Technology, Pedagogy and Education

Routledge
Taylor & Francis Group

ISSN: 1475-939X (Print) 1747-5139 (Online) Journal homepage: https://www.tandfonline.com/loi/rtpe20

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TECHNOLOGY, PEDAGOGY AND EDUCATION
https://doi.org/10.1080/1475939X.2020.1737210

Virtual, augmented and mixed reality in K–12 education: a review of the literature

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ABSTRACT

This article provides the first review of the existing literature consolidating research into the use of virtual, augmented and mixed reality technologies within K–12 educational environments. The review explores the peer-reviewed scholarly studies conducted between 2006 and May 2017, which involved the use of virtual reality (VR), augmented reality (AR) or mixed reality (MR) technologies in the instruction of students in elementary, middle or high school. The literature revealed common themes including collaboration, communication, critical thinking, attitude, engagement, learning, motivation, performance or achievement, and technology (used or proposed). This literature review will contribute to the field by providing clarity on definitions for VR, AR and MR technologies in consideration of educational use, present an overview of the existing research on VR, AR and MR specific to K–12 educational environments and identify future research needs and directions.

ARTICLE HISTORY

Received 20 February 2018
Accepted 3 August 2019

KEYWORDS

Virtual reality; augmented reality; mixed reality; K–12; twenty-first-century competencies

Introduction

While virtual reality (VR) immerses users into an artificial world (Carmigniani et al., 2011, p. 342), augmented reality (AR) allows virtual objects to be superimposed on the real world (Azuma, 1997). Mixed reality (MR) refers to a real environment that allows for shared interaction with virtual experiences (Holz et al., 2011). The benefits of learning through VR, AR and MR include increased content understanding of spatial structure and function, learning of language associations, long-term memory retention, improved physical task performance, and increased motivation and engagement (Bacca et al., 2014; Lee, 2012; Lindgren & Johnson-Glenberg, 2013; Radu, 2014).

Although the potential uses for VR, AR and MR technologies in education are many, some educators question how schools, which have struggled to integrate even basic computer technology, will overcome K–12 technology integration barriers (Herold, 2014). Historically, access to these technologies has required high-cost head-mounted displays and technology with computational requirements that were expensive and skill-intensive to use (Baya & Sherman, n.d.). Recently, advances in smartphone technologies that allow for access to some VR content, coupled with increased smartphone ownership worldwide, have culminated in widespread, low-cost accessibility to VR and AR applications (Ralph, 2015).

Attention to the full reality continuum is timely as the ongoing evolution of VR, AR and MR technologies is resulting in an 'All Reality' framework which does not look at these technologies in isolation but rather considers the many ways our perception of reality will evolve through technology (Mann et al., 2018). This rapid advancement of technology is quickly evolving the many ways 'reality' can be experienced (Mann et al., 2018). Concentrating on only one of VR, AR or MR technologies limits

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the opportunity to establish pedagogy that spans consideration of the consumption, creation and manipulation of information across and through multiple realities and dimensions.

Focus on K–12 (i.e. Kindergarten to Year 12) environments is important as both the 2016 and 2017 New Media Consortium (NMC) K–12 Horizon reports, which are compiled to inform educators of emerging trends in educational technology, have stated VR (including AR in this definition) technologies will be adopted within K–12 schools within the next two to three years (Adams Becker, Freeman et al., 2016; Freeman et al., 2017). Building on this, the 2017 NMC technology outlook for Nordic schools has aimed the focus towards MR as the technology of adoption over the next two to three years due to the 'intersecting of virtual and physical realities' (Adams Becker, Cummins et al., 2017, p. 15). Technology use is no longer limited to higher education environments, and to ensure effective use of technology in K–12 environments it is imperative that research exists to support pedagogical understanding and application.

Previous literature reviews have investigated the overall use of AR in educational environments (Akçayır & Akçayır, 2017; Bacca et al., 2014; Radu, 2014), AR games in education (Koutromanos et al., 2015) and the effectiveness of VR-based instruction (Merchant et al., 2014). At the time of this literature review, there were no literature reviews that examined the full reality continuum of VR, AR and MR use in K–12 environments.

Definitions of augmented, virtual and mixed reality

Reality is considered to span a continuum (Figure 1) (Milgram & Kishino, 1994). Recent advances in technology foreshadow future capabilities to access the full continuum of reality (Campbell et al., 2016; Mann et al., 2018). During the research for this literature review, differences in the interpretation of VR, AR and MR definitions posed challenges in the collection and analysis of relevant studies. For technological clarity, the researchers provide definitions of VR, AR and MR in the next section; however, it is important to note that the ongoing evolution of these technologies is blurring the lines commonly used to distinguish them.

Virtual reality

VR refers to the complete immersion of a user 'in a synthetic world without seeing the real world' (Carmigniani et al., 2011, p. 342). Understanding VR requires insight into the differences between

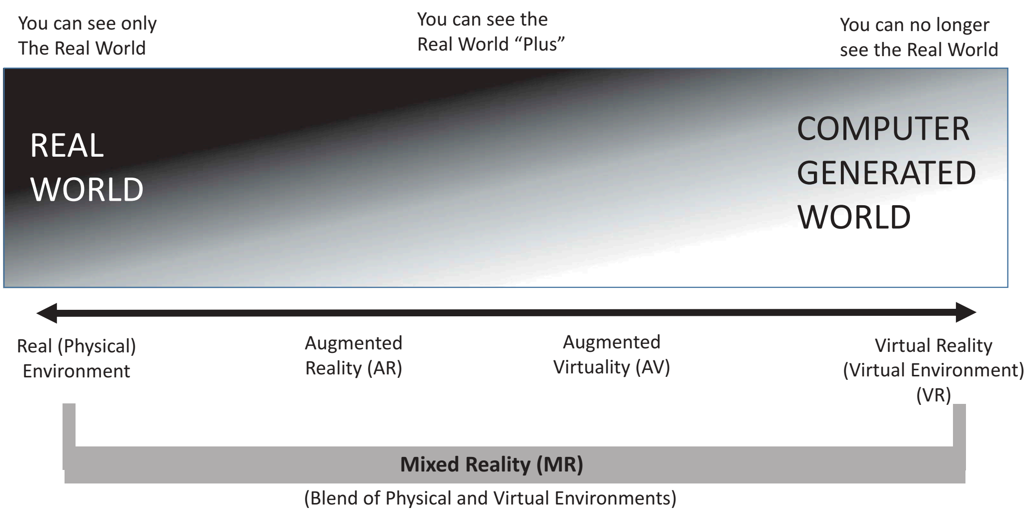

Figure 1. The reality spectrum. Adapted from the simplified representation of a 'virtuality continuum' (Milgram & Kishino, 1994, p. 3) and immersive computing spectrum (Joyce, 2018).

fully immersive, immersive and non-immersive VR as well as consideration of virtual environments and 360-degree pictures or videos (real-world pictures or videos taken by using technology such as a camera or multiple cameras encompassing panoramic views or 360-degree images). This section serves to provide delineations of VR use.

Fully immersive VR refers to the use of a head-mounted display, connected to or comprising a computer which allows the user to physically move or use a joystick to control movement within a 3D virtual environment (Lee & Wong, 2014; Southgate et al., 2016). Non-immersive VR, also referred to as desktop VR, involves accessing a virtual environment, 360-degree images/videos or other 3D environments using a desktop computer and monitor with peripherals such as a joystick, mouse or gloves to control movement and explore (Lee & Wong, 2014). 360-degree images or videos refer to images or videos that capture the entire 360-degree view of the location being filmed.

One of the challenges found in reviewing the studies within K–12 so far is that the terminology for VR has not tended to differentiate between the levels of immersion for VR, using the terms 'immersive' and 'desktop' VR interchangeably to describe an experience. This is an important consideration as recent advances in technology have provided the opportunity for users to experience 360-degree images and videos using smartphones and low-cost viewers, thus providing a level of immersion greater than desktop immersion (Ralph, 2015). Sometimes known as budget or cheap VR (Ralph, 2015), smartphones and low-cost headsets offer a cost-effective means for cash-strapped K–12 schools to provide the opportunity for users to be immersed in other locations, places and times. The scope of this literature review did not include studies that focused on virtual environments, virtual participation, virtual schools or the development or design of virtual worlds.

Augmented reality

AR has been defined as an overlay of information or virtual objects into the real world, allowing a reality where virtual objects seem to coexist in the same space with the real world (Azuma, 1997). Augmented reality requires a trigger to activate an augmentation (a superimposition of 3D material). Triggers have been defined using the terms 'marker-based', 'markerless', 'image-based', 'positional' and 'locational' AR (Chen & Tsai, 2012; Di Serio et al., 2013; Furió et al., 2015).

Marker-based AR refers to the use of an artificial image such as a black and white code (i.e. a barcode or quick response [QR] code) to trigger an augmentation (Chen & Tsai, 2012; Furió et al., 2015). Some researchers have extended this term to include all images which trigger an AR action (Pence, 2010). Including all images within the term 'marker-based' does not differentiate this concept from the term 'markerless' AR, which is defined as the use of an image (i.e. poster, landmark) that does not include an artificial marker (Chen & Tsai, 2012; Di Serio et al., 2013). Furthermore, some researchers use the term 'markerless' to include GPS-based locational or positional triggers within this definition (Pence, 2010). And yet, including GPS into markerless AR does not seem to recognise locational or positional AR, which uses GPS, wireless, or other geo-locational or positional data to trigger an augmentation (Chen & Tsai, 2012; Koutromanos et al., 2015). Recently, some researchers have been using the term 'image-based AR' without differentiating between marker and markerless at all (Diaz et al., 2015). The term 'positional' or 'location-based' AR is generally agreed to denote non-image AR which uses GPS or wireless locational data (Chen & Tsai, 2012; Chiang et al., 2014).

Mixed reality

Stretching along the virtuality continuum between AR and augmented virtuality is mixed reality. MR is a combination of both AR and VR that offers the ability to physically interact with virtual objects in the real world (Milgram & Kishino, 1994; Yusoff et al., 2011). MR differs from AR in that while AR allows the overlay of a virtual/digital object into the real world, MR allows offers a means to incorporate the full body with real and virtual elements across the reality continuum (Lindgren & Johnson-Glenberg, 2013). Within an MR environment, the user is not only able to 'see' the virtual/digital overlay or object, but they can also physically or mentally interact with and/or manipulate it. It is this ability to interact with digital/virtual overlays in the real world that differentiates AR and MR. Although the cost and processing power required for MR exceeds what is available in most K–12 educational environments, ongoing technology advancements will allow for further considerations of MR capabilities and potentials.

Twenty-first-century competencies/global competencies

The growth of the knowledge-based economy has identified the need to ensure learners develop certain employability skills that have become known as twenty-first-century skills (21CS) or more recently, global competencies (Asia Society/OECD, 2018; Assefa & Gershman, 2012; Chu et al., 2016; Kong et al., 2014; Larson & Miller, 2011; Voogt & Pareja Roblin, 2012). The Ontario Ministry of Education (OME) *21st-Century Competencies: Foundation Document for Discussion* (2016) identifies six categories for 21CS: critical thinking and problem solving; innovation, creativity and entrepreneurship; learning to learn/self-aware and self-directed learning; communication; collaboration; and global citizenship. The importance of developing 21CS and global competencies is a key consideration for educators striving to ensure learners' success in the global and digital economy (Asia Society/OECD, 2018; OME, 2016). This review revealed findings related to the development and/or use of critical thinking/problem solving, communication and collaboration skills which led to the connection made within this review to the 21CS.

Previous literature reviews

Five previous peer-reviewed literature reviews have examined VR and AR in education focusing on overall educational environments (Akçayır & Akçayır, 2017; Bacca et al., 2014; Radu, 2014), AR games (Koutromanos et al., 2015) and VR-based instruction (Merchant et al., 2014). No literature review focused specifically on MR use in education was discovered. These reviews are discussed in turn below.

The first literature review was a systematic review of 68 research articles selected from the Social Science Citation Index database (Akçayır & Akçayır, 2017). The review concentrated on the advantages, and challenges, associated with using AR in education. The advantages of AR included positive learning outcomes, increased engagement and enjoyment, collaboration between students and teachers, and visualisation of abstract material (Akçayır & Akçayır, 2017). The challenges of using AR in education included difficulty using AR technology, and students experiencing cognitive overload. Akçayır and Akçayır's (2017) review is limited because the articles selected were not required to be scholarly, the AR technology studied was not well defined, and the educational focus was broad including both K–12 and higher education settings.

The second literature review was a systematic review using an in-depth methodology to select 32 studies published between 2003 and 2013 from six indexed journals (Bacca et al., 2014). The review presented six main findings. First, the number of studies published about AR use in education is increasing. Second, most studies concentrated on science education in K–12 or university settings. Third, the studied populations in Bacca et al.'s (2014) review lacked diversity and did not include focus or control groups. Fourth, the most common access method for AR was marker-based AR, followed by location-based AR and then markerless AR (Bacca et al., 2014). Fifth, the use of AR resulted in learning gains, and increased motivation, interaction and collaboration by the students. Finally, the review outlined that challenges in using AR included the inability of the teacher to create content, technological difficulties and shifting students' attention away from the virtual information and towards the learning goals. Bacca et al.'s (2014) literature review limitations are that it focused exclusively on AR applications and included a broad range of populations including K–12 and higher education.

The third literature review was a meta-review and cross-media analysis of 26 studies comparing the effect of AR versus non-AR applications on learning (Radu, 2014). Studies examined included both conference papers and journal articles. Benefits of AR included: (1) increased content understanding, learning spatial concepts and language associations better improved long-term memory retention, and; (2) increased physical task performance and collaboration. Detriments to using AR included problems with paying attention to the AR and the outside environment simultaneously, challenges in using the technology, and difficulty with classroom integration and differences in student learning. Factors influencing learning with AR included offering content in a non-text-based format, presenting information in multiple formats, physical interaction with the content, directing attention to learning material, interacting with 3D material and increasing collaboration. Limitations of this literature review included a broad focus on educational populations and a long date range of included studies.

The fourth literature review examined the use of AR game-based apps using mobile devices in primary and secondary school environments (Koutromanos et al., 2015). Seven peer-reviewed, empirical journal papers, dated from 2000 to 2014, were selected from the ScienceDirect and ERIC databases. The review reported positive outcomes for learning including increased collaboration and communication, with some groups showing a deeper understanding of complex issues. Additionally, the review noted that AR games in informal learning environments could enhance active learning and positively affect learning outcomes through increased student involvement and participation (Koutromanos et al., 2015). The literature review was limited as it included only seven studies across a broad timeframe and population.

The fifth literature review investigated VR games, simulations and virtual worlds (Merchant et al., 2014). A meta-analysis of 67 empirical studies dated 1987 to 2011 was conducted. The review found that VR games, simulations and virtual worlds had a positive impact on learning in that students were able to retain the information acquired through games and that students were more likely to spend additional time in the virtual world or game environment. Limitations of this review included focusing on desktop-based and not immersive VR, and a dated set of studies.

To date, the existing literature reviews have explored themes of learning outcomes, instructional design, educational usefulness, and advantages and challenges but have not examined the pedagogical outcomes specific to K–12 environments (Akçayır & Akçayır, 2017; Bacca et al., 2014; Koutromanos et al., 2015; Merchant et al., 2014; Radu, 2014). Where previous literature reviews have isolated VR, AR and MR technologies, the evolution of the reality continuum requires that future research not consider these technologies in isolation, but rather consider the influence of a greater 'reality' on learning and pedagogy. While VR, AR and MR are well positioned to have an impact on K–12 education, research is only just beginning (Birchfield & Megowan-Romanowicz, 2009; Kerawalla et al., 2006; Lindgren & Johnson-Glenberg, 2013).

Method

This literature review employed the use of a narrative review that was carried out systematically. A narrative review allows the researcher to examine literature in such a way as to provide clarification, interpretation and critique (Greenhalgh et al., 2018). Use of a narrative review allowed the researcher to combine VR, AR and MR research studies together to present the first synthesis of pedagogical considerations across the full reality spectrum. In order to reduce bias, a systematic approach was taken to guide the researcher in the selection and analysis of literature (Ramey & Rao, 2011). A meta-analysis was not used due to the wide range of variables inherent within the studies, which did not permit a quantitative analysis due to lack of a consistent focus, lack of a common technology used or lack of a common methodology.

The steps taken in this narrative review of the literature are outlined in Figure 2.

Data collection and analysis procedure

The articles for this literature review were compiled following a systematic search using the universities' online library, Google Scholar, email citation alerts and reference sections of relevant articles and literature reviews. The search was conducted using multiple terms including 'augmented reality', 'AR', 'virtual reality', 'VR', 'mixed reality', 'MR', 'augment', '3D', 'K–12', 'elementary', 'primary', 'secondary', 'high school', 'learning' and 'education'. The selected studies were peer-reviewed, with populations of students in K–12 educational settings, published in English in available journals. Conference papers, opinion

Figure 2. Narrative review of the literature approached systematically. Adapted from articles on systematic reviews from Ramey and Rao (2011) and Turner et al. (2010).

papers, online news, magazine articles and essays were not included. After analysis, 29 studies published from 2006 through to 2017 were selected for inclusion in this literature review. Of the 29 studies selected, 24 investigated AR, three investigated MR and two investigated VR. There is very little scholarly research focused on MR or VR in K–12 environments, which impacted the ability to balance the articles across the reality spectrum. A variety of data collection methods were used within the studies selected for inclusion within this literature review. These methods are outlined in Figure 3 below.

To analyse the research outlined within the 29 selected studies, the researchers coded the articles using the coding questions outlined in Figure 4.

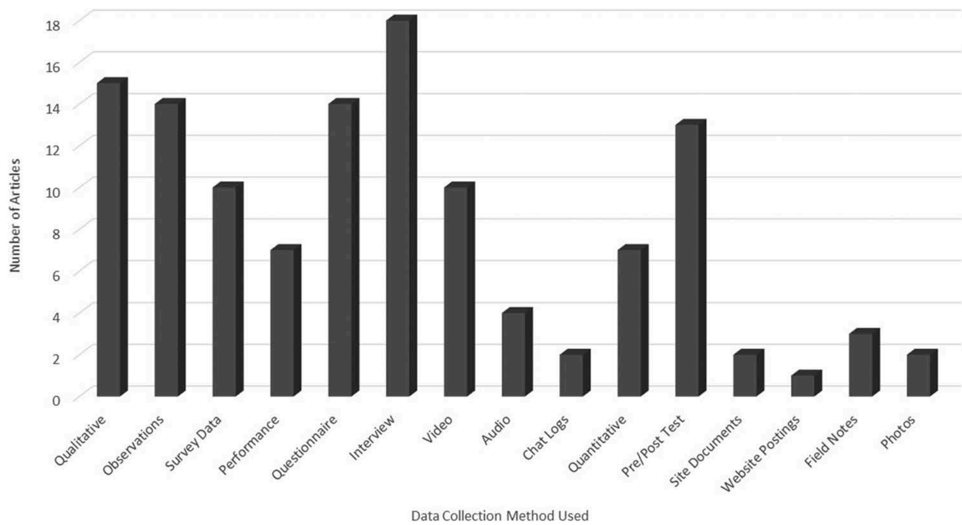

Figure 3. Data collection methods. Methods used to collect data in 29 articles selected for the narrative literature review.

1. Authors
2. Year
3. Title
4. Type of Literature (Study, Literature Review, Article, Online Source, Conference Proceeding)
5. How the "Reality" (AR, VR AND MR) was accessed
6. The technology used (Desktop PC, Webcam, Mobile Device, Head Mounted Display [HMD], Tablet, Laptop, Whiteboard / Projector, type of AR Software, Wireless Gamepad/Remote, Other SW used, Other (robots etc.)
7. Was a particular SW or App Designed for the study
8. Population (Who was studied)
9. Sample size
10. Sample description
11. Reliability (Did the study use/mention a method of determining the reliability, trustworthiness, and credibility of the data)
12. Validity (Did the study use/mention a method of determining the validity of the data)
13. Quality of data (Did the researchers perform any data checks in their analyses of the data in consideration of the reliability or validity of their findings, for example, were the findings reviewed by more than one researcher, external researchers, did the researcher triangulate the findings across data method collection
14. Subject area (What educational subject did the study consider e.g., Math, Science, Art)
15. Type of study (i.e. Mixed methods, Experiment, Longitudinal design experiment, Empirical study, Quasi-experimental, Case study)
16. Type of data collected (Qualitative, Observations, Survey Data, Performance (Achievement), Questionnaire, Interview, Video, Audio, Chat logs, Quantitative, Pre/Post Tests, Site Documents, Web site postings, Field Notes, Photos)
17. Behaviours (Did the researchers mention a change in subjects' behaviours (No mention, positive, negative, no-change)
18. Attitudes (No mention, positive, negative, no-change)
19. Learning (No mention, positive, negative, no-change)
20. Design involved (Was there a software or technology design completed for the study)
21. Was a software (SW) or application (APP) proposed or used?
22. Was there a control group?
23. What was the purpose of the paper?
24. What were the studies' limitations?
25. Overall themes (What were the main themes which emerged from the study findings)
26. Theme (What was the dominant theme of discussion)
27. Sub-theme(s) (What additional themes were highlighted, even briefly)
28. Key details discussed (What was the main finding the study presented)
29. Was the study focused on the creation or consumption of subject material?

Figure 4. Narrative review coding questions. Questions used to code, select and analyse narrative literature review articles.

The studies selected were focused on K–12 students and examined elementary (13), middle school (11) and high school (9) students with two studies also including higher education and teacher subjects (Figure 5).

A variety of technologies were used within the studies including tablets, mobile devices, AR and other software and desktop computers (Figure 6).

Narrative literature review findings

To date, existing literature reviews have explored themes of learning outcomes, instructional design, educational usefulness, and advantages and challenges of VR and AR in education. This

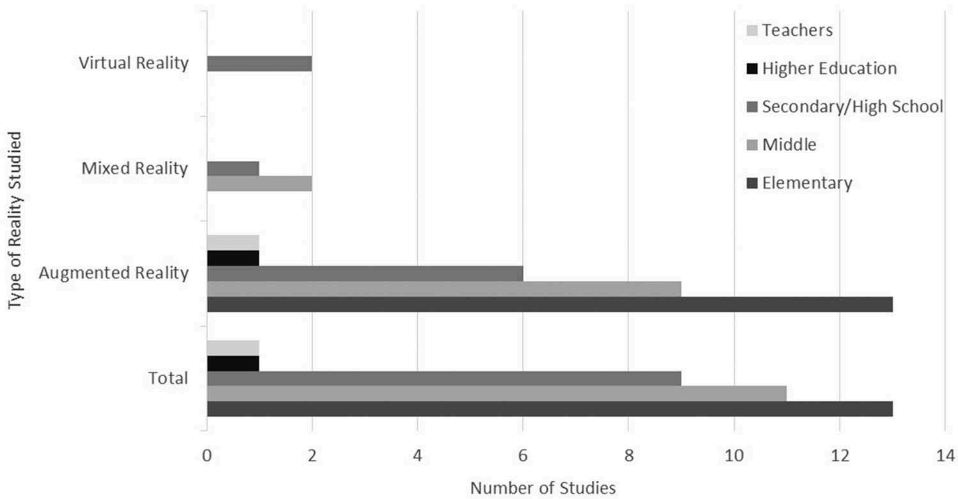

Figure 5. Population characteristics. A breakdown of the study populations found across the narrative review.

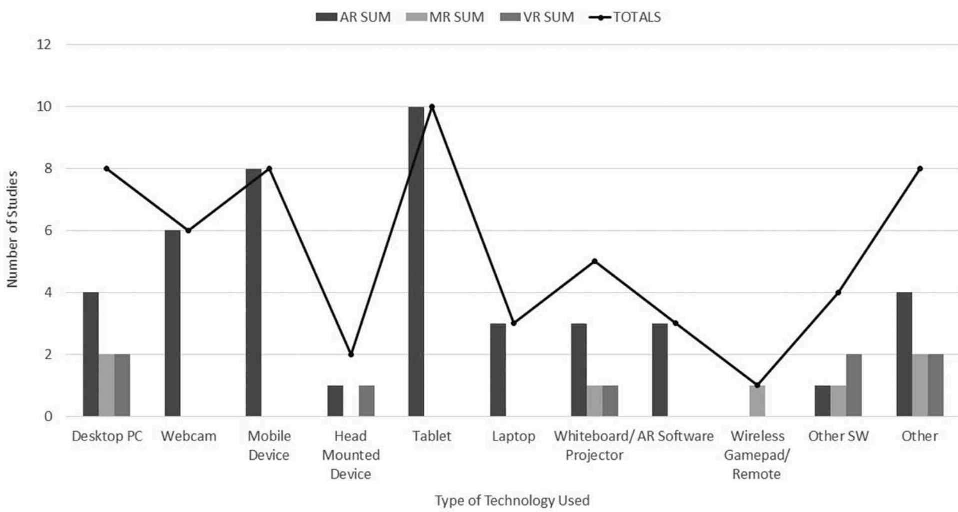

Figure 6. Type of technology used. A summary of technologies used in the narrative review studies.

review includes studies published between 2006 and 2017 and intends to consolidate the current state of research into the use of VR, AR and MR technologies in K–12 education. The review presents the findings aligned to the themes of attitude, motivation, engagement and performance/learning outcomes followed by the 21CS findings aligned to critical thinking/ problem solving, collaboration and communication. Figure 7 provides a visual representation of the themes which emerged from this narrative review.

Attitude

Studies have shown that students report a positive attitude of experiences learning through AR, VR and AR/virtual environments (Civelek et al., 2014; Furió et al., 2015; Huang et al., 2016). Studies which

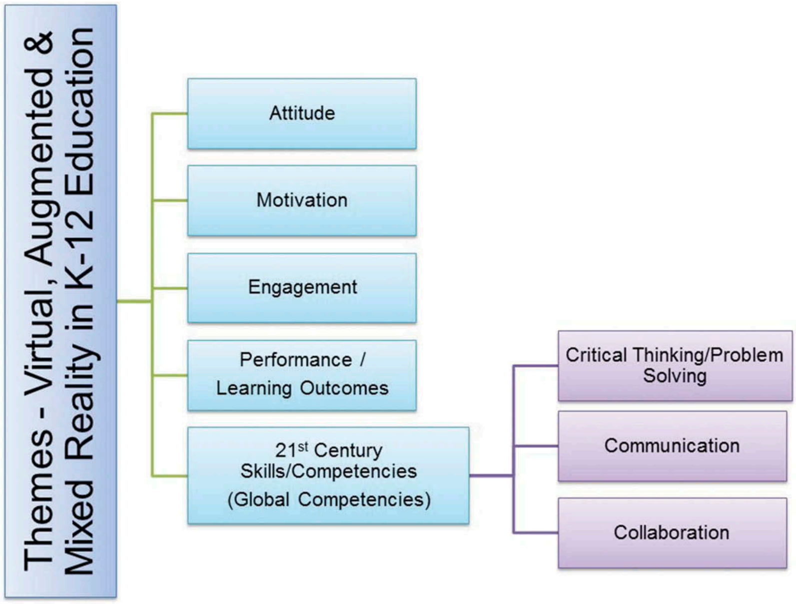

Figure 7. Narrative literature review research findings by theme. Augmented, virtual and mixed reality technologies in K–12 education.

included a control group found that those students using haptic (devices that provide the user with the ability to touch, smell, taste or otherwise interact physically with virtual objects) augmentation and AR mini-games preferred learning through AR in comparison to the non-AR traditional classroom lesson (Civelek et al., 2014; Furió et al., 2015). Middle school students learning through an MR environment reported positive attitudes towards learning and believed playing games in an MR environment helped them to learn (Lindgren et al., 2016). A study using an AR concept map application (CMAR) as scaffolding to support learning resulted in greater self-confidence and elementary students reported significantly greater satisfaction with learning than students who used AR alone (Chen et al., 2016a).

Bressler and Bodzin (2013) considered the concept of 'Flow – a psychological state that is challenging, intrinsically rewarding and enjoyable' (p. 506) and found that the average student experienced a substantive flow experience when using an AR game, and that middle and high school students' learning interest in science subjects increased following the use of the AR game (Bressler & Bodzin, 2013). Qualitative data found that neither a student's gender, nor interest in science, had an impact on their experience of flow (Bressler & Bodzin, 2013).

Motivation

The level of students' desire to participate in learning is often referred to as student motivation (Furió et al., 2015). The extent to which students are motivated by a teaching strategy or learning activity has a positive effect on their achievement (Furió et al., 2015). Findings indicate that learning through AR results in greater student motivation, learner interest, enjoyment and satisfaction from using AR in comparison to more traditional classroom instruction (Di Serio et al., 2013; Furió et al., 2015; Tobar-Muñoz et al., 2017). Students in the Civelek et al. (2014) study responded that their motivation to learn physics was significant when using a haptic augmented simulation in a virtual environment. Middle school students showed statistically greater motivation, attention and satisfaction as determined through quantitative analysis using a Shapiro Wilk test (test of normality used to test for nullhypothesis), for learning through AR instruction than through slide-based non-AR instruction (Di Serio et al., 2013).

Another study found that middle and high school students were observed to become competitive with their peers when using the AR simulation and the study's researchers hypothesised this finding was due to the desire of teams to 'win' (Dunleavy et al., 2009). The researcher's hypothesis was that having two teams completing the scenario in tandem side by side perhaps naturally facilitated the scenario being viewed as a race and motivated the students to see who could finish first (Dunleavy et al., 2009). This same study also demonstrated through interview data that the students were motivated to solve problems using the AR program and that they felt being out of doors provided a more authentic environment as to how a scientist might use mathematics (Dunleavy et al., 2009). Further, middle school students reported they were motivated to solve problems and would repeat their AR learning experience (Dunleavy et al., 2009; Furió et al., 2015; Laine et al., 2016).

Engagement

Engagement refers to the extent to which a learner applies a level of attention and curiosity to a situation to achieve a desirable result (Krause & Coates, 2008; Student Engagement, 2014). Greater learning outcomes and increased motivation result from positive student engagement (Krause & Coates, 2008). Measures of learner engagement are useful to determine the effectiveness of the environment and learning community in progressing high-quality learning (Krause & Coates, 2008). Students' engagement in learning is thought to increase when learners can connect their learning with the world around them (Goldspink & Foster, 2013; Greene et al., 2004; Zhao & Kuh, 2004). Students who learned through AR instruction paid more attention, exhibited greater levels of concentration, engagement and participation, and were less likely to deviate in conversation and attention than when they learned through a non-AR environment (Chen et al., 2016a; Chiang et al., 2014; Kerawalla et al., 2006; Lindgren et al., 2016).

Questionnaire data collected through a study involving science subject material found that learning about outer space through MR resulted in increased feelings of immersion, greater concentration and an increase in skill and ability to overcome challenges in comparison to data collected from the control group (Lindgren et al., 2016). Interview data found that middle school students felt using an AR app to explore geometric shapes was 'more exciting than normal class' and 'interesting', while middle school students in a visual art class found the AR teaching scenario to be 'attention-grabbing' (Di Serio et al., 2013; Laine et al., 2016). Students using AR colouring pages were observed to be very excited and stimulated when watching the image 'pop out' of the colouring page (Huang et al., 2016).

Interview data revealed that having access to differentiated information increased middle and high school students' engagement with math, language and scientific literacy through the use of an AR game (Dunleavy et al., 2009). Further analysis discovered that disengaged middle and high school students became engaged and motivated while interacting with the mobile game AR simulation (Dunleavy et al., 2009). When using a CMAR application, elementary students reported the activities maintained their attention and were significantly more relevant than when they used the AR alone (Chen et al., 2016a).

Performance/learning outcomes

Within this review, studies used pre- and post-tests, interview and questionnaire data to measure changes in learner outcomes individually or in comparison to a control group. Furió et al. (2015) found students answered more questions correctly following AR use, and Chen and Wang (2015) found through analysis of pre–post test data that AR-embedded instruction positively affected Grade 7 students' learning achievement in earth science instruction. Post-test *t*-test analysis revealed statistically significant increases in learning achievement for the elementary school students using CMAR intervention in comparison to the students in the AR-only group, and interviews with students found that they felt the use of CMAR helped to clarify and simplify learning materials (Chen et al., 2016a). Students' learning achievements were not impacted by their learning preferences nor by their ICT competence when using AR-embedded instruction (Chen & Wang, 2015).

Hung et al. (2017) found there was no statistical difference in the retention of material learned between the use of an AR graphic book, a picture book and physical interaction when teaching Grade 5 students about bacteria. Chang et al. (2010) determined through quantitative analysis of pre- and post-tests that there was no significant learning difference for middle and high school students learning vocabulary using mixed and virtual robot environments. One study found that high school boys outperformed high school girls to a statistically significant degree within an AR environment; however, the same study determined that there was no significant learning difference between the AR and non-AR environment (Echeverria et al., 2012). Squire and Jan (2007) determined through observational data that elementary students who struggled with reading also wrestled with the AR interaction within the study. Novelty concerns were noted by Dunleavy et al. (2009), who observed that middle and high school students often did not complete the learning activity as they would spend too much time 'beaming' information to each other.

Lee and Wong (2014) studied the impact of a desktop VR-based learning environment for learners with different spatial abilities and found that students scored statistically better using the VR program Vfrog to dissect a specimen virtually in comparison to students taught traditionally using PowerPoint slides. High school students with low spatial visualisation ability (how easily a learner can 'see' and manipulate shapes in a VR environment) showed statistically significant learning gains using the VR program Vfrog; however, students with high spatial visualisation ability did not experience the same learning gains (Lee & Wong, 2014).

Students learning abstract physics concepts in a VR environment had greater learning gains than those of learners in a regular class (Civelek et al., 2014). A statistically significant number of high school students felt the use of a haptic AR simulation in VRE would help them better learn abstract physics concepts such as gravitational pull (Civelek et al., 2014). Use of an MR environment was found to significantly increase students' understanding of physics concepts specific to physics in space in comparison to the control group (Lindgren et al., 2016). Grade 9 at-risk students increased their performance scores by 22.6% in multiple-choice question scores and 40.4% in explanation scores, based on pre- and post-testing, following use of the MR environment; however, performance was not the focus of the pre- and post-testing and without a control group further testing is needed (Birchfield & Megowan-Romanowicz, 2009).

Twenty-first-century competencies/global competencies

This literature review identified recurring themes aligning to the 21CS: critical thinking/problem solving, communication and collaboration. Definitions and frameworks for critical thinking/problem solving, communication and collaboration vary in terms of source or focus. Figure 8 summarises the definitions used by the researchers for this review.

Critical thinking/problem solving

Examples of the use or the development of critical thinking/problem-solving skills were highlighted in several studies. Specifically, students were found to 'engage in an inquiry process to solve problems as well as acquire, process, interpret, synthesise, and critically analyse information … make connections, and transfer learning to other situations' (Council of Ministers of Education [CMEC], 2016; OME, 2016). Chiang et al. (2014) found students' discussions during the knowledge construction phase of a lag-sequential analysis were statistically significant in comparison to students in the control group whose results demonstrated they were unable to apply their knowledge to other concepts. When using AR games and location-based AR, two studies found that students had a greater capacity to learn the subject material, demonstrated deeper knowledge construction and engaged in ongoing inquiry when using AR

CRITICAL THINKING/PROBLEM SOLVING	COMMUNICATION	COLLABORATION
"Critical thinking and problem solving involve addressing complex issues and problems by acquiring, processing, analysing and interpreting information to make informed judgments, decisions and actions. The capacity to engage in cognitive processes to understand and resolve problems includes the willingness to achieve one's potential as a constructive and reflective citizen. Learning is deepened when situated in meaningful, real-world, authentic experiences" (Ontario Ministry of Education, 2017, p.1) "The term critical thinking refers to the use of those cognitive skills or strategies that increase the probability of a desirable outcome … Critical thinking is purposeful, reasoned, and goal-directed. It is the kind of thinking involved in solving problems, formulating inferences, calculating likelihoods, and making decisions". (Halpern, 1998, p. 450) "Students use critical thinking skills to plan and conduct research, manage projects, solve problems, and make informed decisions using appropriate digital tools and resources. Students: A) identify and define authentic problems and significant questions for investigation. B) plan and manage activities to develop a solution or complete a project. C) collect and analyze data to identify solutions and/or make informed decisions. D) use multiple processes and diverse perspectives to explore alternative solutions" (Dede, 2010, p.59)	"Communication involves receiving and expressing meaning (e.g., reading and writing, viewing and creating, listening and speaking) in different contexts and with different audiences and purposes. Effective communication increasingly involves understanding both local and global perspectives, societal and cultural contexts, and adapting and changing using a variety of media appropriately, responsibly, safely, and with regard to one's digital footprint" (Ontario Ministry of Education, 2017, p.2) "Knowledge building/progressive discourse aimed at advancing the state of the field; discourse to achieve a more inclusive, higher-order analysis; open community knowledge spaces encourage peer-to-peer and extended interactions" (Scardamalia, Bransford, Kozma & Quellmaz, 2014, p.246)	"Collaboration involves the interplay of the cognitive (including thinking and reasoning), interpersonal, and intrapersonal competencies necessary to participate effectively and ethically in teams. Ever-increasing versatility and depth of skill are applied across diverse situations, roles, groups, and perspectives in order to co-construct knowledge, meaning, and content, and learn from, and with, others in physical and virtual environments" (Ontario Ministry of Education, 2017, p.2) "Collective or shared intelligence emerges from collaboration and competition of many individuals and aims to enhance the social pool of existing knowledge. Team members aim to achieve a focus and threshold for productive interaction and work with networked ICT. Advances in community knowledge are prized, over-and-above individual success, while enabling each participant to contribute to that success" (Scardamalia, Bransford, Kozma & Quellmaz, 2014, p.246)

Figure 8. Twenty-first-century competencies – definitions for critical thinking/problem solving, communication and collaboration. Data from Dede (2010), Halpern (1998), OME (2016) and Scardamalia et al. (2014).

(Chiang et al., 2014; Furió et al., 2015). As well, the use of positional AR during an inquiry assignment resulted in learners spending more time comparing, discussing and examining subject material (Chiang et al., 2014). Elementary students using AR were able to more effectively bridge from the 'ask' a question phase to 'propose' a solution phase in comparison to those students in the control group (Chiang et al., 2014). Two studies highlighted the ability of VR and AR technologies to effectively change the way people learn by furthering learners' understanding and comprehension (Chiang et al., 2014; Lin et al., 2016).

Communication

Communication today extends beyond traditional oral and written literacy, requiring that students now must learn and communicate through a variety of media formats including videos, social media and other non-text-based media (Bezemer & Kress, 2008; Jewitt, 2008; Kress, 1997; Shaw, 2014). This review found findings which highlighted the development of communication skills and the ability to learn with and through the technology. Within an earth science MR learning environment, Birchfield and Megowan-Romanowicz (2009) found Grade 9 at-risk students communicated 35% more often, led discussions and engaged with their teachers and peers to a greater extent than was occurring in regular classroom instruction. When presented with the opportunity to receive instruction and communicate through technology, students were found to prefer learning through an iPhone lesson, in comparison to the traditional classroom lesson (Furió et al., 2015). Kerawalla et al. (2006) found, however, that the ability for students to learn using AR was dependent upon the amount of time the teacher allowed for hands-on exploration, highlighting the need that students have the appropriate digital skillsets for the effective use of the technology.

Collaboration

Collaboration can be demonstrated through students' ability to respectfully work as part of a team while contributing to the learning of others through cooperative and consultative discourse using an array of tools and technologies (OME, 2016; Scardamalia et al., 2014). Within this review, observational data found middle and high school students engaged in collaborative activities such as exchanging handheld units to communicate to solve problems (Dunleavy et al., 2009). Chiang et al. (2014) found that students using AR were more likely to engage in discussion around their opinions than students in the control group. High school students felt using a haptic AR simulation in an immersive VRE promoted collaborative learning of physics (Civelek et al., 2014). Hew and Cheung (2010) documented the capability for VR and AR to remove geographical boundaries and encourage learners to engage socially with their peers even when physically separate.

Greater student interaction was also found by Han et al. (2015) when students learned through an AR robot; however, it was noted that the form of AR technology (robot or computer based) did not have an impact on how well students collaborated with the technology. Dunleavy et al. (2009) noted that if an individual had problems with their technology during a group learning activity, this had an impact on the entire team when completing team-based activities. Students learning through digital augmentation along with knowledge-building scaffolds indicated that collaborating in a small group was the most helpful scaffold (Yoon et al., 2012).

Conclusion

VR, AR and MR involve the use of a variety of computer hardware and software technologies. The rapid advancement of technology is resulting in easier and lower cost access to the software and hardware needed to consume and create AR and VR content. MR content access is still a challenge due to the need for computational capabilities which are currently beyond the scope (limits such as access to computers which have the required computational capabilities) of most K–12 schooling environments; however, MR offers much potential for the future. A discussion of findings related to the positive and negative implications of using these technologies in K–12 educational environments is necessary to further develop meaningful pedagogy.

Of the 29 studies included in this review, 24 looked at AR, three looked at MR and two looked at VR. There were studies found which were not included in this review which explored the use of virtual environments and virtual classrooms; however, because these studies explored students participating virtually or explored the design of virtual learning environments as opposed to exploring the information through virtual immersion in the subject material, these were not included. The AR studies included in this review investigated art (3), language (3), library instruction (1), math (3) and science (14). The non-science, technology, engineering and math (STEM) studies looked at art, language and library instruction. The studies involving art investigated dramatic play (Han et al., 2015); early art education (Huang et al., 2016) and motivation in a visual art course (Di Serio et al., 2013). The studies involving language looked at English language learning (Mahadzir & Phung, 2013), reading comprehension (Mahadzir & Phung, 2013) and interaction with an AR picture book (Cheng & Tsai, 2016); while another explored using AR to enhance student instruction related to using the library (Chen & Tsai, 2012). The remaining studies focused on STEM subjects' math and science. Math studies included algebra and geometry (Estapa & Nadolny, 2015), geometric shapes (Laine et al., 2016) and math, language arts and scientific literacy (Dunleavy et al., 2009). Science topics included electrostatics (point charges and static electricity) (Echeverria et al., 2012), environmental science argumentation skills (Squire & Jan, 2007), environmental education field trips (Kamarainen et al., 2013), primary school science (sun/earth, day/night) (Kerawalla et al., 2006), water cycles (Furió et al., 2015), bacteria (Drachsler et al., 2017), Bernoulli's principle (Yoon et al., 2017), electrical conductivity (Yoon et al., 2012), electromagnetism (Ibanez et al., 2014), aquatic plants (Chiang et al., 2014; Huang et al., 2016), earth science (day/night/seasons) (Chen & Wang, 2015) and food chains (Chen et al., 2016a).

The VR studies were both science based and examined computer-generated VEs and student interaction via desktop VR to learn biology (Lee & Wong, 2014) and more immersive haptic VR to learn physics (Civelek et al., 2014). The researcher was unable to find any studies within any population group which examined the use of immersive VR using non-computer-generated VE such as 360-degree images or videos. This is of note as many have referred to the advantages of using VR immersion through 360-degree images or videos (i.e. Google expeditions, United Nations Virtual Reality) to develop empathy and greater understanding; however, there were not any studies found that have investigated this formally with K–12 students. Such a study, ideally in comparison to a control group, would be extremely useful in determining pedagogical implications and best practices.

The MR studies reviewed involved the use of a semi-immersive physical environment to learn about geologic evolution (Birchfield & Megowan-Romanowicz, 2009) and a floor projection technology to instruct on outer space (Lindgren et al., 2016). The third MR study employed the use of a robot to teach English as a second language (Chang et al., 2010).

The majority of studies (24 of 29) proposed or used a software or application design. Proposing a design for future use as part of a study in AR, VR or MR is not surprising as the need to economise the creation of the content requires such studies; however, proposing a design tends to result in research with results focused on the impact of that specific software or application, as opposed to research which is focused on the greater consideration of the teaching and learning needs and opportunities within AR, VR or MR environments. The greatest challenge encountered through this literature review was finding studies which examined the use of AR, VR and MR for K–12 educational purposes. The researcher considered that the lack of study in these areas was the result of three factors: (1) rapid diffusion of AR, VR technology access through the proliferation of smartphones (so studies are just now being able to be conducted); (2) a lack of existing K–12 educational content available to study; and (3) differences in technology availability access across schools and countries.

Although educational applications are only just emerging, research into educational uses of VR, AR and MR has increased significantly over the last four years (Bacca et al., 2014; Chen et al., 2016b; Lindgren & Johnson-Glenberg, 2013; Wu et al., 2013). Several studies have highlighted the potential for VR, AR and MR to offer deeper learning opportunities by offering a unique mix of both real and virtual environments (Adams Becker, Cummins et al., 2017; Bower et al., 2014; Kerawalla et al., 2006; Lindgren & Johnson-Glenberg, 2013; Teichner, 2014; Wu et al., 2013). Research into higher education and distance education has highlighted the capability for AR and VR to remove geographical boundaries and allow 'teachers and learners who are separated by distance [to] engage in social activity in learning' (Hew & Cheung, 2010, p. 34). The ability for these technologies to afford interaction with material in 3D, physical and cognitive immersion with learning material, and collaborative and interactive work on complex and abstract concepts has been highlighted (Adams Becker, Cummins et al., 2017; Bower et al., 2014; Kerawalla et al., 2006; Lindgren & Johnson-Glenberg, 2013; Teichner, 2014; Wu et al., 2013). Although research is only just beginning, AR, VR and MR are well positioned to have an impact on K–12 education (Birchfield & Megowan-Romanowicz, 2009; Kerawalla et al., 2006; Lindgren & Johnson-Glenberg, 2013).

Future research

Studies to date have largely focused on presenting existing information to students through AR, VR and MR technologies. In this respect, these technologies are considered largely as an 'alternative' approach to delivering or presenting information that is currently taught through other means. It is important to consider not only students' ability to consume instruction and information through technology but further, the need for students to create and produce using these emerging technologies. As data continue to grow exponentially year over year, students must acquire the digital skillsets to manage and manipulate this vast amount of data, not simply consume it. These technologies offer new considerations around how we can present, consume and manipulate information in non-text formats. There continues to be a need in K–12 education (and beyond) to further study AR, VR and MR technologies considering both single-subject and cross-curriculum capabilities and impacts.

One area in which there is a dearth of research is in relation to immersive head-mounted-display VR and immersive VR as accessed through a smartphone with a low-cost budget viewer. There were very few studies found which investigated these technologies use in K–12 learning environments. Studies in this area should consider both the subject content, which content would be most fitting, as well as the experiences of students exploring existing 360-degree video or pictures in comparison to a control group exploring the information through traditional video. Furthermore, it is important that researchers examine the affordances and constraints related to the consumption of material through immersion in 360-degree pictures or videos; specifically, in comparison to a control group watching a video or experiencing non-VR instruction.

Most of the studies reviewed focused on proposing a software, application or product design relating to a specific subject, while only a few studies proposed a framework – either pedagogical or developmental – to use for developing future content. This highlights the need for future researchers to consider employing more diverse research methods across the study parameters to provide insight into what subject material results in greater learning gains for the student in comparison with traditional instruction methods. The purpose of technology use in education must not be simply to 'technologise' existing material that is already taught effectively.

A final consideration for further research focuses on the need to consider technology as a means of creation and discovery. Research thus far has focused on the consumption of material through AR, VR and MR; however, more research is needed to investigate how students can create versus consume. Further to this, the use of AR, VR and MR to explore and manipulate information within an expanded reality environment offers many exciting possibilities for students who today have access to information across a wide variety of media formats not previously considered.

Students today require a level of digital literacy not yet mandated within the existing curriculum. Twenty-first-century skills refer to a skill set needed to create, consume, critically evaluate and contextualise information from a variety of formats. Although AR and VR technologies have been around for some time now, these technologies are just scratching the surface in educational applications (Bujak et al., 2013).

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Melanie J. Maas has a unique blend of business, technology and education experience. Her interest in furthering the use of technology in teaching and learning environments has led Maas to tie together her business, technology and academic research experiences to advance the use of existing and emerging technologies in education and workplace settings. Her research explores: augmented, virtual and mixed reality and artificial intelligence technologies; and the use of technology to offer personalised learning environments. Maas is an innovative and forward-thinking individual who excels at seeing the bigger picture and bringing people together towards one common vision.

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