilities	ACM Computing Surveys	108
	RV	Gadalla, E.	Metaverse-retail service quality: a future framework for retail service quality in the 3D internet	Journal of Marketing Management	14
	RV	Ryskeldiev, B.	Distributed Metaverse: creating a decentralized blockchain-based model for peer-to-peer sharing of virtual spaces for mixed-reality applications	ACM International Conference Proceeding Series	9
CR	ME	Chio, H.	A content service deployment plan for Metaverse museum exhibitions—Centering on the combination of beacons and HMDs	International Journal of Information Management	51
	ME	Park, S.	A Metaverse: taxonomy, components, applications, and open challenges	IEEE Access	48
	RV	Kanematsu, H.	Virtual STEM class for nuclear safety education in Metaverse	Procedia Computer Science	15
IN	ME	Bourlakis, M.	Retail spatial evolution: paving the way from traditional to Metaverse retailing	Electronic Commerce Research	43
	RV	Jaynes, C.	The Metaverse–A networked collection of inexpensive, self-configuring, immersive environments	Proceedings of the Workshop on Virtual Environments, EGVE'03	27
	RV	Xi, N.	The challenges of entering the Metaverse: an experiment on the effect of extended reality on workload	Information Systems Frontiers	20

CF, scientific thinking; ST, systemic thinking; CR, critical thinking; IN, innovative thinking; ME, mirror world; RV, virtual reality.

extended environments such as virtual and augmented reality, where people interact in a simulated but realistic way. The above causes new definitions that explain how the Metaverse is being incorporated into people's lives. Questions are generated that can guide future lines of research as complex as the evolution of digital transformations.

To finish the results of this study, Table 5 shows some probable lines of research that can guide future studies related to systemic, scientific, critical, and innovative thinking written as perfectible and debatable questions. These can promote the emergence of teaching-learning methodologies for the new generations of students and contributions by researchers and academicians interested in strengthening the implications of the Metaverse in society.

4. Discussion

The post-COVID trend of interest in the Metaverse and its applications in people's lives includes the educational field. The evident growth of studies on the subject is marked by a difference of 159 publications in 2022 over the 14 publications in 2021, which had the second-highest number of scientific studies. The acceleration during the last 2 years (2022–2021) represents the search for new paths to overcome the educational challenges generated by the COVID-19 pandemic, for example, the disruptive technologies that were implemented in educational institutions (Cortés Rodríguez et al., 2022; Park and Kim, 2022; Rocha et al., 2022). The production highlights the virtues of the Metaverse in educational contexts and the feasibility of implementing these immersive environments through research results.

There is a constant of placing the Metaverse and mirror worlds equally as immersive spaces in educational contexts during the period analyzed. As seen in the results, the distance between the total publications related to mirror worlds and virtual reality is evident (n = 84). However, virtual reality is the second most studied type of Metaverse. Consider that Kye et al. (2021) recognize the enormous potential of mirror worlds with digital laboratories and virtual educational spaces that reflect the real world or software such as Zoom or Google Earth. There is a tendency for studies to analyze disruptive environments where emerging ways of understanding a situation and collaborations in real time can be generated.

Concerning the types of thinking that could be developed in the Metaverse, a predominance of studies focused on innovative thinking and systematic thinking. In the results, it was found that the difference between the publications of innovative thinking ($n = 69$) and systemic thinking ($n = 69$) with critical thinking ($n = 47$) and scientific thinking ($n = 46$) was almost double. According to Ramírez-Montoya et al. (2022), critical thinking is the intellectual process generated through observation, experience, reflection, and reasoning or communication. Scientific thinking is higher-order thinking involving logical, analytical, systematic, inductive, and deductive thinking to solve problems. From this point, it was possible to identify the importance of promoting virtual spaces that encourage developing both types of thinking, critical and scientific, since they are critical thoughts for any professional who enters the labor field. Therefore, the importance of

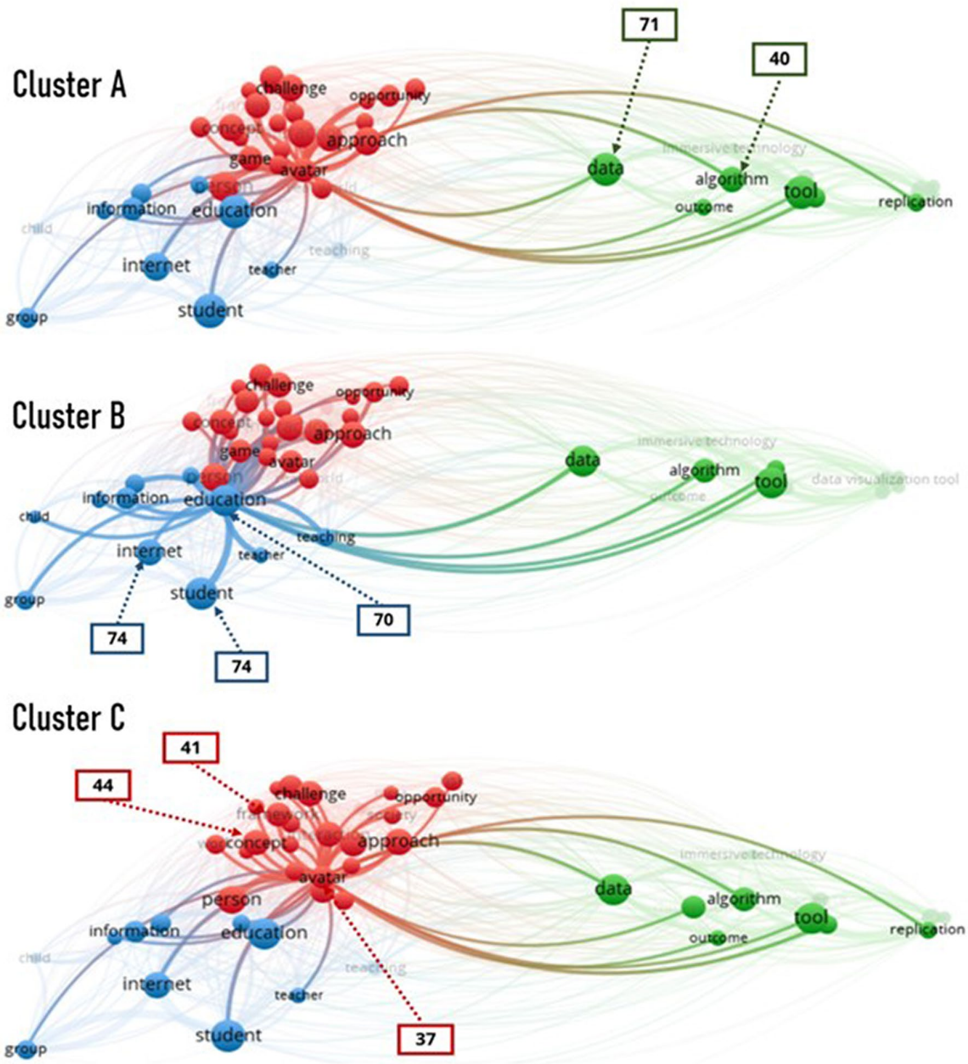

FIGURE 11
Semantic map by keywords.

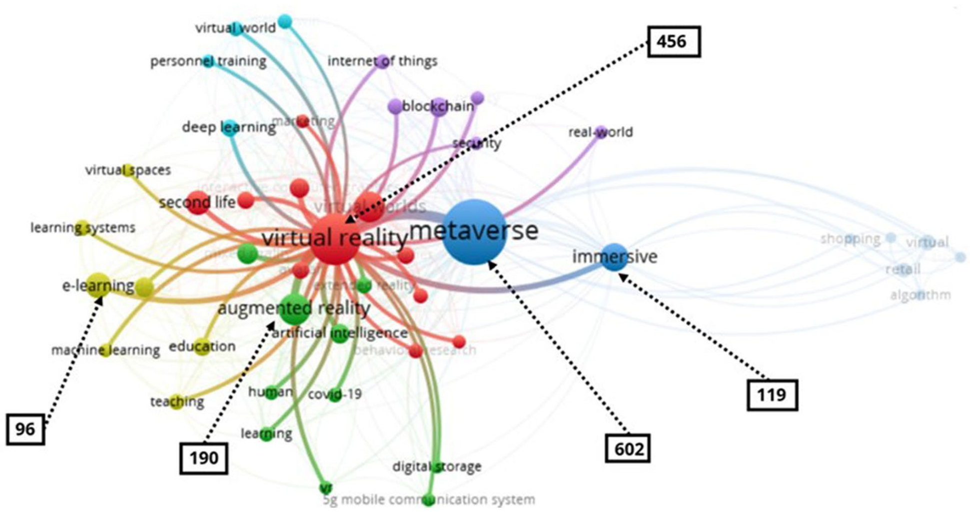

FIGURE 12
Analysis by summary.

TABLE 5 Questions that emerge from the MV-E4.0 linking.

PC components	Possible research questions
ST	What frameworks and taxonomies must be built to design successful learning spaces in the Metaverse?
CF	From the complex thinking perspective, how should instruments be designed to assess the impact, acceptance, and perception of the Metaverse's implementation to offer alternative realities for work, education, health, and marketing?
CR	How must technologies evolve to migrate metaverses to an integrated network of virtual worlds that generate immersive realism, the ubiquity of access and identity, interoperability, scalability, digital security, and personal data protection?
IN	What challenges must be overcome so training methodologies can be developed in the Metaverse that contribute to better understanding?

CF, scientific thinking; ST, systemic thinking; CR, critical thinking; IN, innovative thinking.

immersive environments that promote critical and scientific thinking in future research is recognized.

It is necessary to develop three-dimensional worlds that allow multidimensional communication channels that significantly attract users to promote the development of critical thinking. The studies showed that current academic research concerning the reflection and observation of the students in their environment is limited. However, the Metaverse can promote the ability to actively and skillfully conceptualize, apply, analyze, synthesize, and evaluate information acquired or generated through observation, experience, reflection, reasoning, or communication. Virtual campuses can positively impact society and provide students with an interactive environment that links to and impacts the physical world (Duan et al., 2021). Thus, it is viable to promote more studies that guide students' critical thinking within these immersive environments so that they can transfer these skills to the physical world and their work fields when they finish their professional training.

Finally, there is a study space between Complex Thinking and the Metaverse. The results identified that the Metaverse includes complex virtual spaces where participants develop complex thinking skills such as collaborating, managing, and communicating with their peers. Likewise, studies established that the Metaverse encompasses community spaces where content can be accessed and members can interact. However, Park and Kim (2022) recognized that Metaverse approaches need to be applied concerning user interaction, implementation, and application. Analysis of these new models and approaches within emerging metaverses is still lacking. Therefore, the field is open to generating knowledge and focusing studies on analyzing the development of complex thinking and student learning within the Metaverse with new models and approaches in these virtual environments.

5. Conclusion

Concerning the study's central question, how can research on the Metaverse be categorized within the framework of complex thinking, and what lines of knowledge generation can be promoted? It was found that, after analyzing the systematic literature review, we could corroborate three clusters or organizers of publications in both questions, highlighting the following:

Cluster A is related to data analysis research, where the application of algorithms to assess interaction in virtual worlds comes into play.

Cluster B considers formal and non-formal academic experiences, emphasizing usability and acceptance and a means to access rich content and interactions.

Cluster C refers to the frameworks and methodologies to design innovative experiences and reconfigure environments where the Multiverse can be used.

It is worth mentioning that, in the direct review of the categorization of studies of the Metaverse without links to complex thinking, until 2022, they were mainly organized into four categories: (a) mirror worlds, (b) virtual reality, (c) lifelogging, and (d) augmented reality.

Recognizing that Complex Thinking is made up of four sub-competencies: systemic, scientific, critical, and innovative thinking, we return to the table of questions triggered where the topic of future lines of research between Complex Thinking and the Metaverse was addressed. We highlight that the lines of knowledge generation to be promoted are related to the reference frameworks and taxonomies for the design of learning environments in the Metaverse, the design of instruments to assess the impact, acceptance, and perception of the Metaverse in different areas of life such as education, and the integration of the Metaverse and its different mirror worlds to validate its immersive realism, ubiquity, interoperability, scalability, digital security and protection of personal data. Finally, future research can consider new ways to drive training with better results in immersive environments of the Multiverse.

The Metaverse is a topic with very recent interest, as seen in the SLR, so naturally, more scientific publications should appear that account for formal and non-formal learning experiences in the Metaverse, with which other research lines can contribute to the field of knowledge. In addition, with the imbrication of the Metaverse and Complex Thinking, other lines of study can promote each of the four types of thinking and their relationship with an environment that fosters cognitive abilities sufficient for the Knowledge Society and Education 4.0.

One of the limitations of this study is that the recovery of the selected articles was limited to the first semester of 2022, which surely left out publications that came to light at the end of that year. Another area of opportunity is that as it is a bibliographical investigation, it needs to be periodically updated and renewed to include the generation of knowledge from subsequent years.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

IP, CG-R, and LG-M contributed to conception and design of the study. IP and CG-R organized the database. CG-R performed the statistical analysis and wrote the manuscripts. IP wrote discussion. LG-M wrote the results. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Visualization of sorting algorithms in the virtual reality environment

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This study examines the use of virtual reality (VR) in programming, specifically in visualization of sorting methods. Addressing students' needs to better understand and implement sorting methods, "VR sorting" application was developed to visualize the bubble sorting and selection sorting abstract methods in the VR environment. The effects of visualization were evaluated drawing on an extended taxonomy, specifically developed by the authors of this study. The results indicate that VR might significantly enhance students' understanding of sorting tasks, further allowing them to employ these skills in practice. Specifically, 76.9% of students, who studied sorting methods in virtual environment drawing on "VR sorting" application, demonstrated higher outcomes in implementing sorting tasks. VR visualization of sorting methods, differs from existing ways of visualizing learning in the context of constructivism. Since VR allows the student to construct the algorithm himself directly interacting machine memory in the form of cells where the data is stored and managing the progress of sorting. These results shed some light to future research avenues on VR enabled constructive visualization.

KEYWORDS

visualization, sorting methods, virtual reality, constructive visualization, bubble sorting, selection sorting

1. Introduction

Sorting is a basic concept in data analysis since arranging data in a certain order allows to optimize data processing. In Kazakhstan, the most easy-to-implement bubble sorting and selection sorting methods are generally taught at the undergraduate level within the "Algorithms and data structures" and "Programming" courses. However, the abstract nature of the sorting task and the simultaneous presence of several actions with unordered data make it difficult for students to fully comprehend the sorting methods. Thus, teachers apply various methods and tools: drawing sorting steps on paper; presentations and flowcharts, handouts, animation applications on a computer, dance videos, and mobile applications to visualize sorting algorithm (Bernát, 2014; Faria, 2017). The rise of modern digital technology has given unprecedented opportunities to visualize learning materials in augmented and virtual reality (Huang et al., 2017; Lim et al., 2022; Patil et al., 2022). Hence, learning effects of visualization using virtual reality has become subject of new research.

This study aims to test the effectiveness of visualization in VR for studying abstract concepts, specifically bubble and selection sorting methods. It is led by theoretical and empirical hypothesis.

Theoretical hypothesis of the research supposes that evolution of visualization as a teaching method is happening under the influence of global trends in education, initiated by the emergence of new technologies to implement the visualization effects.

The empirical hypothesis assumes that high level of visualization and direct interaction of students with objects in the VR environment provide better understanding of the sorting methods and develop their hard skills of solving practical problems in real life. In general, 150 undergraduate students in their first and second year of study of one of the regional universities of Kazakhstan participated in the study.

1.1. Procedure

The students of the control group studied sorting algorithms in an ordinary way by viewing presentations and drawing sorting steps on paper while solving practical tasks. The students of the experimental group were given an opportunity to solve tasks in the VR environment using the "VR sorting" application and the VR headset Oculus Quest 2. To evaluate students' learning outcomes five practical tasks were specifically designed.

2. Literature review

2.1. Approaches to visualization of sorting methods

The studies on visualization of sorting methods draw on animation, game, and constructive approaches along with traditional approaches such as using paper and pencil for tracing. The application of each of these approaches to study sorting methods is informed by general trends in education as digitalization of content and teaching methods. It should be noted that an increasing interest among students in understanding and applying sorting algorithms has been influenced by the widespread study of algorithmization and programming courses within the educational programs of universities in computer science. At the beginning, students learnt about the implementation of sorting algorithms through traditional lectures, tracking the sorting process by drawing each step on the board (or paper, or presentation). In programming workshops, students were encouraged to visualize an outcome of each sorting step in accordance with the execution code and preferably with comments to better understand the realization of the sorting algorithm in fact (Mukasheva, 2013). The Table 1 presents an example of a step-by-step implementation of the sorting algorithm in descending order by the selection sorting method in C ++.

One of the visualization methods for learning sorting algorithms is by computer application, which visualizes the progress of sorting with animation effects (Visualization of Sorting Algorithms, 2013; Scanu et al., 2022). Animation displays the current and subsequent state of the algorithm in the form of different graphic images while accompanying it with sound. It is assumed that animation allows to better understand an inner process of the algorithm, such as moving an element in the right direction in sorting algorithms. In their study, Kerren and Stasko (2002) divide between two important aspects of algorithm visualization using animation: the connection of animation with the internal behavior of the algorithm and the visualization technique. The connection with internal behavior refers to the extent to which the animation of the algorithm credibly represents the abstractions and step-by-step operations (state) included in the content of the algorithm. In this regard, researchers of the study point to 3D animation of algorithms, auralization, and web deployment as the most promising areas in visualization technology. The studies note the positive impact of animation on understanding of sorting algorithms, however, there are also studies which state that animation application does not demonstrate a significant advantage in studying this topic (Faria, 2017). The disadvantage of this visualization is that the animation shows the movement of data but unable to explain why the movement occurs. The study maintained by Faria (2017) presents the preferences and wishes of students in the visualization of sorting algorithms. It was revealed that while visualizing sorting, students deemed it important to control the speed of animation, clearly separate sorting steps, change the color of elements when sorting conditions are maintained. The visualization with animation videos involving participation of humans demonstrates the use of play or active movement in learning sorting algorithms (Zoltán and László, 2011; Bubble Sort Dance, 2020). Perhaps this visualization approach would contribute to raise learning interest and motivation, as students would be able to independently replicate and test these movements and algorithms practically (Harvard, 2017).

Due to the widespread use of mobile technologies, mobile applications, which visually demonstrate sorting algorithms with animation effects, have emerged. These sorting apps generate a sequence of random numbers that can be sorted using touch interactions. The study by Boticki et al. (2012) note that a skillful combination of learning aims with game elements and a reward system (accumulation of points for correctly solved tasks) in mobile applications has a positive effect on motivation to study these methods independently without any teacher assistance at a convenient time for the student. The dynamic visualization with animation effects provides direct participation of students in the sorting process, which enables them to understand the implementation of the algorithm and draw conclusions about the sorting results.

2.2. Constructive visualization using virtual reality

The virtual reality (VR), which is one of the latest achievements in the field of digital technologies, provides completely different, new opportunities for visualizing real and abstract phenomena/processes in the form of a natural experience with the effect of immersion into a simulative environment. Rapidly developing and becoming more accessible, VR technology offers great opportunities to achieve visual experiences in both cost-effective and compelling ways. The developers draw significant attention to using holoportation and holographic techniques in VR in order to enhance the effects of reality (Park and Lee, 2022), which can initiate unprecedented opportunities for constructive visualization, as well as data visualization using VR for deeper understanding and information analysis (Lee et al., 2021). In fact, there are huge differences between the physical world and fuzzy abstract phenomena, but in the case of VR, the gap between "real" and mediated experience is getting smaller and smaller every year. "These two are not exactly alike, but VR is far more psychologically powerful than any media ever invented and poised to revolutionize our lives," wrote (Bailenson, 2019), one of the leading experts on the use of VR in education.

The "constructive visualization" paradigm proposed by Huron et al. (2014) suggests creating an easy-to-use dynamic visualization

TABLE 1 The results of visualization of selection sorting methods when solving problems in the course "Programming in C ++."

Task condition: Implementation of the sorting algorithm in descending order by the selection sorting method in C++	
Code fragment in C++	*Visualization of the descending sort algorithm*
... cout<<"\n The source array:" ; **for** (i=0; i<n; i++) { arr[i]=random(30)%13-7; cout<<" " <<arr[i]; } cout<<"\n\n Sorting has started:\n"; **for** (i=0; i<n; i++) { max=arr[i]; Nmax=i; **for** (j=i+1; j<n; j++) *// to find max and Nmax* **if** (max<arr[j]) { max= arr[j]; Nmax=j; }; bufer= arr[i]; *// saving the first element of the array* arr[i]=max; *// to send max instead of the i-th element* *// sending the saved i-th element to the bufer instead of max* arr[Nmax]=bufer; cout<<"\n "<<i<<"- step :"; **for** (k=0; k<n; k++) cout<<" " << arr[k]; } cout<<"\n\n Sorted array:"; **for** (i=0; i<n; i++) cout<<" " << arr[i]; ...	The source array: -1 4 -7 -3 5 -4 -7 4 -1 1 Sorting has started: 0- step : 5 4 -7 -3 -1 -4 -7 4 -1 1 1- step : 5 4 -7 -3 -1 -4 -7 4 -1 1 2- step : 5 4 4 -3 -1 -4 -7 -7 -1 1 3- step : 5 4 4 1 -1 -4 -7 -7 -1 -3 4- step : 5 4 4 1 -1 -4 -7 -7 -1 -3 5- step : 5 4 4 1 -1 -1 -7 -7 -4 -3 6- step : 5 4 4 1 -1 -1 -3 -7 -4 -7 7- step : 5 4 4 1 -1 -1 -3 -4 -7 -7 8- step : 5 4 4 1 -1 -1 -3 -4 -7 -7 9- step : 5 4 4 1 -1 -1 -3 -4 -7 -7 Sorted array: 5 4 4 1 -1 -1 -3 -4 -7 -7

that can interact with its components (tokens—blocks), adjust and design new visualizations. The idea of constructive visualization based on ideas of Piaget (1967) and Papert and Harel (1991) applies constructionist concepts to the design of information visualization and includes components such as token, grammar, environment, assembly model, accompanied by the processes of initialization, assembly, display, and updating of the visualization necessary for this approach. The authors of the study emphasize that one of the strengths of constructive visualization is its focus on the direct manipulation of tokens as primitives. This advantage of constructive visualization takes on a new character in learning using VR, since the high level of simulation and interaction in the VR environment allows students to feel the surrounding virtual world with various objects as in real world (Di Natale et al., 2020; Feyzi and Yasrebi, 2020). For example, the VR application "VR sorting" developed by us allows one to hold cubes with numbers in your hands, swap them in ascending or descending order. Research is increasingly showing that experiential learning with VR enhances students' interests, motivation, and creativity (Dede, 1995; Dalgarno and Lee, 2009; Chan et al., 2011; Allcoat and Mühlenen, 2018; Huang et al., 2020; Cicek et al., 2021; Triana et al., 2021; Cassola et al., 2022; Sanzana et al., 2022; Shi et al., 2022; Yeh et al., 2022) used VR to teach dance, which recognizes movements. Learning by experience implies that new knowledge and hard skills are obtained experimentally, and first-hand acquaintance with phenomena and facts is the most viable and effective way of knowing and understanding the world. In this context, as well as in connection with the rapid spread of immersive technologies, constructive visualization may well become the leading paradigm in improving the quality and access to education.

All visualization methods (tracing, animation, and constructive VR visualization) are aimed at improving the understanding of sorting algorithms. Using the example of visualization of sorting methods, one can imagine the evolution of methods for visualizing educational material as a promising teaching method. The approaches to the visualization of sorting methods that we have considered allow us to distinguish three main types of visualization: static, dynamic, and constructive (Figure 1).

The static visualization implies a visual representation of one or more completed/intermediate states of a process or object. For static visualization, paper facilities, presentations, and mockups/frameworks of objects are generally used. The visualization of step-by-step selection sorting method as C++ code is an example of static visualization of sorting algorithm (Table 1).

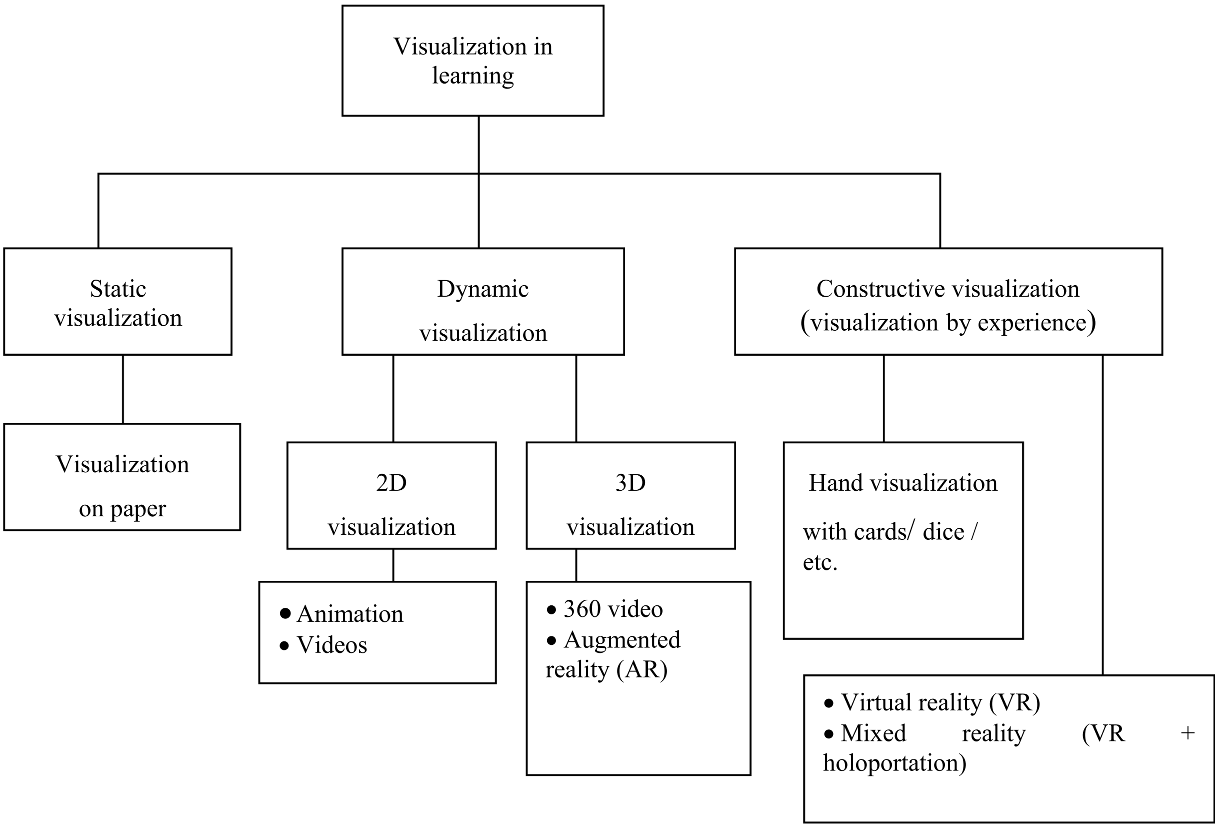


FIGURE 1
Evolution of the main approaches to the visualization of learning material.

Dynamic visualization of learning materials for training allows learners to visually track temporal and spatial changes in processes/phenomena and objects (Rolfes et al., 2020). Widely used nowadays, 2D and 3D animated videos, 360 video and augmented reality (AR) contribute to the visualization of many processes and phenomena difficult to realize in reality (Daher and Sleem, 2021; Abdul Hanid et al., 2022; Bobrovnikov et al., 2022; Paredes-Velasco et al., 2023).

The constructive approach is used in a variety of contexts in education. In programming education, a whole stage of design (development) is devoted to assembling or constructing modules of software and verifying their consistency with one another. Some elements of constructive visualization were mentioned in earlier studies by Vygotsky (1934), Piaget (1967), Papert and Harel (1991), and Wilson (1996). With the advancement of new learning tools, constructive visualization has got reinvigorated interest. Visualization of learning with VR or full immersion in the learning environment, which allows immediate participation in the processes and interactions with objects, differs from other ways of visualization as it facilitates the acquisition of new knowledge and develops practical skills drawing on one's own experience (Jonassen, 1991).

2.3. Assessing the educational effects of visualization in VR

The outcomes of an evaluation of non-digital and digital learning games for teaching sorting algorithms presented in the studies suggest that non-digital games are more likely to focus on lower levels of learning taxonomy (remembering and understanding), while digital games with good visualization mostly get to the application level of learning process (Battistella et al., 2017). In evaluating the effectiveness of visualization, the impact of learning visualization on other types of learning activities, such as motivation, involvement and cooperation, plays a significant role (Hundhausen, 2002; Naps T. et al., 2003; Naps T. L. et al., 2003; Myller et al., 2009; Hayashia et al., 2013). The extended taxonomy by Myller et al. (2009), developed on the basis of the relationship between engagement and visualization, distinguishes the following levels of learning activities that can be an outcome of visualization exposure: No viewing, Viewing, Controlled viewing, Entering input, Responding, Changing, Modifying, Constructing, Presenting, and Reviewing. Another taxonomy developed by Ihantola et al. (2005) to evaluate the visualization of algorithms is aimed at defining various aspects of using audiovisual systems in education with less effort than the hardware and software details of the application system. The taxonomy of Ihantola et al. (2005) for evaluating the visualization of algorithms differs from learning style taxonomies in that it focuses on software rather than the learning process itself (Bloom, 1956; Kolb, 1984; Felder, 1996). These taxonomies can be applied together to deepen the understanding of which systems facilitate learning. To evaluate the effectiveness of visualization in "VR sorting," an extended taxonomy was used, which includes components of the learning engagement taxonomy (Myller et al., 2009), the effective creation of visualization algorithms (Ihantola et al., 2005) and copyright components (Table 2).

TABLE 2 An extended taxonomy of evaluating the effects of visualizations with VR.

Taxonomy source	Levels of visualization effects	Characteristics
Myller taxonomy (2009)	Controlling	Visualization is considered, the student controls the visualization, for example, understands that it is possible to move objects
	Responding	Student understands that there are questions (or conditions) associated with visualization, tries to address these questions
	Modifying	Student makes changes to the original visualization
	Constructing	Student constructs his own version of the visualization, which differs from the original one
	Presenting	Student presents visualizations to others for discussion
	Reviewing	Student revises the visualization to correct the previous version
Copyright	Implementation	Student implements his own version of visualization to achieve the final result
Ihantola taxonomy (2005)	Scope of use	Student uses visualizations in a broad context
Copyright	Adaptability	The student uses visualizations to adapt to the conditions of a particular subject area
Copyright	Integrity	Student applies visualization for a full-fledged result

FIGURE 2
Selection sorting method on VR board.

The levels of visualization effects of the extended taxonomy and their characteristics in accordance with Likert scale scores were used to evaluate learning outcomes using the "VR sorting" application (Appendix 1).

3. Research design

3.1. Procedure

As a tool, we have developed a virtual reality application—"VR sorting." With VR sorting, students can sort the elements of a 10-element array using two methods. The bubble sorting and selection sorting methods are explained on the VR board. At the beginning of training, a menu appears on the VR board and a sorting method can be selected (Figure 2). After choosing a method, for example, selection sorting, each step of the sorting process is displayed on the board, if necessary, the review is repeated.

Next, students can use virtual hands to sort in the virtual environment. At each step, the student can pick up the cubes with numbers with one or two hands and swap them according to the sorting condition. Manual sorting in VR can be repeated multiple times, as the execution time and the number of repetitions are chosen by the student (Figure 3). If an error occurs, the sorting process restarts.

The Oculus Quest 2 headset was used to immerse into the VR. The "VR sorting" application was developed on the Unity 3D platform using the Oculus Integration package, the Visual Studio integrated development environment, the C # programming language and 3D models. 3D models are created using Blender 3D. The finished content is saved in apk. format file and downloaded to the headset. SideQuest app and USB cable used to download content to VR headset.

3.2. Participants

To test the empirical hypothesis of the study, two groups of students were selected. To study sorting methods, the VR sorting application was used in the experimental group of 78 students, and presentations and flowcharts were used in the control group of 72 students. The participants of the study are undergraduate students of the educational program "Informatics" of one of the regional universities of Kazakhstan at the age of 17–20 years. This study was reviewed and approved by the Institutional Ethics Committee of the K. Zhubanov ARU. This is a case study of one regional university that

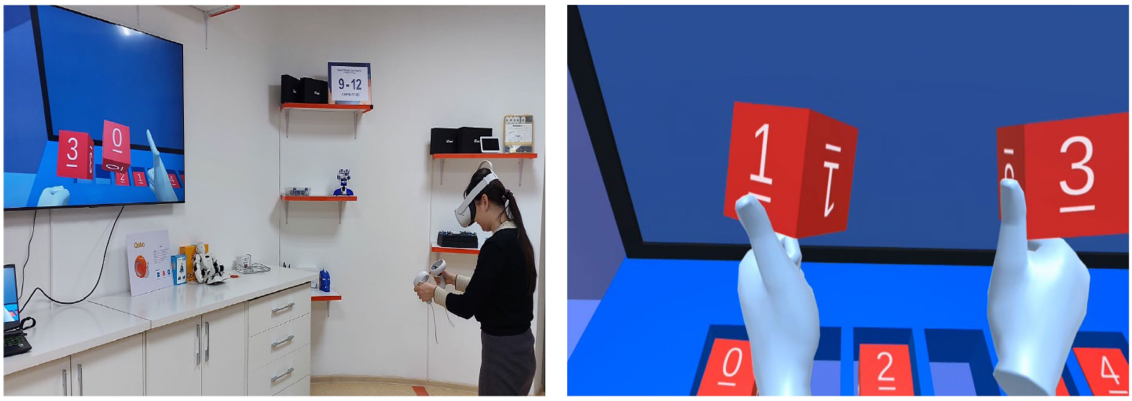
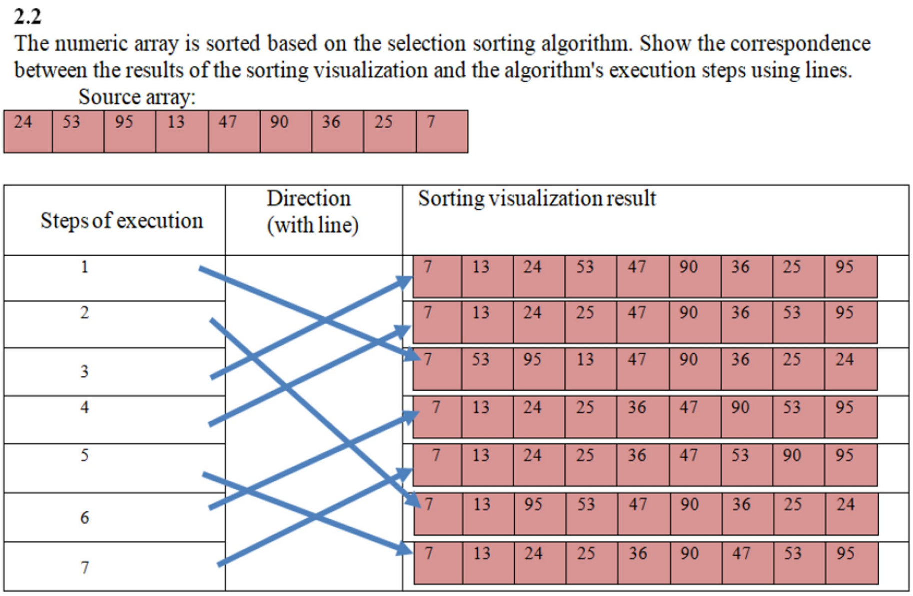


FIGURE 3
Sorting process.



2.2
The numeric array is sorted based on the selection sorting algorithm. Show the correspondence between the results of the sorting visualization and the algorithm's execution steps using lines.
Source array:

24	53	95	13	47	90	36	25	7

Steps of execution	Direction (with line)	Sorting visualization result								
1		7	13	24	53	47	90	36	25	95
2		7	13	24	25	47	90	36	53	95
3		7	53	95	13	47	90	36	25	24
4		7	13	24	25	36	47	90	53	95
5		7	13	24	25	36	47	53	90	95
6		7	13	95	53	47	90	36	25	24
7		7	13	24	25	36	90	47	53	95

FIGURE 4
Example of solving Task 2.

does not apply to students at other universities. Students who participated in the research received additional points in the course "Algorithms and Data Structures" and "Programming" in the semester ranking.

3.3. Methods

To determine the level of understanding of sorting methods and appropriate application skills, five tasks were developed (Appendix 2). Decisions Task 1 and 2 define two main indicators of the study of sorting methods. The first is related to how the student understands the conditions of the bubble sorting and selection sorting methods, the second indicator is whether the student correctly fulfills this condition for each new position (shift) or the current sort element. The key condition when using bubble sorting (Task 1, item 1.1) is to swap two elements that are next to each other in the sort direction. The condition of the selection sorting method is to find the smallest element of the list and swap the current and smallest element (Task 1, p.1.2). Difference Task 2 from Task 1, the sorting steps are not in order, the student matches the serial numbers to the corresponding sorting step (Figure 4).

Solutions of the following problems 3, 4, 5 (Appendix 2) also show the skills of using the learned sorting methods in practice. In particular, students completed tasks on the location of lakes, the areas of which began to change due to global climate change (In Wikipedia, 2021): sorting lakes by area size (Task 3); visual comparison to each of the lakes in the sorted list of the picture corresponding to it (Task 4); and visual matching to each of the area in the sorted list of the corresponding pattern of lakes (Task 5).

Responses were scored on a seven-point Likert scale, since it was required to define the correct responses for each sorting step.

TABLE 3 Interelement correlation matrix according to Cronbach's alpha.

	Task 1	Task 2	Task 3	Task 4	Task 5
Task 1	1.000	0.716	0.460	0.382	0.353
Task 2	0.716	1.000	0.483	0.383	0,379
Task 3	0.460	0.483	1.000	0.410	0,416
Task 4	0.382	0.383	0.410	1.000	0.740
Task 5	0.353	0.379	0.416	0.740	1.000

TABLE 4 Mean and standard deviation.

Tasks	Experimental group (78)		Control group (72)	
	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
Task 1	6.05	1.56	4.88	2.16
Task 2	5.12	1.92	3.35	2.42
Task 3	5.62	1.64	4.40	2.20
Task 4	4.22	2.14	3,10	2.16
Task 5	4.03	2.00	2.93	2.14

Responses on a seven-point scale are divided into four levels in accordance with the extended taxonomy of assessing the effects of visualization with VR (Table 2): "low"—1 point; "medium "—2 or 3 points; "good"—4 or 5 points; "high"—6 or 7 points (Appendix 1).

4. Results

The reliability and internal consistency of the tasks we developed were tested using Cronbach's alpha. The value $\alpha = 0.816$ confirms the reliability of test items. The inter-element correlation matrix (Table 3) shows the presence of a reliable correlation between tasks 1–5.

Across all five tasks, an average score of the experimental group were higher than those of the control group (Table 4). Overall, Task 1 in the experimental group has the lowest standard deviation (M = 6.05, SD = 1.56), Task 2 in the control group has the highest standard deviation (M = 3.05, SD = 2.42).

Table 5 shows the data of the experimental and control groups on the levels of educational effects of visualization. Analysis of the results of solving Task 1 and Task 2 shows that students of the experimental group who studied sorting methods using VR better understand the conditions of the bubble sorting and selection sorting methods and correctly perform sorting. Accordingly, the proportion of students in the experimental group with results that correspond to a high level of visualization effect (6–7 points) according to the solution of Task 1 was 76.9%, Task 2–51.3% (Table 5; Figure 5).

The greatest contrast is observed in solving Task 2, as the difference in the results of students in the experimental and control groups who scored low (1 point) is 29.5%. At the same time, a significant portion of students in the control group (33.3%) had difficulty performing the sorting steps because Task 2 did not show the directions of transposition of elements according to the sorting condition, as in the answers to Task 1. In addition, students in the experimental group had the opportunity to repeatedly perform manual sorting in a highly visualized VR environment, which promoted not only a thorough understanding of the method, but also automaticity in sorting (Table 5; Figure 5).

In Task 3, the results of both groups demonstrated significant deviations in students' responses, which correspond to low and high levels of effect visualization (Appendix 1; Table 5). In particular, the proportion of students in the experimental group, who scored 1 point in Task 3 is 2.6% while this indicator for the control group is 18.1%. The difference in responses of students in the experimental (62.8%) and control (40.3%) groups corresponding to 6–7 point (high level) was 22.5%. It is assumed that this contrast might be because of visualization on the visual attention of learners (Anderson et al., 2005; Johnson, 2013; Vecera et al., 2014). In the static visualization of sorting as a presentation, students in the control group primarily use cognitive resources to understand the abstract side of the task. In addition, visual resources are also used in parallel to compare numerical values of the data (lake area sizes). A manual analysis of the control group responses showed that, while sorting, students in the control group mostly paid attention to the first digits of a number, rather than its values.

The results for Task 4 and 5 showed that the number of students in both groups whose responses belong to the low (1 point) and medium (2–3 points) levels increased significantly (Table 5; Figure 6). Specifically, in Task 4, 41% of students in the experimental group, 65.3% in the control group scored 1–3 points. Similarly, in Task 5, 44.9% of students of the experimental group and 66.6% of students of the control group scored 1–3 points. Consequently, the proportion of students scored high (6–7 points) in Task 4 and 5 is significantly less than in the previous three tasks (Task 1–3; Table 5). This data show that students' responses were influenced by other factors, such as knowledge from another field (e.g., geography) and the capacity to read visual information (e.g., drawings of lakes).

Further, Pearson chi-square (χ^2) was used to define the static values of differences in the results of the experimental and control groups, as well as to confirm the validity of the obtained results (Rusyn et al., 2021; Roša and Lobanova, 2022; Yan et al., 2023). Using Pearson's Chi-square test (χ^2) requires acceptance of one, of the two hypotheses H0 and H1.

> H_0: VR visualization does not improve students' understanding of sorting methods.
>
> H_1: A high level of visualization and direct interaction with objects in the VR environment can provide students with a better understanding of sorting methods and development of hard skills in solving practical problems.

The calculation of χ^2 for each of the five tasks confirmed the following: for Task 1—$\chi^2_{exp} = 18.271$, $p = 0.006$; Task 2—$\chi^2_{exp} = 32.351$, $p = 0.000$; Task 3—$\chi^2_{exp} = 17.752$, $p = 0.007$; Task 4—$\chi^2_{exp} = 14.585$, $p = 0.024$; and Task 5—$\chi^2_{exp} = 17.562$, $p = 0.007$. If the degree of freedom $\nu = 6$, then $p \leq 0.05$, $\chi^2_{crit} = 12.592$. For the asymptotic significance of each problem for $p \leq 0.05$, the condition $\chi^2_{exp} > \chi^2_{crit}$ is maintained, accordingly, the null hypothesis (H0) is rejected and the alternative hypothesis (H1) is accepted for all problems.

TABLE 5 Indicators of the experimental and control groups by levels of visualization effects (Appendix 1).

Tasks	Level							
	Low level (1-point)		Medium level (2–3-point)		Good level (4–5-point)		High level (6–7-point)	
	Number of students in percentage							
	E_G	C_G	E_G	C_G	E_G	C_G	E_G	C_G
Task 1	2.6%	4.2%	7.7%	30.6%	12.8%	16.6%	76.9%	48.7%
Task 2	3.8%	33.3%	20.5%	29.1%	24.3%	8.4%	51.3%	29.1%
Task 3	2.6%	18.1%	7.6%	16.6%	27%	25%	62.8%	40.3%
Task 4	11.5%	34.7%	29.5%	30.6%	25.6%	15.3%	33.4%	19.4%
Task 5	10.3%	37.5%	34.6%	29.1%	26.9%	15.3%	28.2%	18.1%

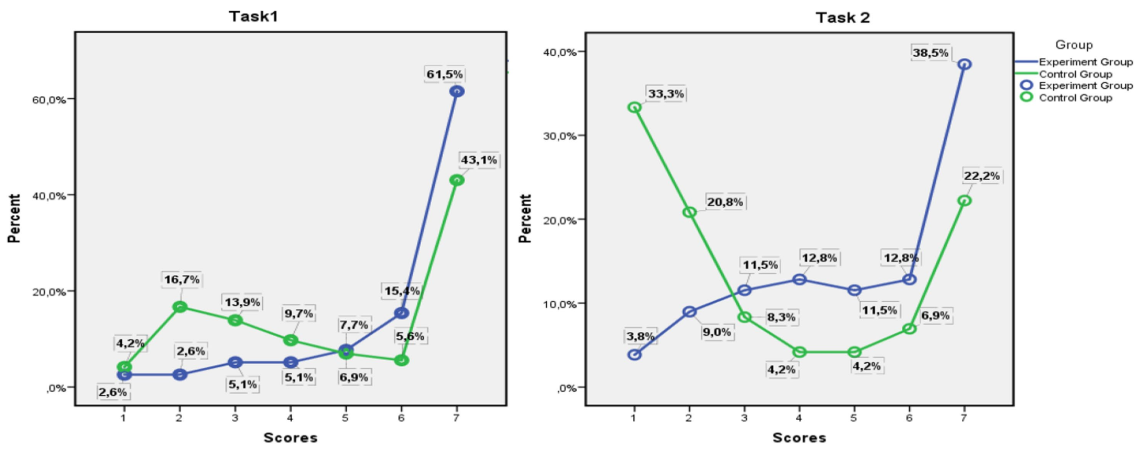


FIGURE 5
Results of implementation of Task 1 and Task 2.

5. Discussion

The theoretical hypothesis of this study suggested that current trends in the educational space, new advances in technology, and other factors may have an impact on the evolution of visualization as a teaching method. Each of the three approaches to visualization of educational material we identified is directly related to specific period of time, for example, traditional paper-based visualization methods have been replaced over time by presentations, animations, and videos using various digital technologies (Figure 1). The evolution of the main approaches to visualization proposed by us is based on the analysis of various types of visualization of abstract sorting, represented by the bubble sorting and selection sorting methods. While this may represent the specific case of demonstrating the evolution of mainstream visualization approaches, the findings of a number of studies suggest that digital learning support has been increasingly initiating new approaches to visualization. In particular, Bishop and Lange (2005), Caserta and Zendra (2011), Hayek et al. (2016), Van Leeuwen et al. (2018), and Nasr-Azadani et al. (2022) noted that the combined use of effects such as 2D and 3D, 360 video and immersive VR could lead to new and more efficient ways of visualization. The prospects and emergence of new character of constructive visualization with the advent of VR has also been noted in the works of Di Natale et al. (2020), Feyzi and Yasrebi (2020), and Li et al. (2023).

One of the hard stages in pedagogical research is related to the assessment of the effects of technologies on learning (Sembayev et al., 2021). Visualization with VR provides more opportunities for learning than other types of visualization (Figure 1). Therefore, the taxonomies of Myller et al. (2009) and Ihantola et al. (2005) were expanded by including "Implementation," "Adaptiveness," and "Integrity" levels (Table 2). The inclusion of these levels in the assessment of visualization effects can be explained by the "constructive visualization" paradigm (Huron et al., 2014, 2016). The constructive visualization implies the active participation of the student in the visualization itself, accompanied by the processes of initialization of tokens (bricks with numbers), grammar (sorting conditions), assembly (sorting), visualization display, and updating (sorting steps) necessary for this approach. As in the taxonomy of Bloom (1956), Biggs and Collis (1982), and Bespalko (1989) and other more recent studies assessing the impact of digital technology on learning outcomes (Meyers and Nulty, 2009; Ryan, 2014; Mukasheva and Omirzakova, 2021), "Adaptability" and "Integrity" are also classified as high-level visualization effects with VR (Appendix 1).

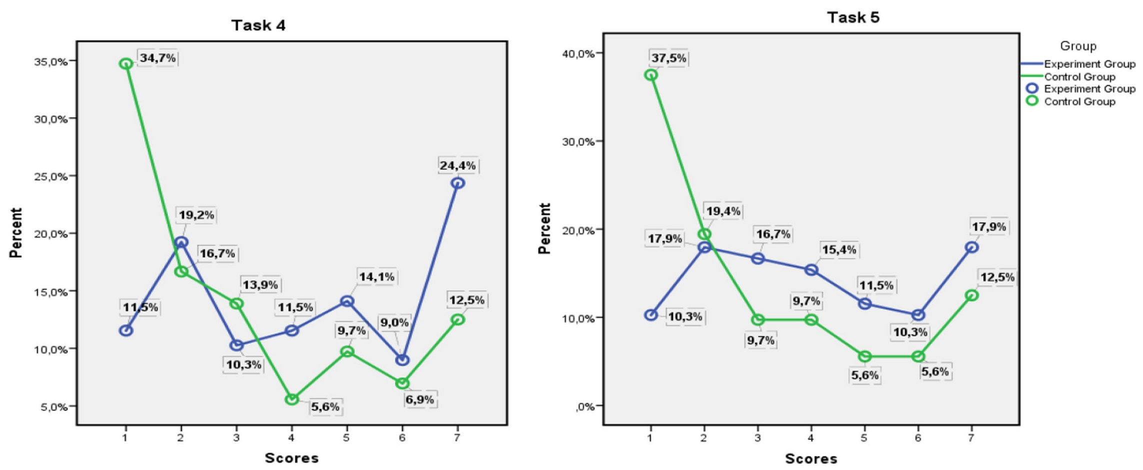


FIGURE 6
Results of implementation of Task 4 and Task 5.

In this study, extension of taxonomy allowed to gradually evaluate learning effects of visualization when solving 1–5 Tasks by students. Specifically, in performing the first three tasks, more than half of the students who studied sorting methods using VR showed results corresponding to a high level of visualization effects: Task 1–76.9%; Task 2–51.3%, and Task 3–62.8%. The correct definition of the sorting method and the clear performance of sorting steps without any errors by students of the experimental group demonstrate that visualization using VR contributed to a deeper understanding of sorting methods and confidently apply them in solving practical tasks. These results build on previous studies that have shown that VR helps improve student skills (Guzsvinecz et al., 2020; Li et al., 2022; Nugraha and Kosasih, 2022). However, the answers of the students of the experimental group to tasks 4–5 confirmed that in order to achieve a high level of effects that include Scope, Adaptability, Integrity, and visualization using VR for a wide range of tasks is required, rather than sorting methods. In this regard, this study aligns with the findings of the study conducted by Lee and Shvetsova (2019), which confirmed that VR contributes to developing a range of competencies.

6. Conclusion and future research

Educators have always been attracted to the visualization of learning material since it is one of the effective teaching methods. In this regard, digital technologies have contributed to the improvement of visualization. The evolution of visualization in learning (Figure 1) mapped in this study is one of the initial attempts to interpret existing ways of visualizing learning materials. This interpretation is not ultimate since visualization as a teaching method has been continuously evolving. Hence, further research is required to expand to research areas as 2D, 3D, and VR visualization using artificial intelligence (Nisar et al., 2021; Sabir et al., 2021a,b), as well as gesture learning visualization in VR environments and its recognition prospects (Huang et al., 2017; Bayegizova et al., 2022).

In line with previous research (Dai et al., 2023; Huang et al., 2023; Wang et al., 2023), empirical results demonstrate that VR allows to create a multifunctional training environment with high visualization and interactivity and helps to visually present the learning materials with abstract content and processes/phenomena. Moreover, the results of the study confirmed that a high level of visualization and direct action with the operated objects in the VR environment have a significant impact on students' understanding of abstract concepts and processes such as sorting methods and contribute to acquisition of practical skills. The extended taxonomy used in this study (Appendix 1) allowed to evaluate the impact of visualization effects in VR on students' knowledge and practice skills. The future research might develop criteria and characterize the levels of influence of the effects of visualization in VR on the cognitive abilities of learners.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by K. Zhubanov Aktobe regional university. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MM and ZK contributed to the concept and design of the study. MM wrote the methodology. ZK has developed the software and conducted statistical analysis and data processing. MM, ZK, and NP wrote separate sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1195200/full#supplementary-material

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