THE FUTURE OF

XR TECHNOLOGY IN HEALTHCARE SIMULATION

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SSH
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EXECUTIVE SUMMARY

The Society for Simulation in Healthcare (SSH) commissioned the Future of XR Technology in Healthcare Simulation white paper. Experts initiated writing the white paper at the 2024 IMSH conference, following a focused meeting to discuss existing, evolving, and emerging XR technologies. They synthesized their observations and offered recommendations on the state of the science and the future of XR technologies.

The purpose of this white paper is to help inform educators on what is coming next and help guide innovators on how to build tools that will help advance education and ensure patient safety. The guiding document intends to influence the development and use with future recommendations for XR technologies, the promulgation of use, technology standards and future research.

The white paper is built on the following sections:

- **Section 1 - Technology Description:** Extended Reality (XR) serves as an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), each offering varying levels of immersion and interaction between the physical and digital worlds. These technologies enhance healthcare education by providing dynamic, multi-sensory experiences individualized to learning needs. XR technologies face challenges such as inconsistent definitions, rapidly evolving hardware, and the need for standardized frameworks.

- **Section 2 - Current State:** XR technologies are increasingly critical to healthcare education, offering immersive training experiences that range from procedural skills to interprofessional collaboration. The white paper emphasizes standards and best practices, understanding cognitive load management, and curricular alignment. Challenges like accessibility, cost, and required technical expertise need addressing to support sustainable adoption.

- **Section 3 - Future State:** The future of XR is to have an increased realism and the integration of AI and haptics in pursuit of immersive, impactful training. Overcoming hardware challenges around ergonomics and minimizing cognitive overload with intuitive interfaces will help improve user comfort and engagement levels. This mix of synchronous and asynchronous interactions and AI-aided personalized feedback, along with accessibility and scalability, opens doors for new avenues in healthcare education that are more inclusive and productive.

  The strategic areas of focus include:
  - Enhancing Realism and Immersion: Technological advancements should aim to increase the realism of XR simulations, including improved ergonomics and simulating natural physics such as gravity.
  - Managing Cognitive Load: Simplified and intuitive designs can reduce cognitive strain and optimize the user experience.
  - Integrating Haptics and AI: Enhanced haptic feedback and real time AI-driven adaptability can personalize learning, making XR more effective for training needs.
  - Addressing Accessibility and Equity: Future developments must prioritize inclusivity, ensuring XR is accessible for all users, including those with disabilities and limited connectivity.

- Promoting Cost-Effectiveness and Scalability: Reducing costs and ensuring scalability will facilitate broader adoption of XR in healthcare training.
- Fostering Collaboration and Research: Cross-disciplinary partnerships between healthcare, technology, and academia are essential for advancing XR in simulation, in addition to rigorous research to assess the long-term effects of XR on learning outcomes and patient care.

Conclusion:
The proposed white paper will serve as a foundational document that influences and guides research and development efforts and encourages implementating XR solutions in healthcare education.

Section 1: TECHNOLOGY DESCRIPTION

Technology Taxonomy (XR)

Extended Reality (XR) is an umbrella term that describes multiple subdomains or classifications of reality and various classifications of immersive technology (Khan & Lippert, 2022; Li & Keskitalo, 2022; Stefandis et al., 2024). XR includes virtual reality (VR), augmented reality (AR), and mixed reality (MR). These subsets focus on how each of the technologies interact with the real and virtual worlds. The differentiation between them is based on the degree of immersion and the perception of the user's experience interfacing with the reality-virtuality continuum (Milgram & Kishino, 1994).

Definitions

The XR taxonomy provides a framework for understanding various immersive technologies, yet due to the rapid evolution of the field, definitions for each modality remain inconsistent. Spiegel et al. (2024) highlight the lack of a common taxonomy within the construct, leaving definitions for each modality unstandardized. The ongoing challenge is determining how potential synergistic modalities can be defined and integrated into existing categories.

To provide some context, general definitions are summarized from the literature in Table 1. However, this is only one way these can be defined. For the purposes of this paper, the definitions used in this paper are included in Table 1.

Table 1. Summarized Definitions of Reality Modalities

Term	Definition
Augmented Reality (AR)	Augments the real physical world with computer generated three-dimensional (3D) virtual objects (Fitria, 2023).
Mixed Reality (MR)	MR combines VR and AR to provide a new environment that synergizes interactions between virtual and real worlds in real time (Kang & Lee, 2023).
Virtual Reality (VR)	Displays a virtual environment as if they are in the real world (Fitria, 2023). Full immersion into a new environment.
Extended Reality (XR)	Overarching term for the integration of other types of reality (AR, MR, VR) creating a new digital world for the user (Chuah, 2019).

Desktop or immersive VR (IVR) further distinguishes VR. Desktop VR lets users interact with a 3D world displayed on a computer screen (Choi et al., 2021; Mendez et al., 2020; Shorey & Ng, 2021). In contrast, IVR offers an advanced, first-person, 3D, computer-generated version of the physical world (Aebersold & Dunbar, 2021; Choi et al., 2021; Cieslowski et al., 2023a; Harmon, 2021; Kyaw et al., 2019; Lau, 2023; Mendez et al., 2020; Shorey & Ng, 2021).

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Further, IVR supports multiuser interactions, utilizes headset and hand control technologies, incorporates sensory inputs, and facilitates personalized learning experiences (Aebersold & Dunbar, 2021; Choi et al., 2021; Cieslowski et al., 2023a; Harmon, 2021; Kyaw et al., 2019; Lau, 2023; Mendez et al., 2020; Shorey & Ng, 2021). The rapid evolution of these technologies often introduces advancements faster than research can fully capture or evaluate, underscoring the challenge of maintaining up to date evidence.

Technical Standards for Products

As XR technologies advance rapidly to support multiuser interactions, sensory integration, and personalized learning, establishing clear technical standards becomes increasingly important. These standards guide the implementation of XR in healthcare education, ensuring that the tools used are effective, safe, and adaptable to various educational settings (Willett et al., 2024). The following section explores the specific hardware and software requirements essential for reliable, immersive learning experiences within healthcare curricula.

Hardware for XR includes head-mounted displays (HMDs), which can be tethered or untethered. Tethered HMDs, connected to external personal computers or consoles, offer higher processing power, superior graphics quality, and lower latency but are less mobile and have a complex setup. They can also be significantly more expensive, making scalability a consideration. Untethered HMDs provide greater mobility and ease of use, making them suitable for various training environments. However, they may have lower processing power, higher latency, and limited battery life (Willett et.al. 2024). Reliable high-speed internet access and product support are essential considerations, as some HMDs run applications using high-speed computers, while others operate locally or use cloud-stored content (Helou et al., 2023).

When comparing XR software for healthcare education, it is crucial to consider applications, user interfaces, and support for moderated versus asynchronous learning environments (Takec et al., 2021). Software platforms range from custom-developed applications to third-party products. Key factors include the nature of immersive experiences (asynchronous or moderated), the ability to create and customize scenarios, content accessibility for users without headsets, and appropriate haptic feedback (Kluge et al., 2022). Additionally, the method of accessing content on the HMD, whether through direct download, computer connections, or mobile device management (MDM) systems, is an important consideration (Sung et al., 2024).

Hardware Components

An XR system's primary interface is the display system, typically an HMD that uses high-resolution Organic Light light-emitting diode (OLED) or Liquid Crystal Display (LCD) panels for visual output (Barteit et al., 2021). In AR systems, transparent displays overlay digital content onto the real-world view. Lenses create a stereoscopic 3D effect by aligning the visual output with the user's eyes. The computing platform supports the HMD and input devices, which process the visual rendering, physics simulations, and game logic in real time.

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HMDs can be physically tethered to a high-performance computing system for advanced rendering and processing capabilities. They can also handle the processing on the headset itself, maximizing portability while sacrificing visual fidelity (Bailey et al., 2022).

Sensors can be used to track user movements and positions and capture information about the physical environment. The Inertial Measurement Unit (IMU), typically seen in HMDs, consists of an accelerometer, gyroscope, and magnetometer, which tracks head orientation and movement. The accelerometer measures linear motion, the gyroscope detects rotational motion, and the magnetometer helps maintain orientation. These systems provide varying Degrees of Freedom (DoF), with most supporting six DoF and allowing users to move in three-dimensional space (up/down, forward/backward, left/right) and rotate around three axes (pitch, yaw, and roll) (Varjo, n.d.). Positional tracking can use inside-out (HMD-associated) and/or outside-in (external base station) sensors (Pimax, n.d.). Eye tracking uses infrared sensors or cameras to monitor the movement and position of the user's eyes, enabling interaction and optimizing rendering based on where the user is looking (Stein et al., 2021).

Input devices, primarily hand-held controllers, combine buttons, joysticks, triggers, and motion sensors to enable interaction with virtual environments (Kreimeier et al., 2019). These controllers typically offer 6 DoF tracking for full spatial interaction, often with haptic feedback to simulate physical sensations. Wand-like controllers with touchpads or buttons are also standard for precise tasks like pointing or drawing. Hand tracking is becoming more popular, eliminating the need for controllers by using sensors to track hand and finger movements directly, enabling natural gestures (Masurovsky et al., 2020). Gesture recognition enhances input by interpreting specific hand movements (e.g., pinching or swiping) as commands.

Software Components

Two primary categories of software exist for XR: mobile and desktop. Mobile XR headsets typically run on customized versions of the Android operating system (Android, n.d.), tailored specifically to each device. An exception to this is the Apple Vision Pro, which operates on Apple's proprietary visionOS (Apple, n.d.). Applications for mobile XR are installed as Application Packages (APKs), either downloaded from an application (app) store or sideloaded directly onto the headset in debug mode. These mobile headsets are generally called "all-in-one" or "non-tethered" devices, offering portability and ease of use.

In contrast, desktop or tethered systems rely on VR headsets that are physically connected to a desktop computer, which handles the processing of graphics, tracking, and other tasks. The headset itself functions purely as a display. This configuration enables more complex and performance-intensive applications in XR but comes with the drawback of limited mobility due to the physical tether. Users need to be mindful of the tether cable to avoid entanglement or damage, especially in larger interaction spaces. The two most common software platforms for tethered systems are SteamVR by Valve (Valve Corporation, n.d.) and Meta's desktop software (Meta, n.d).

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Augmented Reality (AR) applications running on mobile phones typically use Android (Android, n.d.) or Apple iOS (Apple, n.d.) platforms. For these applications, the necessary sensors and proper device configuration are required, and AR implementation can vary widely across different devices.

Software Standards

OpenXR (The Khronos Group, n.d.) is a standard Application Programmable Interface (API) that can create cross-platform applications easily and quickly. This open-source API provides a single interface for developers to port applications between different headsets. OpenXR translates controller schemes, tracking data, device states, and more through a single API layer, eliminating the need to develop separate solutions for each proprietary headset (The Khronos Group, n.d.).

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With foundational hardware and software standards established, XR technologies are increasingly central to simulation-based education (SBE), from procedural training to interprofessional applications (Brown et al., 2023b; Mathew & Pillai, 2020). As XR continues to evolve, considerations like cognitive load, user-friendly design, curricular alignment and best practice are essential to optimizing educational impact. These developments highlight XR's adaptability, supporting immersive training across diverse disciplines.

XR has been proposed as a modality for SBE for various content areas, tasks, and competencies (Khan & Lippert, 2022; Mathew & Pillai, 2020). For example, XR may support procedural skill development and evaluation (Mathew & Pillai, 2020). Authors have described the integration of XR across multiple programs (Brown et al., 2023b) and for specific course development such as anatomy/physiology (Anderson et al., 2022; Curran et al., 2023; Herur-Raman et al., 2021) and communication (Herur-Raman et al., 2021) as well as specific content areas such as cardiovascular disorders (Anderson et al., 2022). Surgical and other types of training may also occur via this methodology (Stefandis et al., 2024). Further, XR has been used to implement clinical practice opportunities that may be difficult to deliver, such as interprofessional education (IPE) simulations or specialties such as pediatrics (Brown et al., 2023a; Cieslowski et al., 2023b). However, this is only a small sampling of where XR may be incorporated.

Managing Cognitive Load in Extended Reality (XR)
Cognitive load refers to the mental effort required to process information and perform tasks (Brazil, 2023). The complexity of the task influences it, the individual's prior knowledge and experience, and the available cognitive resources.

Opinions and evidence on cognitive load vary across different XR modalities. XR can reduce cognitive load by enhancing audio-visual learning, allowing learners to focus on listening and viewing rather than reading and interpreting text (Edward, 2022; PwC, 2020). However, high engagement, informational overload, and unfamiliarity with virtual elements can lead to cognitive overload and acute stress (Brunzini et al., 2022). Evidence suggests that XR's technical complexity and novelty may increase extraneous cognitive load, which is the unnecessary cognitive load imposed by instructional design or environmental factors. Buchner et al. (2021) found that AR glasses can unnecessarily increase cognitive load. Andersen et al. (2016) showed that adding task trainer-based problem completion exercises in VR significantly increased cognitive load and lowered performance, highlighting the need to control extraneous load when using new technology.

Several measures can mitigate cognitive load in XR-based simulations. Intrinsic load, which is the inherent difficulty of the task itself, can be managed by teaching supporting knowledge separately from procedural steps (Nguyen & Clark, 2005). They are sequencing facts, concepts, and principles before procedural tasks can improve instructional efficiency. Avoiding redundant content expressions minimizes extraneous cognitive load. Learners perform better with multimedia lessons containing only animation and audio narration compared to those with added redundant text (Mayer et al., 2001; Moreno & Mayer, 2002). Implementing XR in healthcare education requires strategies to manage cognitive load effectively, ensuring optimal learning outcomes and user experience.

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When designing XR simulations for healthcare education, it is essential to consider the cognitive load imposed on learners. For example, complex tasks can be broken down into smaller, more manageable steps to manage intrinsic load (Nguyen & Clark, 2005). The extraneous load can be minimized by ensuring the XR environment is intuitive and user-friendly, thus avoiding unnecessary cognitive strain (Buchner et al., 2021, & Nguyen & Clark, 2005). A focus can be on optimizing germane load, which is the desirable cognitive load that facilitates learning and skills acquisition, by providing relevant feedback and guidance that supports learning (Nguyen & Clark, 2005, & Andersen et al., 2016). In addition, content relevance can be prioritized to align closely with curriculum and learning goals, user interfaces to reduce cognitive overload can be simplified and training offered to faculty and learners on effectively using XR technology.

XR and Healthcare Simulation Standards of Best Practice® (HSSOBP®)

To ensure the effective use of XR technologies in healthcare simulation, standards should mandate regular professional development for facilitators (INACSL Standards Committee, Hallmark, et al., 2021). This includes training specifically focused on XR technologies, as well as broader education on simulation principles and best practices. Facilitators should be encouraged to participate in professional development workshops, webinars, and conferences to stay current with the latest advancements in XR technology.

Familiarity with the technology enables facilitators to troubleshoot issues as they arise during training sessions. Spending time in the virtual environment helps facilitators gain a deeper appreciation for the challenges and complexities of the simulation, which can enhance their ability to support and guide learners through the experience. This can lead to more effective debriefing sessions, as facilitators can relate to the learner's experiences. The concept of debriefing virtual learning is unique as the facilitator may not witness the SBE and debriefing may be asynchronous. However, as Verkuyl et al. (2018) note, having a reflective debriefing design that promotes learning is the end goal of any SBE.

Modality Selection

Integrating XR with HSSOBP® ensures that technology use is purposeful and aligned with high-quality simulation outcomes, guided by trained facilitators and appropriate modality selection. Correct modality selection is an integral part of simulation design, and it must align with and support pre-developed simulation objectives (INACSL Standards Committee, Watts et al., 2021). Prior to selecting a modality, a needs assessment must take place (Willett et al., 2024). When selecting XR approaches, it is essential to assess the benefits and drawbacks of employing the technologies (Foronda et al., 2024).

XR offers flexibility that other simulation modalities may not offer (Logeswaran et al., 2021). Benefits may include increased immersion (Brunzini et al., 2021; Fealy et al., 2023; Herur-Raman et al., 2021; Willett et al., 2024) and instantaneous feedback, amongst others (Herur-Raman et al., 2021; Li & Keskitalo, 2022). XR also can reach multiple user senses, e.g., visual and tactile (Lee et al., 2021).

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While some may need to learn how to start (Meccawy, 2022), authors have outlined specific considerations for such technologies when choosing a product, such as VR (Justice et al., 2023). In a supplement to their article, Willett et al. (2024) provide a checklist to evaluate VR software to help with selection. As XR technologies advance, such checklists and guidelines will be helpful. It is important to remember that this is an ongoing process, as keeping these up to date may be a challenge, as changes to the technologies occur frequently.

Stakeholder input prior to purchasing XR hardware and software should not be overlooked (Leitenbauer et al., 2023). This should include input from all the targeted users, including the facilitators and learners, as well as technology operations specialists (Leitenbauer et al., 2023). For maximum integration to occur, time should be given to this imperative step of eliciting input.

Guidelines For Design of XR Simulations

SBE effectively bridges the gap between theoretical knowledge and practical application (Elshamaa, 2020). Integrating XR technologies, such as AR and VR, into SBE provides a multimodal experience that enhances realism, immersion, interaction, and performance (Adhikari et al., 2021; Handali et al., 2021). However, the absence of a comprehensive pedagogical framework can limit the optimal use of XR technology.

Aligning simulation design with XR technology is essential to enhancing immersion and multisensory interaction. This alignment creates a harmonious relationship that boosts engagement and enhances learning outcomes. Brunzini et al. (2021) proposed a simulation design framework integrating simulation design components with XR prototypes adaptable to various simulation modalities.

The design process begins with defining learning goals and structuring the simulation environment, including location, layout, and embedded participants, to enhance realism (Almousa et al., 2019; Lipp et al., 2023). The framework also involves specifying tasks and feedback, incorporating tactile sensations, holograms, and virtual monitors to influence user interaction and psychological response (Lelevé et al., 2020). By aligning simulation design with suitable XR technologies, such as hardware and software elements, educators can create realistic training environments that enhance user experience and real-time interactivity (Gani et al., 2022; Sainsbury et al., 2020).

Curricular Integration - Fit into Curriculum

As with any simulation modality, a theoretical framework should guide the curriculum integration of XR technologies. Brown et al. (2023b) describe the design of a VR curriculum guided by concepts of deliberate practice (Ericsson, 2008) and the use of the National League for Nursing (NLN) Jeffries Simulation Theory (Jeffries, 2021). When considering the curricular integration of XR technology into a simulation program, the process may be affected by costs, buy-in, training, mapping, technical aspects, and design. In addition, educators should consider multiple policies and procedures when incorporating XR technologies into the curriculum.

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Costs

Costs may be a challenge when integrating XR technologies (Li & Keskitalo, 2022) but may be less than other forms of simulation (Curran et al., 2023; Stefandis et al., 2024; Willett et al., 2024). However, the frequency of technology updates may affect the overall cost, and continued funds may be required (Draschkow et al., 2023). Additional items that should be considered include personnel-related items such as time (Meccawy, 2022). However, costs related to these technologies need further exploration (Foronda et al., 2024; Stefandis et al., 2024).

Buy-in

In addition to the cost of some products, there may be a significant learning curve (Meccawy, 2022) and hesitancy to use new products in many cases. The technology associated with the XR platform can be intimidating and frustrating when it does not always work according to plan. As with any new platform for educating healthcare professionals, utilizing a change model offers a structured approach with a framework to consider essential elements necessary for initiating and maintaining change (Harrison et al., 2021). Having early adopters (Kotter, 2024) as the initial users can help attract others to adopt the utilization of the product and share the experience enthusiastically with learners at all levels. Additionally, appropriate training may facilitate integration.

Training

As with any simulation modality, training is imperative for maximum curricular integration and implementation (INACSL Standards, Hallmark et al., 2021). Providing faculty or facilitator training may facilitate the incorporation of XR technologies (Mitsch & Liu, 2023). However, researchers found limited literature discussing faculty or facilitator training for healthcare professionals. Some universities developed training programs for facilitators and moderators to expose and prepare faculty and adjuncts to the modalities of XR in the absence of external opportunities.

Mapping

The objectives and outcomes need to be considered, along with a needs assessment (INACSL Standards Committee et al., 2021), to ensure the simulation appropriately aligns with the curricular goals. Educational organizations, e.g., the National League for Nursing (NLN), have offered toolkits to help integrate such technologies (Justice et al., 2023; Willett et al., 2024).

Technical Aspects

When considering XR technologies, the frequency of new types of hardware on the market needs to be contemplated (Draschkow et al., 2023). Technical expertise needed for the devices and software should also be determined (Meccawy, 2022).

Design

There are a multitude of XR products, including hardware and software, on the market. Designing XR simulations requires a specific skill set that offers additional challenges (Draschkow, 2023; Meccawy, 2022). Some require more coding than others (Meccawy, 2022).

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Policies and Procedures

Multiple policies and procedures should be considered when integrating XR technologies. These may relate to side effects, accessibility, and security. Additionally, depending on the environment, whether in an academic or practice setting, these may be driven by committees, accreditation, quality and safety, and/or education departments.

Side Effects

Risks and side effects from use need to be conveyed to users and pose a significant integration challenge (Wild et al., 2024). In the academic setting, special syllabi language for XR technologies has been suggested, including possible side effects from utilization (Anderson et al., 2022). Specialized consent forms can also be considered; however, they may require legal review.

Accessibility

Many organizations, countries, states, etc. are focusing on the accessibility of simulation products so that all users can partake, and XR is no different. The Institute of Electrical and Electronics Engineers (IEEE) (2022) has cautioned that XR technologies may be particularly vulnerable to accessibility issues. Accessibility challenges can include, for example, making the technologies available to those with disabilities; however, it extends beyond this to others, such as distance learners (Wild et al., 2024). Needs for high connectivity may also pose accessibility challenges (Wild et al., 2024), along with body morphology, for example, head size, which may affect how an XR headset fits (Rupp et al., 2023).

While many of these issues need to be addressed by the developers (IEEE, 2022; Rupp et al., 2023; Wild et al., 2024), organizations should be cognizant of accessibility when choosing devices and products. Vendors should be asked about the accessibility of their products. More formalized processes may need to be developed by organizations acquiring XR technologies for accessibility review. Accessibility guidelines should be consulted (Rupp et al., 2023). Additionally, accessibility standards for such technologies are also needed, many of which are currently in development or anticipated (Wild et al., 2024). Simulationists should stay abreast of these.

Security

XR technologies raise security and privacy concerns, particularly regarding risks like cyberattacks and the handling of personal data in educational settings (Meccawy, 2022; Roesner & Kohno, 2021). These issues should be considered in the design, planning, and implementation phases (Gugenheimer et al., 2022).

Organizations should establish security policies through IT departments and advocate for regulations to protect user data (Meccawy, 2022; Draschkow et al., 2023). Developing policies to safeguard health information and seeking funding for XR initiatives are essential to ensuring privacy and fostering interprofessional collaboration between industry and researchers (McGrath, 2024; Draschkow et al., 2023).

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Implementation

HSSOBP® (INACSL Standards Committee, 2021) should be followed for XR technologies, as with any other simulation modality (Bradley et al., 2024; Justice et al., 2023; Willett et al., 2024). Specifically, authors have described using the standards to pilot AR technology prior to curricular integration (Anderson et al., 2021). Standards have also been outlined for curricular integration of VR technologies (Brown et al., 2023b).

Implementation and orientation of XR technologies in healthcare education have not been well described (Anderson et al., 2022; Díaz et al., Under Review; Logeswaran et al., 2021). While essential for user engagement, preparation has been lacking from discussion in many of the studies with XR (Cieslowski et al., 2023; Lee et al., 2021).

Orientation and preparation time may vary by the learner, but more time may be warranted with these technologies (Anderson et al., 2022; Cieslowski et al., 2023b; Kang et al., 2020, as cited in Kim et al., 2021). Learner frustration may occur during orientation (Anderson et al., 2022).

While authors have included pedagogical models for simulation facilitation that include XR technologies, such as VR (Keskitalo & Ruokamo, 2015), there may be differences in how facilitation occurs with this modality. A facilitation guide may be helpful (Brown et al., 2023b).

Device calibration with the learner's eyes is imperative to help protect against cybersickness (Anderson et al., 2022), which should be incorporated during the prebrief (Díaz et al., Under Review). Learners should have written and/or verbal instructions (Anderson et al., 2021; Anderson et al., 2022; Díaz et al., Under Review). Prebriefing should include the orientation to the environment (Brown et al., 2023a; Cieslowski et al., 2023b).

Evaluation

The effectiveness of simulation education using innovative XR technologies is multifactorial. Various factors should be taken into consideration, such as the learner needs and outcomes, if there are willing individuals to implement, and how easy (or not) the technology is to integrate (Buchner & Hofmann, 2022; Proserpio & Gioia, 2007; Rogers, 2003; Seufert et al., 2021; Straub, 2009 as cited in Mulders et al., 2020). Evaluation of the use of these immersive technologies can be focused on the learner or other measures like technology usage. Evaluation tools differ depending on the focus of the evaluation.

Evidence of Efficacy

A recent systematic review shows no substantiated evidence yet to support VR simulation over other traditional types of simulation for healthcare learners (Foronda et al., 2024). Other literature has demonstrated that XR simulations have at least the same outcomes as more established methods (Cieslowski et al., 2023b; Curran et al., 2023).

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The fact remains that XR modalities need further research, such as a comparison between different simulation methods, including against more traditional ones (Brunzini et al., 2021; Cieslowski et al., 2023b; Stefanidis et al., 2024; Foronda et al., 2024) or even to other standard teaching methods (Curran et al., 2023). Evaluation of the impact of such technologies is imperative (Curran et al., 2022). Additional outcomes, such as critical thinking, need to be evaluated (Kim et al., 2021). While trends and evaluation methods need further investigation (Khan & Lippert, 2022), higher levels of Kirkpatrick studies are also needed (Curran et al., 2023; Foronda et al., 2024; Stefandis et al., 2024), along with cost-effectiveness data of the modalities (Foronda et al., 2024). Accessibility testing research is also needed (Wild et al., 2024).

Gerup et al. (2019) describe AR and MR as disruptive technologies in medical education. Advances in computing power and interactive realism, along with reduced costs, have facilitated their rapid implementation, making these technologies more affordable than traditional simulators (Christopoulos et al., 2021; Schild et al., 2021; Xu et al., 2021). Surgical training, particularly for procedures like central line insertion, endotracheal intubation, and laparoscopy, is the most studied application of MR in medical education (Brunzini et al., 2022). Nonsurgical specialties are also beginning to use MR for procedural training and interprofessional communication (Brunzini et al., 2022; Schild et al., 2021).

Studies have shown that AR and MR can improve learning outcomes, including learner confidence, technical skills, performance, and spatial understanding of anatomy (Cieslowski et al., 2023b). However, they may increase cognitive load and cause side effects like motion sickness (Gerup et al., 2020; Xu et al., 2021). While evidence supporting the efficacy of AR and MR is growing, further research is needed to establish their impact on clinical practice and to optimize their use in medical education (Gerup et al., 2020; Xu et al., 2021).

Section 3: FUTURE STATE

The future of XR requires advancing realism and overcoming limitations that can introduce inadvertent errors, effectively applying haptics, balancing synchronous and asynchronous interactions, and integrating artificial intelligence (AI) into the user experience.

Realism and the Inadvertent Introduction of Error in the XR User Experience

In VR, accurately simulating Earth's gravity enhances realism and improves user engagement and satisfaction (La Scaleia, 2020; Mäkinen et al., 2023). When VR gravity closely mirrors real-world gravity, it allows users to interpret the environment naturally through visual and haptic cues, enhancing their motor performance and perceptual judgment (La Scaleia, 2020). This accurate representation of gravity contributes to a more authentic and effective learning experience by maintaining a sense of flow and natural motion, which keeps users fully engaged and motivated (Mäkinen et al., 2023).

In addition, ergonomic issues such as headset weight and balance pose challenges, specifically head-facial, muscle fatigue, and thermal regulation from prolonged use. Most of these challenges are hardware-related (Chen & Wu, 2023; Lau et al., 2023; Mäkinen et al., 2023; Saab et al., 2022;). The weight and fit of HMDs can create pressure points on the face and head due to their design and distribution, leading to discomfort (Lau et al., 2023; Mäkinen et al., 2023; Saab et al., 2022). If the headset is too heavy or not well-balanced, it can result in muscle fatigue and pain, particularly in the neck and shoulders. Further, the insulation effect of the HMD and the heat generated by its electronic components can cause thermal discomfort, trapping heat around the head (Chen & Wu, 2023). Moreover, AR/VR adaptations with hand controllers may lead to difficult hand positions or fatigue, challenging the user experience (Cieslowski et al., 2023b; Saab et al., 2022).

Beyond physical discomfort, cybersickness remains a common issue in VR. Visual ergonomics, such as latency and frame rate, contribute to cybersickness (Chen & Wu, 2023). The screen's proximity and display quality, including resolution and refresh rate, can cause visual fatigue. Poor image quality or improper display settings strain the eyes, especially when there is a mismatch between the visual input and the view the user expects. Software-related ergonomic issues focus on the visual and cognitive experience created by VR content (Chen & Wu, 2023). Latency, the delay in rendering graphics, and the frame rate of visual content can significantly affect user comfort. High latency can cause disorientation and motion sickness, while inconsistent or low frame rates may lead to flickering and visual discomfort (Chen & Wu, 2023).

Hardware and software-related factors can significantly impact the overall VR experience. Hardware-related issues concern the physical and visual aspects of wearing and using VR devices. In contrast, software-related issues affect the quality of the virtual experience and the mental demands placed on the user. Software requiring users to process excessive visual information or interfaces not aligning with natural human movements can overwhelm the user experience and increase the cognitive load (Chen & Wu, 2023; Saab et al., 2022).

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Future developments must address hardware and software limitations to improve XR. Hardware improvements should focus on reducing physical discomfort through better HMD design and weight distribution (Lau et al., 2023; Mäkinen et al., 2023; Saab et al., 2022). In addition, overcoming the adaptation required for hand controls would enhance the user experience. On the software side, enhancing realism, accurately modeling gravity, and creating intuitive interfaces can reduce cognitive load and prevent motion sickness (Chen & Wu, 2023). Creating a sense of flow where users feel fully immersed is crucial for effective learning and satisfaction in XR. Mimicking natural motions like gravity enhances authenticity and effectiveness (La Scaleia, 2020; Mäkinen et al., 2023). By addressing these challenges, XR technology can offer more immersive, comfortable, and compelling user experiences.

Synchronous and Asynchronous Interactions

The future of XR will involve leveraging synchronous and asynchronous methods of XR to maximize the benefits of each, providing a more dynamic and versatile learning environment. Asynchronous XR offers flexibility and scalability, allowing for self-paced learning and repeated practice through simulations (Kimura et al., 2023). However, modifications may be needed to ensure learner prebriefing, including orientation of technologies being utilized and considerations for altered debriefing techniques (Charnetski et al., 2024). In contrast, synchronous XR provides opportunities for collaborative learning, meaningful interactions, a sense of community, and immediate feedback, essential for skills-based education (Corvetto et al., 2024; Foronda et al., 2024). By integrating both approaches, XR can offer a comprehensive and effective learning experience that accommodates various educational and training needs.

Haptic in Interactive Technology Systems (XR)

The initial integration of haptics into healthcare interactive technology systems, such as XR, was primarily in surgical simulation tools (Gani et al., 2022; Thompson et al., 2010; Våpenstad et al., 2013). Haptic technology has advanced to include temperature, contact force, texture, vibration, softness, and weight, which can be experienced in interactive technology systems and applied in various training and entertainment fields. The integration of haptics into interactive technology systems has been occurring for over 30 years, yet it is still in its infancy (Wang et al., 2019).

A challenge with integrating haptics into interactive technology systems includes the additional weight and wiring that haptic technology may require. To overcome this challenge, Yu et al. (2019) explored the application of skin-integrated wireless haptics, which interface with interactive technology systems with positive findings. This advancement could impact education, sports, telerehabilitation, healthcare, and other fields.

As interactive technology systems and haptics continue to advance, integration into various fields brings unknown challenges and complications to light. Considerations need to be explored due to incompatibility due to cybersickness or other unidentified potential harm. Therefore, it is essential to understand the potential for negligence if standards of best practice and specific warnings are not developed (Lim et al., 2020). Farag and Hashem (2022) indicate that the benefits of haptic VR should be integrated with conventional techniques and not used as a replacement.

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Current Trends in AI-driven XR Healthcare Simulation

The role of AI in XR healthcare simulations is becoming increasingly sophisticated, leveraging various data points and analytical methods to enhance training. In the surgical setting, researchers primarily use kinematic data and video clips to assess eye movements, surgical movements such as incision and drilling patterns, tool movements, and adjectives that describe participant habits and characteristics (Lungu et al., 2021). These data points are crucial for evaluating performance and providing feedback (Ahmidi et al., 2010; Bissonette et al., 2019; Megali et al., 2006). This feedback can be further augmented to include the classification of learner level, such as beginner or expert, based on their performance using AI algorithms (Cote et al., 2020; Esteva et al., 2019). This classification helps tailor training programs to the individual needs of the learners, ensuring that each participant receives the appropriate level of challenge and support.

Customized learning plans can also be generated with AI assistance while participating in collaborative virtual learning environments. These personalized plans may be able to be adapted to understanding a learner's progress and areas of difficulty, to provide a more efficient and targeted learning experience (Chen et al., 2020; Khosravi et al., 2019; Nguyen et al., 2021).

AI-powered natural language processing (NLP) can be used to interpret and respond directly to verbal inputs from trainees (Kocaballi et al., 2019). This is particularly useful in training scenarios involving patient interviews and diagnostic questioning. Non-playable characters can generate spontaneous, applicable responses to learner questions to facilitate a more natural conversation pattern guided by the learner. These simulations provide realistic scenarios, preparing trainees for real-life patient and colleague interactions. In addition to Non-Player (or Playable) Character (NPC) patient interactions, AI in XR simulations can train multidisciplinary healthcare professionals in essential communication skills, including closed-loop communication, delivering bad news, and other "soft skills," as well as provide feedback on teamwork and communication. (Brown et al., 2023c; Tudor Car et al., 2020).

XR simulations powered by AI are extensively used in anatomy and physiology education. These simulations offer immersive, interactive experiences that enhance understanding and retention of complex anatomical and physiological concepts while allowing learners to literally "step inside" the structures they are studying (Bogomolova et al., 2020; Le et al., 2018; Maresky et al., 2019). Another specialty utilizing AI technology in XR environments is psychiatry. AI-driven XR simulations are used for psychiatric evaluations and treatments, such as Cognitive Behavioral Therapy (CBT) and the diagnosis of disorders like social anxiety disorder. These simulations provide a safe, reproducible, and controlled environment for both diagnosis and treatment practice (Gutiérrez-Maldonado et al., 2008).

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AI Gap Analysis and Future Directions

Despite significant advancements, many areas for conceivable growth should be expanded upon to realize AI's full potential in XR healthcare simulation training. There is a need for a better understanding of individual learner needs and mastery levels. Current models, as described above, most typically discern "expert" and "non-expert." AI systems must accurately assess and respond to the unique learning trajectories of each participant to better optimize learning at the individual level. In addition, the ability to augment simulation difficulty in real-time for more personalized instruction is currently limited.

Future developments should enhance AI's capacity to dynamically adjust simulations based on real-time data, providing instant feedback and tailored guidance (Baidoo-Anu & Owusu Ansah, 2023). Sources of this guidance have often been NPC (or voice personalities such as phone consultants) capable of expert healthcare professional advice, an ongoing development area that helps sustain high levels of immersion (Liaw et al., 2023). By allowing for real-time feedback during XR training, participants in less resource-rich areas in which professionals may not be available for facilitation of training would allow for high-level, efficient training (Pataranutaporn et al., 2021). Integrating AI in XR healthcare simulation training transforms education, offering immersive, personalized, and efficient learning experiences. By addressing the existing gaps and advancing AI technologies, the future of healthcare training promises even more significant improvements in preparing healthcare professionals for the complexities of care while ensuring patient safety.

The Future of Extended Reality

The future of XR in healthcare includes prioritizing several strategic goals to maximize its impact and potential. These include enhancing realism and immersion, managing cognitive load, integrating haptics and AI, addressing accessibility and equity, promoting cost-effectiveness and scalability, and fostering interdisciplinary and transdisciplinary collaboration and research.

Enhancing Realism and Immersion: Future advancements in XR technology should focus on increasing the realism of virtual experiences, such as accurately simulating natural physics like gravity, improving the ergonomics of hardware, and minimizing physical discomfort for users (La Scaleia, 2020; Mäkinen et al., 2023). These enhancements are essential for more engaging and effective learning environments.

Managing Cognitive Load: Efforts should be made to design XR systems that effectively manage cognitive load. This can be achieved by simplifying user interfaces, eliminating unnecessary content, and ensuring that XR simulations are intuitive and user-friendly, preventing cognitive overload (Nguyen & Clark, 2005).

Integrating Haptics and AI: The next phase of XR development should include improving haptic feedback to create more immersive and tactile experiences (Farag & Hashem, 2022). In addition, leveraging AI integration will personalize learning by dynamically adjusting the difficulty of simulations in real time, providing immediate feedback, and offering tailored guidance to learners (Chen et al., 2020; Khosravi et al., 2019; Nguyen et al., 2021).

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Addressing Accessibility and Equity: Future XR technologies must address accessibility issues, ensuring that they are inclusive for individuals with disabilities and can be integrated into various interprofessional settings, including those with limited resources or connectivity challenges (Wild et al., 2024).

Promoting Cost-Effectiveness and Scalability: XR technologies need to become more cost-effective and scalable to ensure broad adoption and cost-effective maintenance. This includes reducing hardware and software costs, ensuring the long-term sustainability of XR systems, and equipping education centers with the tools needed for effective curriculum integration.

Fostering Interdisciplinary and Transdisciplinary Collaboration and Research: Expanding collaboration between developers, healthcare professionals, and educational institutions is critical to ensuring that XR technologies effectively meet the practical demands of healthcare education and simulation. Moreover, continued research is essential to evaluate the long-term effects of XR on learning outcomes, patient care, and the cost-effectiveness of these immersive experiences.

By focusing on these initiatives, XR in healthcare can become more immersive, effective, accessible, and equitable enhancing the training of healthcare professionals and improving the quality of health care.

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