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Review

Exploring mobile mixed reality for critical thinking in nursing and healthcare education: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Background: The shortage of nursing and healthcare clinical placements has prompted the investigation of ways to supplement authentic learning. Mobile mixed reality has become increasingly available, however, the affordances and design principles for the facilitation of critical thinking are yet to be explored.
Objective: To examine how mobile mixed reality facilitates critical thinking in nursing and healthcare higher education.
Design: Systematic review.
Review methods: A search in seven databases (MEDLINE, PsychINFO, AMED, ERIC, Scopus, Cochrane, and Web of Science) was conducted with 3488 titles and abstracts screened. The quality of the included studies was evaluated using the Mixed Methods Assessment Tool (MMAT).
Results: A total of 12 studies with 1108 participants were included. The breadth of healthcare disciplines was limited to five disciplines that utilised bespoke scenarios on head-mounted displays. Most scenarios were emergency or critical response, with limited time for pre-brief, debrief, or overall user time. Only two studies directly measured critical thinking, with others including indirect reference to diagnoses, interpretation, analysis, or evaluation of healthcare scenarios. Affordances and design principles for the future development of mobile mixed reality for critical thinking in nursing and healthcare higher education are identified.
Conclusions: While some pedagogical affordances of mobile mixed reality can be identified in a narrow number of healthcare disciplines, there remain to be limited valid measures of critical thinking used to quantify effectiveness. Future studies would benefit from considering scenarios beyond emergency and critical responses, including longitudinal studies that reflect the development of critical thinking over time, and exploration of co-designed scenarios with and by nursing and healthcare students.

1. Background

1.1. Issues in clinical education

The worldwide shortage of nursing and healthcare workers (Sexton et al., 2022; World Health Organization, 2022) has impacted the availability of staff to supervise students in clinical placements (Song and Kim, 2023). The reduced clinical exposure has reported detrimental effects on students' confidence, readiness for practice, and development of critical thinking (El Hussein et al., 2023). Alternative approaches to supplement student exposure to clinical learning environments are presently required.

1.2. Mobile mixed reality (mMR)

Mixed reality has been defined as environments that present the virtual world and real-world together (Milgram and Kishino, 1994). The increased ubiquity of mobile devices has enabled students to access mobile learning at a self-determined, time, place, and pace (International Telecommunication Union, 2022; Universities UK, 2022).

Preliminary affordances of mMR in nursing and healthcare education have included: the safe application of skills (Cochrane et al., 2018a;

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Guze, 2015; Schneidereith, 2015; Vaughn et al., 2016); cost-effectiveness (Cochrane et al., 2019; Smith and Friel, 2021); enhanced authentic learning (Cochrane et al., 2018b; Guze, 2015); improved students' motivation and engagement (Smith and Friel, 2021); enhanced student feedback (Guze, 2015); and promotion of repetitive practice for skill improvement (Guze, 2015; Stretton et al., 2018).

1.3. Critical thinking

Critical thinking refers to "purposeful, self-regulatory judgement which results in interpretation, analysis, evaluation, and inference as well as explanation" (Facione, 1990 p3). It is essential to enable an analysis of a situation and draw on evidence to make informed, safe, and effective clinical judgements (Carbogim et al., 2018; Chan, 2013; Forsberg et al., 2014; Shin et al., 2015; Simmons, 2010). However, there is increasing concern about the limited critical thinking in graduate health students (El Hussein et al., 2023; Koivisto et al., 2018).

While there have been recent reviews in nursing (Theobald et al., 2021; Havola et al., 2020), interventions have focused on simulation using mannequins, virtual patients, serious games, or augmented reality which can be more expensive and less portable than mMR. The use of mMR for critical thinking in health education remains unexplored.

1.4. Research questions

This systematic review investigated how mobile mixed reality facilitates critical thinking in nursing and healthcare higher education. The research questions (RQ) include:

RQ1. What are the pedagogical affordances of mMR utilised in healthcare education?

RQ2. What are the perceptions, motivation and engagement of students and staff on the use of mMR to develop critical thinking?

RQ3. What are the pedagogical considerations for developing critical thinking in healthcare education?

RQ4. What are the design principles of mMR for facilitating critical thinking in healthcare education?

Randles and Finnegan (2023) outline different review types. As this review includes a focused research question with an associated search strategy, inclusion criteria and screening process, the authors have complied this research as a systematic review.

2. Review methods

This review utilised the Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols (PRISMA) guidelines (Page et al., 2021), with the protocol registered in PROSPERO (Protocol registration ID: CRD42021286931).

2.1. Search strategy

Seven databases (MEDLINE, PsychINFO, AMED, ERIC, Scopus, Cochrane, and Web of Science) were searched up to the 19th of November 2022. Reference lists of included studies were reviewed along with grey literature from internet searches. Search terms were established from the research questions using the PICO criteria (participants, interventions, comparisons, and outcomes). Search strings were not amended for the included databases (Appendix A).

2.2. Eligibility criteria

This review included studies that (i) involved university or tertiary education students, (ii) focused on health higher education, (iii) used mMR, and (iv) referred to the facilitation of critical thinking. Due to the dynamic nature of the intervention (mMR), all study designs were eligible. Studies were limited to those written in English language.

The review excluded conference proceedings and primary investigation of simulation suites and Cave Automated Virtual Environment (CAVE)s.

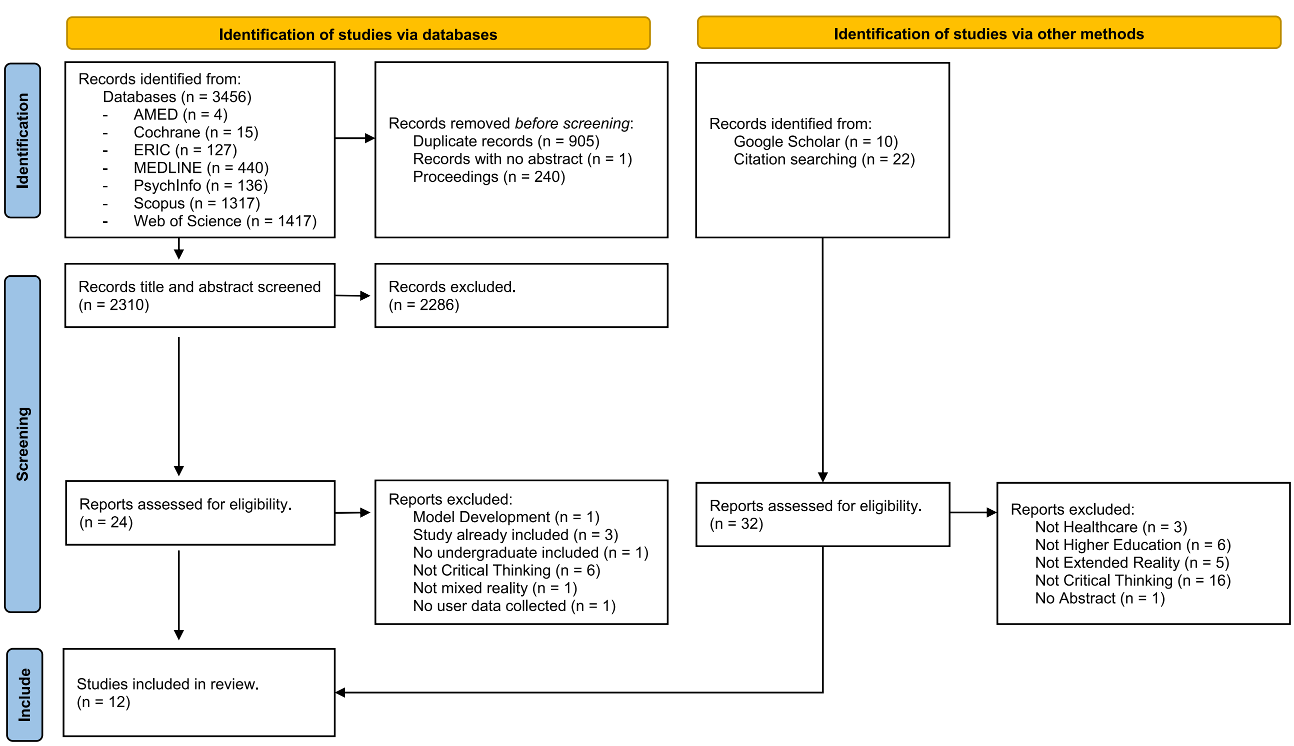

Fig. 1. PRISMA flow diagram for searches of databases and other sources.

2.3. Data extraction

Records were exported to Covidence (www.covidence.org) with titles and abstracts independently screened by two authors before screening identified full-text articles. Covidence was selected as the data management and extraction tool as it has been utilised and advocated for in other health-based systematic reviews. Any conflicts were discussed by the reviewers, or a third reviewer was consulted until a resolution was met. Duplicates were excluded. Cohen's kappa indicated a high level of agreement between the authors for interrater reliability (kappa = 0.84; 95%CI = 0.63 to 1.0; P = 0.92) (McHugh, 2012).

Coding procedures were developed according to the PICO criteria. The population (P) focused on healthcare higher education- including country, health discipline and sample size. Coding of the mMR intervention (I) included extraction of device type and mode in comparison (C) to conventional or alternate approaches where available. The primary outcomes (O) were (i) the development of critical thinking and (ii) perceptions of the use of mixed reality in healthcare education.

2.4. Quality assessment

The quality of the included studies was determined by the mixed methods appraisal tool (MMAT) (Hong et al., 2019). The MMAT is designed for systematic reviews that include qualitative, quantitative and mixed-methods studies (Hong et al., 2019). While the calculation of an overall score is discouraged, the MMAT provides a more detailed presentation of the ratings of each criterion to better inform the quality of included studies.

3. Results

The database search returned 3456 papers. After removing duplicates, and proceedings, 2310 papers were available. Titles and abstracts were screened with 2286 papers excluded. Following the review of 24 papers retrieved for full-text evaluation, an additional 13 studies failed to meet the inclusion criteria, resulting in 11 papers from the database search. An additional 32 grey literature papers were identified after a hand search of the reviewed full-text articles and scholarly websites (e.g., Google Scholar). After title and abstract then full-text review, one additional paper met the inclusion criteria (Zackoff et al., 2020) resulting in a total of 12 papers included in the review (Fig. 1). Key themes were extracted for each study using the PICO criteria (Table 1), guided by Braun and Clarke's (2022) six phases of reflexive thematic analysis to identify, analyse and report emerging patterns. Appendix B summarises papers excluded after full-text review.

3.1. Quality of literature

Inter-rater reliability for the MMAT was 76/80 criterion (96.67 %). Summarised in Appendix C, eight studies met all the methodological quality criteria for their identified MMAT study design categories (Birt and Cowling, 2017; Hanson et al., 2020; Kenngott et al., 2021; Mäkinen et al., 2020; McCoy et al., 2016; Sararit et al., 2018; Yu et al., 2021; Zackoff et al., 2020). Two studies (Alverson et al., 2004; Collins and Ditzel, 2021) had criteria that were unable to be clearly identified ("can't tell"); and one study (Cochrane et al., 2020) had criteria that were either unable to be determined ("can't tell") or was not met ("No"). Ramakrishnan et al. (2020) was categorised as a qualitative study according to the MMAT study designs. However, due to the absence of a research question, the study failed to meet any of the MMAT methodological quality criteria.

3.2. Population

The ten original studies included a total of 976 undergraduate participants within 1108 total participants including "expert" participants. Five health disciplines were identified: nursing (Collins and Ditzel, 2021; Kenngott et al., 2021; Ramakrishnan et al., 2020; Yu et al., 2021), nursing and midwifery (Hanson et al., 2020), dentistry (Sararit et al., 2018), medicine (Alverson et al., 2004; Kenngott et al., 2021; Mäkinen et al., 2020; McCoy et al., 2016; Zackoff et al., 2020), and paramedicine (Birt and Cowling, 2017; Cochrane et al., 2020). Only Kenngott et al. (2021) highlighted the differences between the two disciplines (nursing and medical students). Age was only identified in Yu et al. (2021) (mean of 22.40 years old); and sex was identified in three studies (Alverson et al., 2004; Cochrane et al., 2020; Yu et al., 2021). Experience ranged from first-year undergraduates to final-year interns. Cochrane et al. (2020) compared the experience of novice (students) to experts (practising paramedics) and Sararit et al. (2018) compared the performance of fourth- and fifth-year dental students.

3.3. Intervention

The first research question (RQ1) focused on the affordances of mMR in nursing and healthcare education. Included studies employed a variety of mobile devices and software, developed several different scenarios, and outlined affordances (Fig. 2) which are expanded in 3.3.6.

3.3.1. Mobile mixed reality (mMR)

Six studies incorporated untethered head mounted displays (HMDs), included Google Cardboard (Birt and Cowling, 2017; Cochrane et al., 2020; Sararit et al., 2018), Oculus Go (Cochrane et al., 2020; Ramakrishnan et al., 2020), Microsoft HoloLens (Collins and Ditzel, 2021), or attached a set of stereoscopic lenses to a mobile phone (Hanson et al., 2020). Four studies utilised tethered HMDs, including Oculus Rift (Kenngott et al., 2021), HTC Vive Pro (Yu et al., 2021), or were unbranded (Alverson et al., 2004). While the Oculus Go headset was designed to be tether-less, the HMDs in Ramakrishnan et al. (2020) were continuously connected to a charger.

Some studies included adjunct hardware to the HMDs. Birt and Cowling (2017) included 3D printed laryngoscope and forceps with augmented reality markers to simulate the removal of a foreign body lodged in a "throat". Yu et al. (2021) integrated a hand-tracking Leap Motion Controller with the HTC Vive Pro headset, and Kenngott et al. (2021) utilised a mouse and keyboard to interact with an older version of an Oculus Rift that did not have integrated gesture control.

3.3.2. Mixed reality software

A variety of software was used to develop the mixed reality environments including Flatland (C/C++) (Alverson et al., 2004), Unity3D (Sararit et al., 2018; Zackoff et al., 2020), Oculus SDK (Ramakrishnan et al., 2020), and Google Cardboard SDK (Sararit et al., 2018). 360-degree environments utilised Seekbeak (Cochrane et al., 2020), WondaVR (Cochrane et al., 2020), Pixvana's SPIN-Studio (Ramakrishnan et al., 2020) and Adobe Premier Pro and Adobe After Effects to render the environments (Ramakrishnan et al., 2020). Studies that included 3D Modelling used Autodesk products (Kenngott et al., 2021) while Kenngott et al. (2021) and Yu et al. (2021) included custom-built software.

Some studies utilised heat maps or gaze tracking software and analytics (Cochrane et al., 2020; Ramakrishnan et al., 2020), or incorporated measures of stress such as galvanic skin resistance (Cochrane et al., 2020; Sararit et al., 2018) and heart rate (Cochrane et al., 2020).

3.3.3. Adverse effects

Adverse effects were not dependent on device tethering. Participants using an unbranded HMD in Alverson et al. (2004) described the physiological effects of nausea, dizziness, motion sickness, eye strain, disorientation and feeling unbalanced. Post-survey feedback in Cochrane et al. (2020) attributed vertigo to reduced latency experienced using Google Cardboard, and participants were symptomatic when using stereoscopic lenses on a mobile device (Hanson et al., 2020).

Table 1
Summary of included studies.

Author (country)	Study design	Population	Intervention	Outcome (measure)	Findings
Alverson et al. (2004) New Mexico, US	Quantitative Descriptive Study	**Medicine** (Usability Study: n = 26; Knowledge Acquisition Study: n = 30; Knowledge Structure: n = 48) **Cohort**: 1st- 4th Year UG students (mean 2.96 years of UG programme) Sex (M: F): (Usability Study: 12:14; Knowledge Acquisition Study: NA; Knowledge Structure Study: 28:20)	**Mobile:** Nil **MR**: VR; Unbranded HMD (T) **Learning Activity:** Car Crash scene (*90 min*)	**CT**: "Problem solving-knowledge structure" **Other**: Usability; Knowledge acquisition	**CT**: opportunity to make mistakes and repeat actions in VR beneficial. **Usability**: easier to identify objects rather than find object; VR not a detractor to learning experience. **Knowledge**: Knowledge structure significantly improved. **Barriers:** HMD hard to use with glasses, were loose fitting, heavy, and adverse symptoms experienced; users need time to familiarise to environment; felt more engaged than in standard text-based scenarios.
Birt and Cowling (2017) Gold Coast, Australia	Qualitative Study (DBR)	**Paramedicine** (n = 27) **Cohort**: 2nd Year UG distance students Sex (M: F) 13:14	**Mobile:** BYOD **MR**: AR, VR, MR; [ColorCross] Google Cardboard HMD (U) & 3D printed instruments. **Learning Activity:** Laryngoscopy (*unlimited*)	**CT**: "Critical thinking"; "Problem solving" **Other**: Usability (student blogs); Satisfaction	**Usability:** positive reports of engagement, spatial awareness, and user satisfaction. **Barriers:** difficulties with setup and scene progression; time spent on orientating to equipment rather than learning activity.
Cochrane et al. (2020) Auckland, New Zealand	Mixed Methods (DBR)	**Paramedicine** (2017 n = 32; 2018: n = 30) **Cohort**: (2017: UG paramedic students & professional paramedics; 2018: 23 UG paramedic students (8 1st year) & 7 professional paramedics) Sex (M: F): 16:14 (2018)	**Mobile:** BYOD **MR**: VE; Google Cardboard HMD (U) (2017), Oculus Go HMD (U) (2018)* **Learning Activity:** Familiarisation *(15 s)* 2017- First responder mobile simulation (*1 min*) 2018- Ambulance ride pre-real-world scene (*4 min*)	**CT**: 2017- "critical thinking"; 2018- "situational awareness" **Other**: 2017- Stress (GSR, HR) subjective interview; 2018- Stress (HR via smartwatch), subjective survey & interview	**CT:** positive reports that informs decision making of patient diagnosis; correlation of subjective feedback, quantitative heart rate, stress response and identification of critical elements (analysis). **Usability:** reported enhanced the quality of simulation-based learning, immersiveness, authentic learning, and engagement; improved situational awareness. **Barriers**: reported poor HMD quality and inability to adjust focal length; experience of cybersickness.
Collins and Ditzel (2021) Otago, New Zealand	Mixed Methods	**Nursing** (n = 99) **Cohort**: 2nd year UG students	**Mobile:** BYOD **MR**: MR; HoloLens HMD (U) **Learning Activity:** virtual patient assessment (Asthma and Chest Trauma) in HoloPatients® (*1 h total*)	**CT**: vpLCJR **Other**: Usability	**CT:** 'beginning' or 'developing' skill level on vpLCJR- appropriate for current learning level. **Usability:** Reported as enjoyable, authentic, safe environment for practice. **Barrier:** unable to interact with the avatars.
Hanson et al. (2020) Queensland, Australia	Quantitative non-randomised study	**Nursing and Midwifery** (n = 225) **Cohort**: 2nd Year UG students	**Mobile:** BYOD **MR:** VR; HOMiDO VR Glasses HMD (U) vs CAVE **Learning Activity:** Drug-to receptor effect of autonomic nervous system on heart rate (*NA*)	**CT**: 4 questions in SSES **Other**: Knowledge Acquisition (Likert-scale MCQ); Satisfaction (SSES); Comfort (survey)	**CT:** mean satisfaction in clinical reasoning and clinical learning higher in CAVE2 than handheld devices in SSES. **Knowledge:** significant improvements in both methods from baseline, no significance between groups. **Satisfaction:** no significant difference. **Barrier:** greater discomfort in use of handheld.
Kenngott et al. (2021) Heidelberg, Germany	Quantitative non-randomised study	**Medicine & Nursing** **Cohort**: Medicine UG Students (n = 57); Resident Surgeons (n = 35); Attending Surgeons (n = 13); and Nurses (n = 53)	**Mobile:** Nil **MR**: VR; Oculus Rift HMD (T) **Learning Activity:** Familiarisation *(sufficient time)* Preoperative planning and training of liver surgery (*unlimited*)	**CT**: "Critical Thinking" (Assessment of patient) **Other**: Usability (survey)	**Usability**: positive report of assessment of complex case efficiency; most potential in medical student and resident training and clinical use than with nursing.
Mäkinen et al. (2020) Turku, Finland	Review	**Nursing, Medical & Dental** (n = 26 articles) **Cohort**: UG Students & Practitioners	**Mobile:** Nil **MR:** VR, AR; Multiple **Learning Activity:** Review- literature search of 8 databases, search strategy focused on health education, nursing, VR, simulation, AR, virtual patient, user experience. Identified 3 VR	**CT**: "Decision Making skills" **Other**: Usability	**Usability:** positive report of adoption, usability, engagement, immersion, flow, judgement, presence, and development of skill.

(*continued on next page*)

Table 1 (*continued*)

Author (country)	Study design	Population	Intervention	Outcome (measure)	Findings
			modes used in health education (1) haptic simulators; (2) computer-based simulators; (3) HMDs.		
McCoy et al. (2016) Arizona, US	Review	**Medical** (n = 35 articles) **Cohort:** UG Students (pre-clinical and clinical)	**Mobile:** BYOD **MR:** VR; app/web based virtual patient simulation. **Learning Activity:** Review-literature search of 3 databases and grey literature, search strategy focused on gamified training platforms (electronic games, mobile apps, virtual patient simulation) for medical education.	**CT**: "Clinical decision making" **Other**: Usability	**CT:** report that gamified medical education can provide risk-free clinical decision making. **Usability:** report that can promote learning, engagement, collaboration, authentic learning environments, distance training, analytics, and instant feedback.
Ramakrishnan et al. (2020) Philadelphia, US	Qualitative Study	**Nursing** (n = 332) **Cohort**: UG students	**Mobile:** BYOD **MR:** VR; Oculus Go HMD (U)* **Learning Activity:** Familiarisation (*NA*); Crazy Classroom (situational awareness, patient safety (*5 min*); Autism sim (*7 min*); Shortness of Breath (*3 scenarios*) (17 min); debrief/ reflection (*5 min*)	**CT**: "Decision making"; "Problem based learning" **Other**: Satisfaction	**Usability:** report of minimal adverse effects; suggestion to include interactive quizzes and notes for engagement. **Barriers**: issues with battery and WIFI with tethered HMDs.
Sararit et al. (2018) Bangkok, Thailand	Quantitative non-randomised study	**Dentistry** (n = 20) **Cohort**: 4th - 5th Year UG Students	**Mobile:** ZTE Axon 7 Android **MR:** VR; Google Cardboard HMD (U)* **Learning Activity:** Familiarisation ("*short briefing*"), Emergency management decision making in dental surgery (4 scenarios) (*NA*)	**CT**: Decision Making (correct decisions; response time) **Other**: Stress (eSense smart skin conductance)	**CT:** report of improved response time (analysis) in both groups; stress reduced as scenario progressed.
Yu et al. (2021) South Gyeongsang Province, South Korea	Quantitative non-randomised study	**Nursing** (n = 50) **Cohort**: "Senior" UG students	**Mobile:** Nil **MR:** VR; HTC Vive HMD (T) & Leap Motion Controlled hand-tracker **Learning Activity:** Familiarisation (*10 min*), Scenario introduction (*10 min*); Basic Care (*10 min*); Feeding management (*15 min*); Skincare & Environmental management (*15 min*); Debrief (*20 min*)	**CT**: "Problem solve" **Other**: Skills competency; Knowledge Competency; Performance Self-efficacy; Satisfaction	**Self-Efficacy:** significantly improved in both groups; greater improvement in experimental group. **Knowledge**: No significant difference. **Satisfaction**: Significantly higher in experimental group.
Zackoff et al. (2020) Cincinnati, US	Randomised Controlled Trial	**Medical** (n = 168) **Cohort:** 3rd Year UG Students	**Mobile:** Nil **MR:** VR, Oculus Rift HMD (T) **Learning Activity:** Verbal didactic instruction (60 min); time with high-fidelity mannequin (paediatric respiratory distress and respiratory failure); Intervention group received additional VR curriculum in first week (30 min); including facilitator feedback/debrief	**CT:** Author developed rubric based on students' findings, classification, next steps, and rationale for three 5-minute video vignettes. **Other:** Self assessed competency	**CT:** statistical difference in assessment, identification of examination findings, interpretation, classification, and recognition for escalation of care. **Competency:** significant improvement in self-assessed competency in experimental group.

Key: DBR- Design Based Research; M:F Male: Female; BYOD- "bring-your-own-device"; AR- Augmented Reality; VR- Virtual Reality; MR- Mixed Reality; HMD- Head Mounted Display; CAVE- Cave Automatic Virtual Environment; (T)- tethered; (U)- untethered; NA- Not Available; UG- undergraduate; *- mobile device; CT- Critical Thinking; GSR- Galvanic Skin Resistance; HR- Heart Rate; vpLCJR- Virtual Patient version of the Lasater Clinical Judgement Rubric; SSES- Satisfaction with Simulation Experience Scale.

3.3.4. Scenarios

All virtual environments involved emergency or critical response healthcare, including simulation of responding to a car crash (Alverson et al., 2004), airway management (Birt and Cowling, 2017), first responder ambulance ride (Cochrane et al., 2020), acute pharmacological effect on heart rate (Hanson et al., 2020), trauma management (Collins and Ditzel, 2021), surgical training (Kenngott et al., 2021), shortness of breath (Collins and Ditzel, 2021; Ramakrishnan et al., 2020), dental emergency management (Sararit et al., 2018), acute paediatric respiratory response (Zackoff et al., 2020) and "high-risk" procedural skills in neonatal care (Yu et al., 2021).

Five studies included a pre-brief or time for equipment or virtual environment familiarisation (Cochrane et al., 2020; Kenngott et al., 2021; Ramakrishnan et al., 2020; Sararit et al., 2018; Yu et al., 2021). Scenario run times ranged from one minute to unlimited timeframe. Three studies included a debrief (Ramakrishnan et al., 2020; Yu et al., 2021; Zackoff et al., 2020), while Cochrane et al. (2020) debriefed participants post-intervention for qualitative feedback on usability and immersiveness. Two studies did not specify the time allocated for the intervention phase (Hanson et al., 2020; Sararit et al., 2018).

3.3.5. Co-design

All reported scenarios were designed 'for' the participant rather than designed 'with' the participants. However, McCoy et al. (2016) and

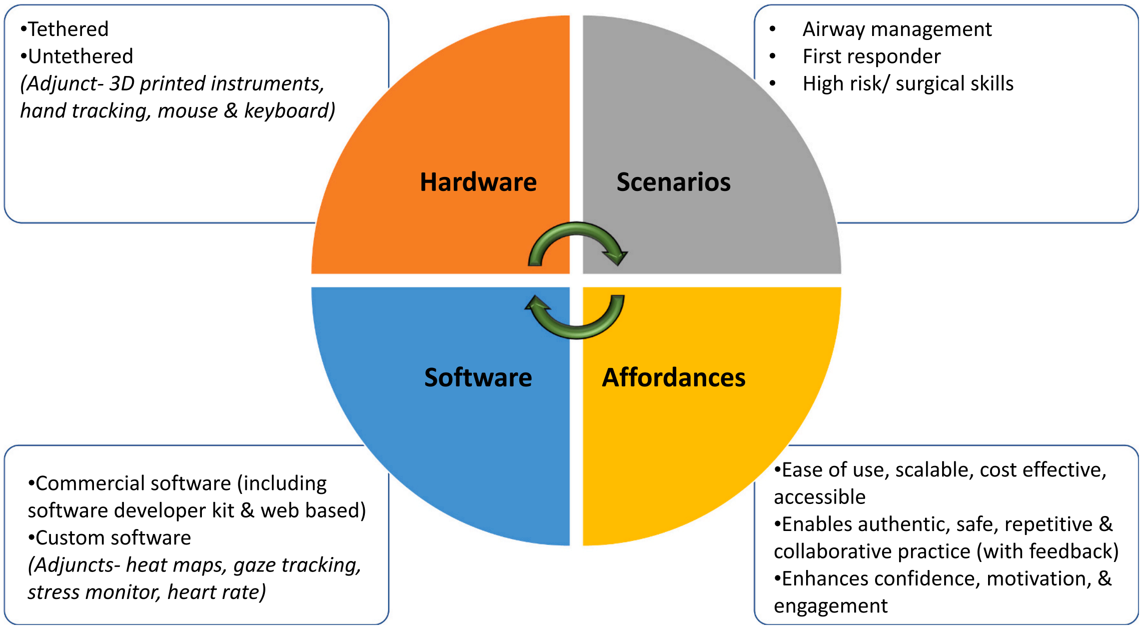

Fig. 2. Interventions in included studies- hardware, software, scenarios and affordances.

Ramakrishnan et al. (2020) postulated that future studies should include co-design with students in the selection and creation of learning environments.

3.3.6. *Affordances of mobile mixed reality for healthcare higher education*

Identified affordances of mMR are included in Table 2, with those referred to in the Introduction (1.1) italicised.

3.4. *Comparison groups*

Four studies compared virtual learning experiences between groups (Hanson et al., 2020; Sararit et al., 2018; Yu et al., 2021; Zackoff et al., 2020). This ranged from comparing experiences in a CAVE to that on a mobile phone with a stereoscopic lens (Hanson et al., 2020); the accuracy and response times of a cohort of fourth to a cohort of fifth-year students in simulated emergency dentistry scenarios (Sararit et al., 2018); infection control performance and learner satisfaction using mixed reality compared to a control group (Yu et al., 2021); and medical students' assessment of paediatric emergency scenarios using mixed reality compared to a control group (Zackoff et al., 2020).

3.5. *Outcome*

3.5.1. *Critical thinking*

The third research question (RQ3) related to pedagogical considerations when developing critical thinking. The heterogeneity of 'critical thinking' was evident with the term referred to either directly, or indirectly as 'clinical reasoning', 'problem-solving' or 'decision-making'. Only two studies included direct measurement of critical thinking. Hanson et al. (2020) utilised a modified Satisfaction with Simulation Experience Scale (SSES) which attributed four questions to "clinical reasoning", reporting that the mean clinical reasoning and clinical learning sub-scales were higher in the CAVE compared to viewing on stereoscopic lenses clipped on to mobile phones. Collins and Ditzel (2021) utilised the Virtual Patient version of the Lasater Clinical Judgement Rubric (vpLCJR), reporting that the HoloLens virtual patient scenarios helped develop students' clinical reasoning and judgement skills.

Birt and Cowling (2017) included a paramedicine case study and described that mixed reality had the potential to enhance critical thinking. Similarly, environments in Cochrane et al. (2020) incorporated critical thinking elements: time to critique the scene (interpretation, analysis, and evaluation), and allowing students to make an informed decision during the simulation (inference). While no direct measure of critical thinking was utilised, the authors reported that paramedic students perceived an increased awareness of their situated environment in the mMR scenario compared to other delivery methods. Similarly, Zackoff et al. (2020) reported the intervention group resulted in statistically significant differences in interpretation, analysis (classification), evaluation, and inference (recognition for escalation of care) when compared to the control group.

Some aligned critical thinking to 'decision making' (Hanson et al., 2020; Mäkinen et al., 2020; McCoy et al., 2016), 'problem-solving' (Alverson et al., 2004) or the ability of nursing students to 'solve problems' (Yu et al., 2021) in real-world learning situations.

3.5.2. *Perceptions*

Research question two (RQ2) related to perceptions, motivations and engagement when using mMR to facilitate critical thinking.

Paramedicine participants in the included studies perceived an increased sense of engagement when using a 3D-printed laryngoscope coupled with Google Cardboard (Birt and Cowling, 2017) and in a first responder mobile simulation (Cochrane et al., 2020) when compared to other known modes of delivery. Participants also highlighted the ease of use (Cochrane et al., 2020; Mäkinen et al., 2020), sense of immersion, presence and improvement in skill and judgement (Mäkinen et al., 2020) when using the mMR systems.

Differing perceptions of usability were highlighted when cohorts included more than one health discipline. Kenngott et al. (2021) investigated the use of the Oculus Rift for perioperative planning and training in a cohort that included medical and nursing students, and resident and attending surgeons. While nurses suggested the potential use of the VR system for clinical application and nursing training, this view was not shared by medical students who determined a higher potential for surgeon and medical students and clinical use than for nursing training. The authors attribute this to nurses wanting to expand their knowledge about the operations, which may not have been appreciated as necessary by the medical students and surgeons.

However, challenges when using virtual environments or devices were also reported. Birt and Cowling (2017) noted that some

Table 2
Affordances of mobile mixed reality for healthcare higher education.

Icon	Affordance	Reference[a]
	Accessibility (low fidelity)	(Birt and Cowling, 2017; Hanson et al., 2020)
	Authentic learning [of unique and complex scenarios]	(Cochrane et al., 2020; Collins and Ditzel, 2021) *(Cochrane et al., 2018b; Guze, 2015)*
	Collaborative professional practice	(McCoy et al., 2016)
	Confidence and self-efficacy in clinical skills	(Ramakrishnan et al., 2020; Yu et al., 2021)
	Cost effectiveness	(Cochrane et al., 2020; Ramakrishnan et al., 2020; Sararit et al., 2018) *(Cochrane et al., 2019; Smith and Friel, 2021)*
	Ease of use (low fidelity)	(Birt and Cowling, 2017)
	Feedback on student performance	(Cochrane et al., 2020; McCoy et al., 2016) *(Guze, 2015)*
	Information literacy, communication, and reflection development	(Cochrane et al., 2020)
	Motivation and engagement	(Alverson et al., 2004; Mäkinen et al., 2020; McCoy et al., 2016) *(Smith and Friel, 2021)*
	Repetitive, deliberate practice for [procedural] skill improvement	(Alverson et al., 2004; Mäkinen et al., 2020; McCoy et al., 2016) *(Guze, 2015; Stretton et al., 2018)*
	Safe application of skills	(Cochrane et al., 2020; Collins and Ditzel, 2021; Mäkinen et al., 2020; McCoy et al., 2016; Ramakrishnan et al., 2020; Yu et al., 2021) *(Cochrane et al., 2018a; Guze, 2015; Schneidereith, 2015; Vaughn et al., 2016)*
	Scalability/Rapid versioning (low fidelity)	(Birt and Cowling, 2017)

[a] References in *italics* denote references from preliminary search.

participants were frustrated by having to align augmented reality markers to progress in the virtual environment which impacted the learning opportunity.

3.6. Design principles

Research question four (RQ4) focused on design principles to inform the future development of mMR environments for critical thinking in healthcare education. Design principles from the included studies are summarised in Table 3.

4. Discussion

This systematic review explored how mobile mixed reality facilitates critical thinking in nursing and healthcare education. While the development of critical thinking is acknowledged as essential to practice and the use of mMR has been found to stimulate authentic learning, the literature focused on developing critical thinking using mMR is limited, as is the use of valid and reliable critical thinking measures to quantify the effectiveness.

4.1. Population

The predominance of five health disciplines (nursing, medicine, dentistry, midwifery, and paramedicine) is not uncommon in investigations of healthcare education (Stretton et al., 2018). With larger cohorts of students and well-established research funding sources compared to other health professions, these disciplines are more viable for the development of technology-enhanced learning including mMR. Future studies that explore or compare findings to other disciplines would help establish transferable design principles, especially for those disciplines that encounter acute and complex scenarios or are licensed as autonomous practitioners (e.g., physiotherapy).

All included studies were situated in developed countries, leaving to question the global digital equity for the use of simulation-based training (Baayd et al., 2023; Martinerie et al., 2018). While prototyping innovative practices may become more accessible and affordable over time, design that proactively integrates scalability across platforms would provide better certainty for populations that would otherwise be excluded.

The inconsistent recording of sex and age in the included studies limits the analysis of how these variables impact the design principles (RQ1) perceptions of mMR (RQ2), and facilitation of critical thinking (RQ3). While research on sex differences and cybersickness appears to be inconclusive (Tian et al., 2022), Grassini and Laumann (2020) found that female participants experienced more discomfort when using HMDs that did not accommodate the reduced interpupillary distance. The authors also suggested that female participants may be less susceptible to discomfort and cybersickness in lower-fidelity, 360-degree environments compared to virtual environments with cognitive tasks. Narciso et al. (2019) identified that female participants experienced realness and presence in 3D stereoscopic 360 environments, while males experienced more in 2D monoscopic environments. Similarly, females had more prevalence of nausea in the 2D condition, with males more symptomatic in the 3D environment.

4.2. Intervention

4.2.1. Mobile mixed reality

Positive affordances of mMR (RQ1) have been outlined (Table 2). While untethered HMDs may include affordances of accessibility, affordability, and scalability; tethered devices may extend the immersive experience due to the processing capacities of the attached computers. Higher refresh rates in tethered devices, appropriate display screen size and ability to adjust the focal length may reduce the susceptibility to cybersickness (Alverson et al., 2004; Cochrane et al., 2020). Adverse effects reported by Alverson et al. (2004) could have been related to early adoption of high-fidelity devices- well before the introduction of commercially available HMDs in 2016 (Harrington et al., 2018).

4.2.2. Scenarios

Most studies included acute or complex health scenarios for the virtual environment which may have been selected as they represent

Table 3
Design principles for mobile mixed reality to facilitate critical thinking in nursing and healthcare education.

Design the project by…
Purposeful Critical Thinking, with…
• Opportunities to **make mistakes and repeat actions** to enhance or correct decision making aids critical thinking (Alverson et al., 2004).
Making it meaningful, with…
• Opportunities for student **co-design** in content selection and design of learning strategies to stimulate engagement in solving complex health care problems (McCoy et al., 2016)
• **Longitudinal exposure time** that aligns with the timeframe of a typical higher education module of learning (Hanson et al., 2020).
• **Valid, reliable [critical thinking] measures** that can be [repeated and] compared to subsequent health education cohorts (Collins and Ditzel, 2021; Hanson et al., 2020).
• **Physiological response to CTS** in acute or complex situations may be measured by stress monitors (Cochrane et al., 2020; Sararit et al., 2018).
• **Satisfaction and Usability** of mobile mixed reality for health education may still be beneficial with novel approaches to pedagogical integration (Alverson et al., 2004; Birt and Cowling, 2017; Cochrane et al., 2020; Collins and Ditzel, 2021; Hanson et al., 2020; Kenngott et al., 2021; Mäkinen et al., 2020; McCoy et al., 2016; Ramakrishnan et al., 2020; Yu et al., 2021).
Considering Mobile Mixed Reality Development, with…
• A **pre-brief** and **familiarisation** to the virtual environment should be included to provide context and familiarity to the environment and/or equipment (Cochrane et al., 2020; Kenngott et al., 2021; Ramakrishnan et al., 2020; Sararit et al., 2018).
• A **debrief** should be included- especially if the learning experience involves traumatic and/or complex traumatic scenarios (Ramakrishnan et al., 2020; Yu et al., 2021).
• Opportunities to **repeat actions** for deliberate practice (Alverson et al., 2004)
• Use of **Room-Scale virtual reality** in future studies (Cochrane et al., 2020; Hanson et al., 2020) (e.g., www.igloovision.com)

real-world scenarios that otherwise could not be represented safely with other learning strategies. Conversely, these intense scenarios are more marketable compared to scenarios that may be less skills-based or represent a longer progression of a health condition. While biometrics has been incorporated to gauge stress in some acute scenarios, the evolution of HMDs (i.e. HP Reverb G2 Omnicept, Meta Quest Pro and Apple Vision Pro) have integrated stress monitors, eye and hand tracking and cognitive load algorithms that may be beneficial in quantifying the effect of the environments when developing critical thinking.

4.2.3. Time

The duration of the virtual scenario significantly impacts the learning experience (Chang et al., 2022), with an intervention of less than four-weeks suggested to lack statistically significant changes in critical thinking (Brudvig et al., 2013). While a limited time in the virtual environments may be consistent to acute trauma scenarios, the short exposure duration in most of the included studies underrepresents conventional face-to-face practical sessions and does not facilitate the development of critical thinking over a semester. Two studies that allowed students unlimited time to explore the environments (Birt and Cowling, 2017; Kenngott et al., 2021) reported that mMR provided critical thinking benefits; however, this was not quantified as it was not directly measured.

The inclusion of pre-brief and debrief are encouraged in the included studies for environment and equipment familiarisation, focus on key learning tasks, and reflection on learning.

4.2.4. Co-design

There was an apparent lack of designing tools and scenarios ‘with’ students, despite two studies suggesting the inclusion of co-design of virtual environments for improved student engagement (McCoy et al., 2016; Ramakrishnan et al., 2020). The term ‘co-design’ has gained attention in educational practice and research as it enhances active collaborative engagement, and creativity and minimises technology-enhanced learning (TEL) failure rates (Bovill, 2020; Könings et al., 2021; Treasure-Jones and Joynes, 2018). The process of co-design provides motivation for learning where students develop their ideas with an intent in something meaningful with others (Wagner, 2012; Wright, 2012). By starting with co-design, learners begin with curiosity as they discern the required knowledge with knowledgeable others (Thomas et al., 2014), allowing students to engage with others in a community of practice (Nicolini et al., 2016).

4.3. Critical thinking

Recent scoping reviews have identified (i) that due to the breadth of multiple definitions, the term ‘critical thinking’ is not well defined in health, and (ii) a high level of heterogeneity in the use, development, and measure of critical thinking (Berg et al., 2021; Havola et al., 2020). While all ten studies referred to critical thinking, only two studies included valid measures (Collins and Ditzel, 2021; Hanson et al., 2020). The term “critical thinking” in health has been synonymously aligned with clinical judgement, clinical reasoning, and decision-making (Griffits et al., 2023). Victor-Chmil (2013) suggests that ‘critical thinking’ is a cognitive process that analyses knowledge, ‘clinical reasoning’ extends this to the context of a clinical situation, while ‘clinical judgement’ is the cognitive, psychomotor, and affective processes demonstrated in both action and behaviour. Some have suggested that critical thinking is only one process employed when making decisions (Carter et al., 2015; Jans et al., 2023)- leaving a clear definition for ‘critical thinking’ unresolved.

Studies in this review utilised the Satisfaction with Simulation Experience Scale (SSES) and Lasater Clinical Judgement Rubric (LCJR), which have been identified as measures of critical thinking in previous studies (Theobald et al., 2021). Critical thinking has been measured in other healthcare simulation literature, not specific to mixed reality using the California Critical Thinking Dispositional Inventory (CCTDI) (Doğan and Şendir, 2022; Ka Ling et al., 2021; Weiler et al., 2018), Health Science Reasoning Test (HSRT) (Allaire, 2015; Blakeslee, 2020; Shinnick and Woo, 2013), Script Concordance Tests (Blanié et al., 2020; Mutter et al., 2020), Nursing Reasoning Scale (Hu et al., 2021; Johnston, 2019), and Yoon's Critical Thinking Disposition (YCTD) Tool (Shin et al., 2015). Other than Allaire (2015), these studies focused on nursing cohorts with generalisability to other allied health professions yet to be explored.

5. Limitations

This review identifies several limitations including diversity of health disciplines, a focus on emergency and critical response scenarios, limited exposure time in the mixed reality environment, poor utilisation of valid measures to quantify the effect on critical thinking, and studies limited to developed countries.

Overall, studies did not adequately identify how the design of the intervention was pedagogically informed. John et al. (2022) suggested that pedagogy should be embodied in the design when integrating mixed reality for education with scaffolded learning and learner accessibility by including flexibility in choosing and adapting the environment through co-design.

6. Conclusions

Advances in the ubiquity and accessibility of mobile mixed reality have enabled the technology to supplement critical thinking and authentic learning for nursing and healthcare education. This review provides insight into the current state of the art and highlights the beneficial affordances and design principles for developing mMR to facilitate critical thinking.

The potential for mMR in nursing and healthcare education is considerable. However, further research is needed to determine the pedagogical benefits of this innovative approach to learning. It is recommended that future studies include valid and reliable measures of critical thinking, consider comparisons between student cohort groups and across disciplines, and include co-design with students across a variety of nursing and healthcare scenarios and environments to stimulate critical thinking.

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CRediT authorship contribution statement

Todd Stretton: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Thomas Cochrane:** Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Charles Sevigny:** Formal analysis, Writing – original draft, Writing – review & editing. **Joseph (Yossi) Rathner:** Formal analysis, Writing – original draft.

Declaration of competing interest

None.

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Appendix A. Systematic review search strings

	Search string	Hits after filtering on language						
		AMED	Cochrane	ERIC	Medline	PsychINFO	SCOPUS	Web of Science
P	health* OR medic* OR surg* OR physiotherap* OR "physical therap*" OR "occupational therap*" OR podiatr* OR nurs* OR "oral health" OR dentis* OR dental OR midwif* OR paramed* OR "perioperative practice" OR anaesthe* OR anesthe* OR counsel* OR psycholog* OR psychotherap* OR pharmac* OR well-being OR wellbeing OR "well-being"	214,353	1,188,277	336,527	14,661,858	2,226,220	16,786,687	20,565,756
P	educat* OR universit* OR undergrad* OR learn* OR teach* OR train* OR lectur* OR pedagog* OR andragog* OR heutagog* OR instruct*	57,526	325,234	1,626,126	2,614,052	1,803,782	7,694,171	33,867,419
I	mLearn* OR "m-learn*" OR "m Learn*" OR "ubiquitous learn*" OR U-learn* OR "U learn*" OR "u-learn*" OR "mobile" OR "cellphone" OR "cell-phone" OR "cell phone" OR "smartphone" OR "smart-phone" OR "smart phone" OR "smart device" OR tablet OR iPad OR Android OR iOS OR headset OR "head set" OR "head-set" OR handheld OR "hand-held" OR "hand held" OR "head mounted display*" OR "head-mounted display*" OR "HMD"	4278	1152	789	11,128	1830	62,504	63,465
I	"Mixed realit*" OR "virtual realit*" OR "virtual space*" OR "virtual world*" OR "virtual environment*" OR "extended realit*" OR "immersive realit*" OR "immersive environment*" OR "augmented realit*" OR simulat* OR gamif* OR "emerging technolog*" OR "education* technolog*" OR "human computer interface*" OR "technology enhanced learning" OR "technology enabled learning" OR "learning technolog*"	4516	30,928	32,475	797,782	102,635	5,473,481	4,052,940
O	"high order" OR "higher order" OR "higher-order" OR "critical-thinking" OR "critical reasoning" OR "critically reason" OR "decision-making" OR "decision making" OR "problem-solving" OR "problem-solve" OR "problem solving" OR "problem solve" OR design* OR "clinical reasoning" OR "clinically reason" OR diagnos*	12,551	94,021	277,514	1,075,077	536,053	4,159,493	2,726,169
		4	**15**	**127**	**440**	**136**	**1317**	**1417**

Appendix B. Excluded full text reviewed articles

Authors (year)	Article details	Reason for exclusion
Cochrane et al. (2019)	Developing a mobile immersive reality framework for enhanced simulation training: Mesh360. Personalised Learning. Diverse Goals. One Heart. ASCILITE 2019, Singapore University of Social Sciences, Singapore. doi:10.1109/TALE.2018.8615124	**Results integrated into included study** (Cochrane et al., 2020)
Cochrane et al. (2017)	Developing virtual collaborative health team educational environments. Me, Us, IT! Proceedings ASCILITE2017: 34th International Conference on Innovation, Practice and Research in the Use of Educational Technologies in Tertiary Education, University of Southern Queensland, Toowoomba, Australia.	**Results integrated into included study** (Cochrane et al., 2020)
Cochrane et al. (2018b)	Authentic interprofessional health education scenarios using mobile VR. *Research in Learning Technology, 26*, Article 2130. doi:10.25304/rlt.v26.2130	**Results integrated into included study** (Cochrane et al., 2020)
De Lima et al. (2016)	A 3D serious game for medical students training in clinical cases. 2016 IEEE International Conference on Serious Games and Applications for Health (SeGAH), Orlando, FL. doi:10.1109/SeGAH.2016.7586255	**H/E: Medical Students- no data collected.**

(*continued on next page*)

(*continued*)

Authors (year)	Article details	Reason for exclusion
		MR: AR CTS: "decision making"
Guze (2015)	Using Technology to Meet the Challenges of Medical Education. *Transactions of the American Clinical and Climatological Association, 126*, 260–270.	H/E: Medical Students **MR: Not specifically MR** **CTS: No- not measured (review)**
Harrington et al. (2018)	Development and evaluation of a trauma decision-making simulator in Oculus virtual reality. *American Journal of Surgery, 215*(1), 42–47. doi:10.1016/j.amjsurg.2017.02.011	**H/E: No- not Undergraduate (life support course)** MR: VR CTS: No- decision making (correct decisions, response time)
Perez-Cabezas et al. (2019)	A Formative Experience in Reality Augmented with Physiotherapy Degree Students. *11th International Conference on Education and New Learning Technologies (EDULEARN)*. Palma, SPAIN. doi:10.21125/edulearn.2019.0775	H/E: Physiotherapy Students MR: AR **CTS: No- not measured (focus on student satisfaction)**
Salgado et al. (2018)	Development of a VR Simulator Prototype for Myocardial Infarction Treatment Training. *Advances in Intelligent Systems and Computing* 12th International Conference on Interactive Mobile Communication Technologies and Learning (IMCL), Hamilton, Canada. doi:10.1007/978-3-030-11,434-3_17	**H/E: No- prototype testing** MR: VR **CTS: No- not measured (focus on design)**
Schneidereith (2015)	Seeing through Google Glass: Using an innovative technology to improve medication safety behaviors in undergraduate nursing students. *Nursing Education Perspectives, 36*(5), 337–339. doi:10.5480/15-1653	H/E: Nursing Students (drug calculation) MR: AR (Google Glass) vs Manikin **CTS: No- not measured (focus on design)**
Smith and Friel (2021)	Development and use of augmented reality models to teach medicinal chemistry. *Currents in Pharmacy Teaching and Learning, 13*(8), 1010–1017. doi:10.1016/j.cptl.2021.06.008	H/E: Pharmacology Students MR: AR (on mobile phones) **CTS: No- not measured (focus on design)**
Stretton et al. (2018)	Exploring mobile mixed reality in healthcare higher education: A systematic review. *Research in Learning Technology, 26*, Article 2131. doi:10.25304/rlt.v26.2131	H/E: Multiple MR: VR and AR **CTS: No- not measured.**
Vaughn et al. (2016)	Piloting augmented reality technology to enhance realism in clinical simulation. *CIN - Computers Informatics Nursing, 34*(9), 402–405. doi:10.1097/CIN.0000000000000251	H/E: Nursing Students MR: AR (Google Glass) **CTS: No- not measured (focus on design)**
Wirza et al. (2020)	Augmented Reality Interface for Complex Anatomy Learning in the Central Nervous System: A Systematic Review. *Journal of Healthcare Engineering, 2020*, Article 8,835,544. doi:10.1155/2020/8835544	H/E: Anatomy MR: AR **CTS: No- not measured (review of available AR applications)**

Appendix C. Quality evaluation of included studies using the mixed methods appraisal tool (MMAT)- version 2018

	Qualitative Studies (QS)					Randomised Controlled Trial (RCT)					Quantitative Non-Randomised Trial (NRT)					Quantitative Descriptive Studies (DS)					Mixed Methods (MM)				
	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
Alverson et al. (2004)																Y	Y	Y	C	Y					
Birt and Cowling (2017)	Y	Y	Y	Y	Y																				
Cochrane et al. (2020)	Y	Y	Y	N	Y											Y	Y	N	Y	C	Y	Y	Y	Y	Y
Collins and Ditzel (2021)	Y	Y	Y	C	Y											Y	Y	Y	Y	C	Y	Y	Y	Y	Y
Hanson et al. (2020)											Y	Y	Y	Y	Y										
Kenngott et al. (2021)											Y	Y	Y	Y	Y										
Mäkinen et al. (2020)	Y	Y	Y	Y	Y																				
McCoy et al. (2016)																Y	Y	Y	Y	Y					
Ramakrishnan et al. (2020)	N	N	N	N	N																				
Sararit et al. (2018)											Y	Y	Y	Y	Y										
Yu et al. (2021)											Y	Y	Y	Y	Y										
Zackoff et al. (2020)						Y	Y	Y	Y	Y															

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