Research Matters / 37
A Cambridge University Press & Assessment publication

ISSN: 1755-6031

Journal homepage: https://www.cambridgeassessment.org.uk/our-research/all-published-resources/research-matters/

Extended Reality (XR) in mathematics assessment: A pedagogical vision

Xinyue Li (Cambridge Maths)

To cite this article: Li, X. (2024). Extended Reality (XR) in mathematics assessment: A pedagogical vision. *Research Matters: A Cambridge University Press & Assessment publication*, *37*, 6–23. https://doi.org/10.17863/CAM.106031

To link this article: https://www.cambridgeassessment.org.uk/Images/research-matters-37-extended-reality-xr-in-mathematics-assessment-a-pedagogical-vision.pdf

Abstract:
Extended reality (XR) – encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR) – emerges as a potential transformative tool in educational realms. This article explores the potential of XR in facilitating mathematics assessments; it proposes a list of mathematical topics that could be effectively mediated by XR's immersive and interactive features. Additionally, it discusses some major challenges which could be barriers to the widespread adoption of XR in educational contexts and sets out a research agenda for further investigation.

Extended Reality (XR) in mathematics assessment: A pedagogical vision

Xinyue Li (Cambridge Mathematics)

The year of 2023 saw a surge of interest in artificial intelligence (AI), with "Hallucinate" being named as Word of the Year 2023 by *Cambridge Dictionary* (Cambridge University Press & Assessment, n.d.), reflecting a growing curiosity about emerging technologies that have the potential to significantly alter human perception and experience (Li & Zaki, 2024). In particular, as stated in the *Futures of Assessment* report, advancements in technology are transforming assessment methods and the vision is that learners in 2050 may be immersed in an educational environment where augmented, virtual and hybrid technologies are comprehensively embedded in assessments (Abu Sitta et al., 2023). Against this background, extended reality (XR) – encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR) – emerges as a potential transformative tool in educational realms. This article explores the potential of XR in facilitating mathematics assessments; it proposes a list of mathematical topics that could be effectively mediated by XR's immersive and interactive features. Additionally, it discusses some major challenges which could be barriers to the widespread adoption of XR in educational contexts and sets out a research agenda for further investigation.

Definition of XR

Extended reality (XR) is "an emerging umbrella term for all the immersive technologies" (Marr, 2019). As the landscape of technological innovation continually evolves, defining XR remains a moving target (Palmas & Klinker, 2020). Currently, XR refers to established technologies including AR, VR, and MR (Lee, 2020), as well as those yet to be developed.

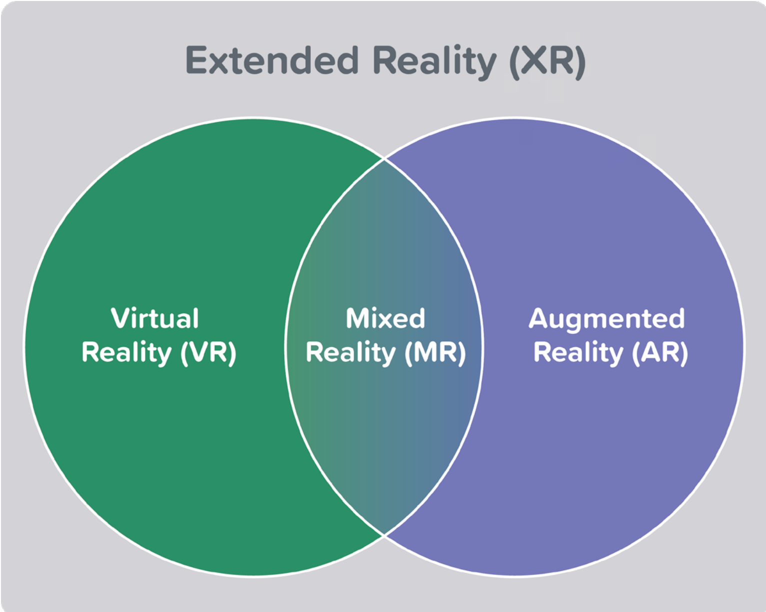

Figure 1: How VR, AR and MR intersect

Types and core features of XR

Virtual Reality

In the *Cambridge Academic Content Dictionary* (Cambridge University Press, 2017), virtual reality (VR) is defined as "a set of images and sounds produced by a computer that seem to represent a real place or situation"; therefore, VR "provides a computer-generated environment wherein the user can enter a virtual environment with a VR headset and interact with it" (Rokhsaritalemi et al., 2020, p. 1).

Augmented Reality

Augmented reality (AR) is a technology that enables the real-time integration of computer-generated virtual elements with either a direct or indirect view of the real world (Azuma, 1997; Lee, 2012). AR-based content can span multiple sensory modalities; for example, visual, auditory, haptic, etc. (Cipresso et al., 2018). While the lack of relation to real space is one of the characteristics of VR, AR presents a new method of visualisation that allows for the addition of computer-generated content to the real world (Rokhsaritalemi et al., 2020, p. 1).

Mixed Reality

The term mixed reality (MR) was introduced by Paul Milgram and Fumio Kishino in their paper "A Taxonomy of Mixed Reality Visual Displays" (1994). It can be understood as a blend of physical and digital worlds, which is based on "advancements in computer vision, graphical processing, display technologies, input systems, and cloud computing" (Microsoft, 2023).

Table 1 below summarises the core features of VR, AR, and MR.

Table 1: Comparison of VR, AR and MR (Developed from Jaquith, 2016; Li & Taber, 2022; Li & Zaki, 2024; McMillan et al., 2017; Rokhsaritalemi et al., 2020; Taber & Li, 2021.)

Features	Virtual Reality (VR)	Augmented Reality (AR)	Mixed Reality (MR)
Display device	Special headsets or glasses required in most situations	Special headsets are optional; can be viewed through a digital device (e.g., a smartphone, a tablet, etc.)	Special headsets are optional
Image source	Computer-generated graphics	Combination of computer-generated elements and real-life elements	Combination of computer-generated elements and real-life elements
Environment	Fully digital/virtual	Real-life and virtual elements are blended seamlessly	Real-life and virtual elements are blended seamlessly
Perspective	Virtual elements will change their position and size according to the user's perspective in the digital/virtual world	Virtual elements are experienced based on the user's perspective in the real world	Virtual elements are experienced based on the user's perspective in the real world
Presence	Feeling of being "transported" to a different location with no sense of the real world the user is in	The user remains aware of the real world, with virtual elements added to their view	The user feels present in the real world with superimposed virtual elements
Awareness	The user cannot see elements of the real world while immersed in VR	The user can identify virtual elements based on their nature and behaviour (e.g., floating text)	The user interacts with virtual elements as if they are part of the real world

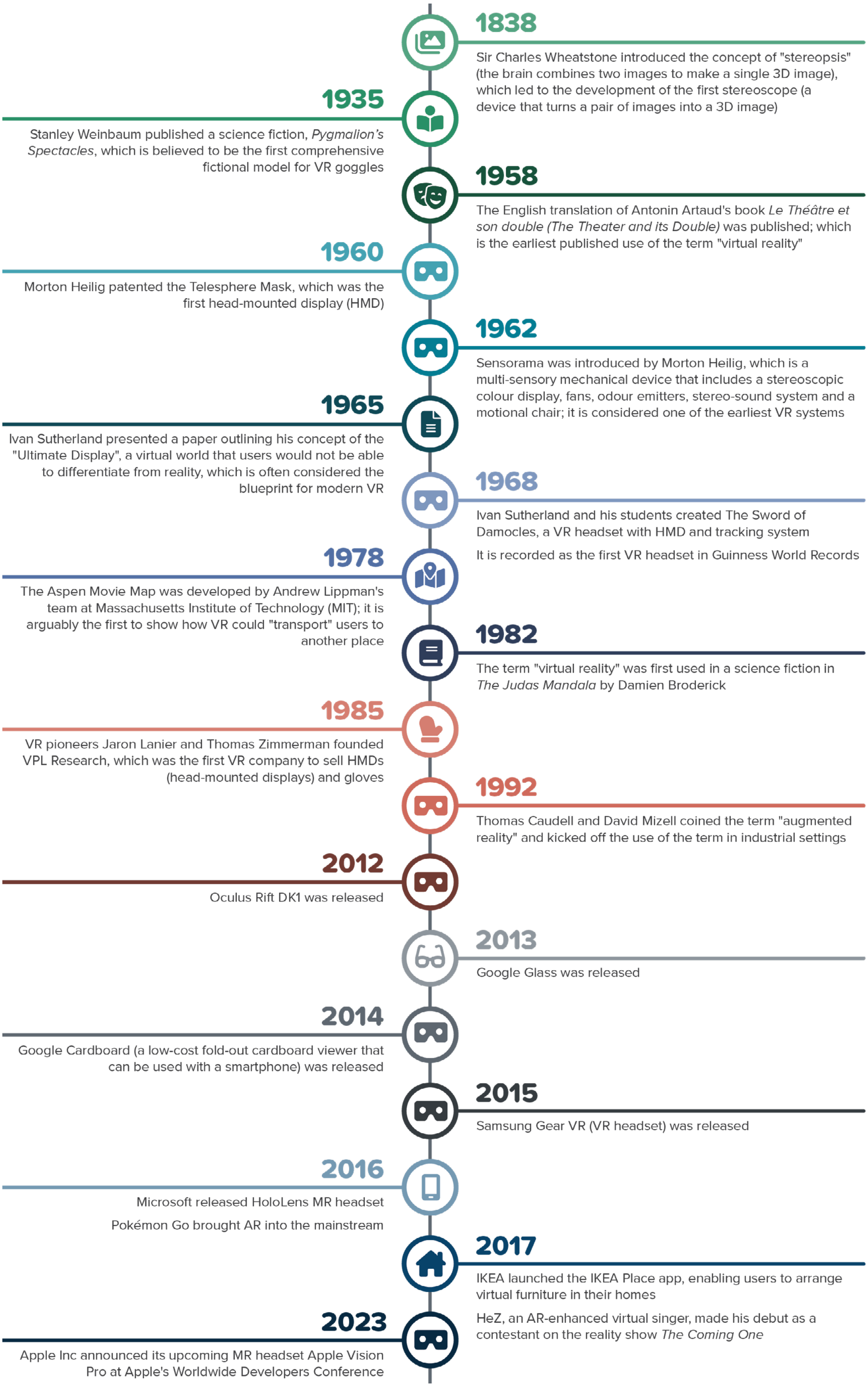

Figure 2: A brief history and evolution of XR

The research landscape

To establish a broad understanding of the research landscape of XR use in mathematics assessment, a systematic literature review was conducted on the *Web of Science* database using "extended reality" or "XR", and "mathematics assessment" as Topic (((TS=(extended reality)) OR TS=(XR)) AND TS=(mathematics assessment)), which returned no results. Therefore, to broaden the search parameters, "extended reality" or "XR", and "mathematics education" were searched (((TS=(extended reality)) OR TS=(XR)) AND TS=(mathematics education)), yielding 27 results. All publications were reviewed for relevance to this article. Two publications used the term XR for a different purpose, five publications used the words "reality" and "extended" in contexts different from those of the present article, two publications were not closely relevant to mathematics education, and one publication focused solely on mathematics but not on XR. Consequently, these publications were excluded from Table 2. The order in Table 2 reflects the sequence shown on the *Web of Science* database.

Table 2: Summary of the literature review

Title: Adoption of virtual and augmented reality for mathematics education: A scoping review **Author(s) and publication year:** Lai, J. W., & Cheong, K. H. (2022) **Study type:** Literature review **Topic:** Implications of immersive XR on mathematics pedagogy in higher education. **Key finding:** The development of an enhanced framework for XR learning environments.
Title: XR maths – designing a collaborative extended realities lab for teaching mathematics **Author(s) and publication year:** Gilardi, M., Hainey, T., Bakhshi, A., Rodriguez, C., & Walker, A. (2021) **Study type:** Empirical study **Topic:** The design of XR applications for educational purposes (in higher education contexts). **Key finding:** A process for designing an XR application for educational purposes.
Title: Exploring the impact of extended reality (XR) on spatial reasoning of elementary students **Author(s) and publication year:** Baumgartner, E., Ferdig, R. E., & Gandolfi, E. (2022) **Study type:** Empirical study **Topic:** An investigation into the impact of XR video content on elementary students' spatial reasoning skills. **Key finding:** The consumption and production of XR videos could improve the spatial reasoning abilities of elementary students.
Title: Coordi: A virtual reality application for reasoning about mathematics in three dimensions **Author(s) and publication year:** Pearl, H., Swanson, H., & Horn, M. (2019) **Study type:** Empirical study **Topic:** Evaluation and refinement of a VR application designed for assisting high school students in plotting points, drawing and manipulating graphs, vectors, objects, and reasoning in 3D space. **Key finding:** This VR application could enhance mathematics learning outcomes.

Title: Playable experiences through technologies: Opportunities and challenges for teaching simulation learning and extended reality solution creation
Author(s) and publication year: See, Z. S., Ledger, S., Goodman, L., Matthews, B., Jones, D., Fealy, S., Har Ooi, W., & Amin, M. (2023)
Study type: Empirical study
Topic: Simulation learning and XR solution creation skills for tertiary education students.
Key finding: Key criteria and a flexible outline for academic researchers and learning designers in higher education, focusing on XR in teaching and inclusive learning design.

Title: XRLabs: Extended reality interactive laboratories
Author(s) and publication year: Kiourt, C., Kalles, D., Lalos, A. S., Papastamatiou, N., Silitziris, P., Paxinou, E., Theodoropoulou, H., Zafeiropoulos, V., Papadopoulos, A., & Pavlidis, G. (2020)
Study type: An introduction to the XRLabs
Topic: An introduction to the XRLabs platform: an XR platform designed to aid in the training of students at all educational levels.
Key finding: The highly interactive platform enables students to engage in sustainable edutainment experiences, particularly beneficial in distance or online learning contexts for Science, Technology, Engineering, and Mathematics (STEM).

Title: Augmented reality in mathematics education: The case of GeoGebra AR
Author(s) and publication year: Tomaschko, M., & Hohenwarter, M. (2019)
Study type: Empirical study
Topic: An exploration of the potential of AR in learning and teaching mathematics, with a special emphasis on GeoGebra AR.
Key finding: Suggestions for potential future developments of the GeoGebra AR app.

Title: Pre-service teachers' professional noticing when viewing standard and holographic recordings of children's mathematics
Author(s) and publication year: Kosko, K. W. (2022)
Study type: Empirical study
Topic: An exploration of the use of holographic representations.
Key finding: Viewing holograms prior to standard videos is more beneficial than viewing standard videos first.

Title: From STEM to STEAM: An enactive and ecological continuum
Author(s) and publication year: Videla, R., Aguayo, C., & Veloz, T. (2021)
Study type: Literature review; secondary analysis on existing empirical studies
Topic: The integration of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education.
Key finding: The development of an enactive and ecological approach.

Title: Kinesthetic learning applied to mathematics using Kinect
Author(s) and publication year: Ayala, N. A. R., Mendívil, E. G., Salinas, P., & Rios, H. (2013)
Study type: Empirical study
Topic: The impact of kinaesthetic learning on mathematics education.
Key finding: AR could boost the learning curve, although its effectiveness is limited by certain factors (e.g., dependency on markers, the range of movement).

Title: Comparative study of technological and communication means to improve the articulation between the secondary and university levels **Author(s) and publication year:** Gómez, M. M., Saldis, N. E., Bielewicz, A., Colasanto, C. M., & Carreño, C. T. (2019) **Study type:** Empirical study **Topic:** An investigation into the use of computer technology and networks among high school students, particularly their perception of these tools as instruments for formal learning in mathematics. An exploration of the development and application of various didactic materials incorporating technology to foster autonomous learning. **Key finding:** The introduction of videos, guides featuring XR (QR codes), and a virtual classroom can enhance students' autonomy in learning. Among the tools tested, videos and XR were preferred, while the virtual classroom was less favoured but still effective.
Title: Using the PerFECt framework to establish an onlife community for theatre in mathematics to teach principles of computing **Author(s) and publication year:** Moumoutzis, N., Paneva-Marinova, D., Xanthaki, C., Arapi, P., Pappas, N., & Christodoulakis, S. (2020) **Study type:** Description of the PerFECt framework **Topic:** An investigation into how modern digital platforms and applications embody new qualities and affordances, and how they can be designed to provide new capabilities to users. **Key finding:** Specific design principles, with a practical example of these principles applied in the design of a community of practice for teachers.
Title: Enhancing STEM education using augmented reality and machine learning **Author(s) and publication year:** Ang, I. J. X., & Lim, K. H. (2019) **Study type:** Applied research **Topic:** The transition of STEM education from traditional textbooks to interactive platforms utilising electronic devices (e.g., AR). **Key finding:** The demonstration of how AR can be integrated into educational platforms to increase learning motivation and students' understanding of STEM subjects.
Title: Multimodal technologies in precision education: Providing new opportunities or adding more challenges? **Author(s) and publication year:** Qushem, U. B., Christopoulos, A., Oyelere, S. S., Ogata, H., & Laakso, M.-J. (2021) **Study type:** Literature review **Topic:** An examination of the role of multimodal technologies in Personalised or Precision Education (PE). **Key finding:** PE techniques could enhance the effectiveness of educational platforms and tools, facilitating the acquisition of knowledge and development of skills for students.
Title: Multimodal analysis of interaction data from embodied education technologies **Author(s) and publication year:** Walkington, C., Nathan, M. J., Huang, W., Hunnicutt, J., & Washington, J. (2023) **Study type:** Empirical study **Topic:** The discussion of the potential of immersive digital technologies such as shared augmented reality (shAR), VR, and motion capture (MC) in enhancing the understanding of human cognition and creating innovative technology-enhanced learning experiences. **Key finding:** The exploration of a multimodal analysis method for studying embodied technologies in educational technology research.

Title: Exploration of kinesthetic gaming for enhancing elementary math education using culturally responsive teaching methodologies **Author(s) and publication year:** Barmpoutis, A., Ding, Q., Anthony, L., Eugene, W., & Suvajdzic, M. (2016) **Study type:** Empirical study **Topic:** An exploration of a novel computer-assisted culturally responsive teaching (CRT) framework specifically designed for teaching mathematics to 5th grade students. **Key finding:** The development and implementation of a CRT framework that blends traditional CRT methods with modern digital technologies.
Title: Harnessing early spatial learning using technological and traditional tools at home **Author(s) and publication year:** Lee, J., Ho, A., & Wood, E. (2018) **Study type:** Literature review; evaluation of educational software programs **Topic:** An investigation into the role of parents and early childhood educators in developing foundational mathematical concepts in young children, specifically geometry and spatial sense. **Key finding:** Highlighting the importance of manipulative play in fostering creative and educational experiences for young learners.

This literature review provides insights into current practices and identifies potential gaps for future research, particularly highlighting that the use of XR in mathematics education, especially in mathematics assessment, is an under-researched field. Although all reviewed publications reported positive findings, ranging from enhanced learning motivation to effective learning outcomes when teaching and learning with XR, much of the existing literature on XR-assisted mathematics education focuses more on XR's technical aspects than on pedagogical perspectives. By reviewing the existing literature, this section plays a crucial role in setting the stage for future empirical studies that are essential to unlock the full potential of XR as a tool for facilitating effective and innovative mathematics assessment. Therefore, this literature review is not just a brief summary of current practices, but a call to action for researchers to embark on rigorous empirical studies that will provide more evidence to guide the effective integration of XR in mathematics education.

The theoretical framework: theorising XR as tools

The theorisation of technology is often missing from the canon of research in the field of technology-assisted education (Oliver, 2013), hence the need to address the topic in this article. Oliver found that there was a limited number of publications focusing on the study of technology from a theoretical perspective, and most of these attempts had drawn on the concept of affordance. Coined by James Gibson (1979), "affordance" was initially developed in the field of ecological psychology as Gibson argued that "affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill" (p. 127).

Affordance can be understood as clues (which can be explicit/obvious or implicit/hidden) that give users hints about how to interact with certain objects. Oliver (2011), among others, argues that affordance-based accounts have positioned technology as the cause of changes in learning, which is being technologically deterministic – a concept posited by Thorstein Veblen, who believed that technology was the agent of social change. However, acknowledging other influential elements in societal growth is crucial, as it would be simplistic to attribute such significant influence solely to technology. Consequently, there is a need for an alternative account to better understand the use of digital technology in education. One of the critical responses to the beliefs that position technology as a determinant of practice is to theorise technology from social perspectives (Oliver, 2013). This is based on constructivist accounts (Thorpe, 2002), and values the agency of learners, which is absent in the deterministic perspective.

It is argued that Vygotsky's ideas are relevant to the uptake of digital technologies in learning (Taber & Li, 2021). For example, for Vygotsky, tools play the "mediating role in human reaction and interaction with the world" (Verenikina, 2010, p. 19). Tools can be categorised as external/physical tools (e.g., artefacts, instruments, etc.) and internal/psychological/symbolic tools (e.g., procedures, methods, concepts, etc.). External tools are designed to "manipulate physical objects", and internal tools can be used by learners to "influence people or themselves" (Verenikina, 2010, p. 19). For the purpose of this article, XR technologies are theorised as external tools.

According to Vygotsky, the use of tools and the ability to improve tools are important for our development as humans, and we can use tools to mediate activities (Taber, 2020). In the context of mathematics education, using a tool to mediate an activity refers to employing a specific device, software, or method to facilitate understanding, engagement, or skill development. Imagine a mathematics class focused on 3D geometry, where concepts such as the properties of 3D shapes, volume, and surface area could be abstract and challenging to understand through traditional two-dimensional (2D) textbooks. In this scenario, the use of VR headsets would enable students to "enter" a virtual space, where they can interact directly with 3D geometric shapes. This experience allows them to view, manipulate, and explore these shapes in ways not possible with a 2D textbook. Consequently, the VR tool not only facilitates a better understanding of geometry through immersive visualisation but also enhances the learning process, making it more effective and enjoyable for students.

As argued by Taber (2020), mediation plays an important role in scaffolding processes that would otherwise be unachievable. If we theorise XR technologies as tools within this context, it leads to a fundamental design principle in digital assessment in mathematics. I suggest that XR technologies should only be adopted when other digital or traditional methods are inadequate. For instance, while XR technologies could offer innovative ways to assess certain mathematics topics (see the following section for detailed examples), they might not be the most effective means for assessing all topics. Other methods, such as the paper-and-pencil approach, might be more suitable for some topics (e.g., basic arithmetic operations) due to their simplicity and directness. Therefore, it is crucial to ensure that XR technologies are used as a means to an end, rather than as an end itself.

The potential of XR in mathematics assessment

It is important to start examining XR technologies that already exist and to learn from the current use of these emerging tools and resources, drawing inferences from them about the potential use and impact of these resources in mathematics assessment, rather than waiting for them to be fully implemented in the classroom or exam hall. Therefore, this section presents a list of some possible topics that can be facilitated through the use of XR technologies in mathematics assessment. The implications and applications of XR technologies were mapped to each of these topics, as presented in Table 3 below. The topics are listed in alphabetical order. The list of topics and their associated implications is not exhaustive; it is intended to provide some of the examples.

Table 3: XR-based resources for facilitating topics in mathematics assessment (developed from Li & Zaki, 2024)

Mathematical topics	Practical implications for XR and integration
Algebra	XR could facilitate algebra-related items in mathematics assessment by enabling test-takers to solve interactive problems overlaid onto their real-world surroundings. This could involve test-takers physically manipulating variables and observing changes in real time, providing a more comprehensive assessment of their understanding and problem-solving skills. For instance, XR could facilitate assessment by initially allowing test-takers to manipulate virtual number lines and geometric representations of algebraic principles. As complexity increases, XR can introduce interactive environments for exploring polynomial factoring, with virtual manipulatives for rearranging terms, and eventually, immersive scenarios for applying algebra in real-world problem-solving, such as calculating trajectories in physics simulations.
Calculus	XR could provide an opportunity for test-takers to engage with and manipulate three-dimensional (3D) mathematical constructs, giving them a live opportunity to demonstrate their understanding of complex concepts such as integrals and derivatives through direct interaction with virtual models. For instance, XR resources may start with visualising the concept of limits by illustrating approaching curves and dynamically showing how values change. For derivatives, test-takers could interact with a 3D graph, physically adjusting the slope of tangents. For integrals, XR could simulate filling volumes under curves, with real-time feedback on the calculations. Assessments could involve test-takers optimising 3D printed structures by applying differential calculus to determine stress points.

Geometry	XR excels in rendering 3D shapes, allowing test-takers to explore and understand geometric properties and theorems in a more intuitive and tangible way. In addition, by interacting with geometric figures in a virtual space, test-takers can develop stronger spatial reasoning skills, crucial for understanding concepts like angles, symmetry, and transformations. This virtual hands-on approach provides a more practical assessment of their ability to understand and apply geometric theorems to both virtual and physical spaces. For instance, XR could enable test-takers to explore the properties of 3D objects by rotating, combining, and dissecting them in virtual space. In addition, it may also include solving interactive puzzles that require applying theorems or calculating areas and volumes of complex shapes overlaid onto the physical classroom.
Statistics	XR could bring a new dimension to statistics-related assessment items, offering test-takers the opportunity to engage with interactive graphs and datasets that integrate seamlessly into their real-world surroundings. This enables a practical evaluation of their ability to interpret and analyse data in an immersive context. For instance, XR could introduce concepts such as mean, median and mode through visual, interactive plots that test-takers can alter by adding or removing data points. In addition, they could use XR to design and conduct virtual experiments, visualise probability distributions, and perform regression analyses with guided tutorials (this can be mediated with artificial intelligence-based tools). Test-takers might be asked to interpret 3D graphs of statistical data projected in the classroom, explaining their insights and conclusions.
Probability theory	XR could create engaging assessment scenarios where test-takers can experiment with and predict outcomes within virtual simulations that are overlaid onto their real-world surroundings, facilitating test-takers' conceptual understanding of probability and their practical applications, and offering a comprehensive evaluation of their problem-solving skills and theoretical understanding. For instance, XR could assist in understanding probability through simple games of chance, like dice rolls and coin flips, with visual representations of outcomes. Test-takers could also engage in complex simulations such as predicting weather patterns or market trends, or risk assessment in business contexts.

Challenges and limitations

As the use of XR in mathematics assessment is currently an under-researched and under-designed field, the absence of rigorous studies limits our understanding of its potential, challenges and limitations. Therefore, this section aims to provide an overview of the challenges and limitations that XR poses in the field of education, rather than solely focusing on mathematics assessment.

Accessibility and scalability

Accessibility remains a significant challenge in implementing XR (Biswas et al., 2021). While schools might be able to supply the necessary hardware and software for test-takers during assessment conducted within the school premises, not every test-taker has access to these resources for practising or revision purposes in out-of-class contexts.

In addition, many researchers have pointed out the limitation of scalability (e.g., Scavarelli et al., 2019). As XR technologies are rapidly evolving, schools need to update the content in assessment continually to keep up with the latest advancements.

Content validity

While XR offers immersive and interactive experiences, there is a risk of overstimulation or distraction, as test-takers might focus more on the novelty of the technology rather than the mathematical topics and skills being assessed. Against this background, it is important to ensure content validity, which could be achieved if assessment items are well aligned with both the subject matter and the required cognitive skills. Therefore, it is crucial to balance the technical engagement with educational objectives when adopting XR technologies in mathematics assessment.

Cost

One of the primary barriers to the widespread adoption of XR in educational contexts is the cost (Al-Ansi et al., 2023). High-quality XR systems require a significant financial investment; the cost of developing and purchasing the necessary equipment, along with its maintenance and regular updates, can be prohibitive for many stakeholders.

Infrastructure

One of the primary challenges in implementing XR in educational contexts is the need for robust infrastructure; like all digital technologies, XR requires robust IT support to maintain and troubleshoot (Al-Ansi et al., 2023). To fully implement XR in mathematics assessment, advanced hardware and software are required to support XR-assisted assessment items. This would normally include high-performance computers, VR/AR/MR headsets or glasses, and a stable internet connectivity.

Interdisciplinary and multidisciplinary collaboration

The utilisation of XR in mathematics assessment presents the challenge of the necessity for an interdisciplinary and multidisciplinary approach in the design process. As Gilardi et al. (2021) highlighted, an effective XR design team must comprise professionals with diverse expertise, including education, graphic and interaction design, and research methods. This implies a significant investment in assembling a team with the right skill set.

Motion sickness

Due to XR technology's immersive nature, it can cause motion sickness (when a user's senses fall out of sync) for certain users (Carter, 2023). This can occur when there is a disconnect between what users see in the virtual environment and their physical perception, leading to discomfort and disorientation. This issue can hinder the learning process and may exclude some test-takers from fully participating in XR-assisted assessment. However, it is possible that this can be reduced by shortening the time of the engagement and allowing test-takers to take regular breaks between stages.

Training

Effective implementation of XR in mathematics assessment requires teachers, practitioners and educators to be adequately trained (Li & Zaki, 2024). This would include not only the technical know-how of operating XR equipment but also the pedagogical skills to integrate these technologies effectively into the curriculum and assessment. In addition, it is also crucial to ensure that the IT support staff are adequately trained to handle any arising issues. This can be a significant challenge for the widespread adoption of XR in educational contexts.

Future directions and recommendations

Based on the discussions presented in this article, this concluding section proposes a research agenda for the widespread adoption of XR in mathematics assessment. This agenda contains various dimensions of how XR technologies can support, enhance and transform mathematics assessment. Some of these dimensions and suggested research foci are briefly presented below, organised in alphabetical order.

Accessibility and inclusivity in XR assessments

- To assess the accessibility of XR technologies for students with special learning needs.
- To explore how XR technologies could be tailored to reflect diverse learning needs in mathematics assessment.

Comparative studies on XR-assisted vs traditional assessment methods

- To investigate the efficacy of XR-assisted mathematics assessment compared to traditional paper-based or other means of digital assessment (e.g., computer-based assessment, etc.).
- To examine the impact of XR technologies on test performance (e.g., reaction speed, depth of understanding, etc.).
- To explore the optimal balance between immersive experience and information processing to avoid overwhelming test-takers.

Longitudinal impact of XR on learning trajectories

- To conduct longitudinal studies to understand the long-term effects of test-takers' engagement with XR technologies on their progression in mathematics learning.
- To evaluate how continued exposure to XR technologies could influence test-takers' attitudes towards mathematics, learning motivation and their self-efficacy.

Scalability and implementation in educational settings

- To evaluate the scalability of XR technologies in schools, considering factors such as cost, infrastructure and teacher readiness.
- To investigate best practices for the adoption and integration of XR-assisted mathematics assessments at various educational levels (e.g., primary, secondary, higher education, etc.).

XR-assisted mathematics assessment design principles

- To develop and refine guidelines for creating effective XR assessment tools.
- To investigate how different design elements (e.g., interactivity, feedback mechanisms, etc.) could influence test performance.
- To understand how interaction patterns with XR can provide insights into test-takers' mathematical thinking processes.
- To foster innovation in XR content creation that aligns with mathematics curriculum standards and assessment criteria.

Acknowledgements

I am grateful to Darren Macey, Dr Rachad Zaki, Lynn Fortin, Ray Knight, and Prof. Keith Taber for their support, enlightenment, encouragement and insightful suggestions which contributed to the shaping of this work.

References

Abu Sitta, F., Maddox, B., Casebourne, I., Hughes, S., Kuvalja, M., Hannam, J., & Oates, T. (2023). *The futures of assessment: Navigating uncertainties through the lenses of anticipatory thinking*. Digital Education Futures Initiative Cambridge; Cambridge University Press & Assessment.

Al-Ansi, A. M., Jaboob, M., Garad, A., & Al-Ansi, A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Social Sciences & Humanities Open, 8*(1), 100532.

Ang, I. J. X., & Lim, K. H. (2019). Enhancing STEM education using augmented reality and machine learning. In *2019 7th International Conference on Smart Computing & Communications (ICSCC)*, 1–5, IEEE.

Ayala, N. A. R., Mendívil, E. G., Salinas, P., & Rios, H. (2013). Kinesthetic learning applied to mathematics using Kinect. *Procedia Computer Science, 25*, 131–135.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments, 6*(4), 355–385.

Barmpoutis, A., Ding, Q., Anthony, L., Eugene, W., & Suvajdzic, M. (2016). Exploration of kinesthetic gaming for enhancing elementary math education using culturally responsive teaching methodologies. In *2016 IEEE Virtual Reality Workshop on K-12 Embodied Learning through Virtual & Augmented Reality (KELVAR)*, 1–4, IEEE.

Baumgartner, E., Ferdig, R. E., & Gandolfi, E. (2022). Exploring the impact of extended reality (XR) on spatial reasoning of elementary students. *TechTrends, 66*(5), 825–836.

Biswas, P., Orero, P., Swaminathan, M., Krishnaswamy, K., & Robinson, P. (2021). Adaptive accessible AR/VR systems. In *Extended abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, Article number 92.

Cambridge University Press & Assessment. (n.d.). Hallucinate. In Cambridge Dictionary.

Cambridge University Press. (2017). Virtual reality. In Cambridge Academic Content Dictionary.

Carter, R. (2023, July 3). XR Today's guide to stopping VR motion sickness. *XR Today*.

Cipresso, P., Giglioli, I. A. C., Raya, M. A., & Riva, G. (2018). The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. *Frontiers in Psychology, 9*.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin Harcourt.

Gilardi, M., Hainey, T., Bakhshi, A., Rodriguez, C., & Walker, A. (2021). XR Maths – designing a collaborative extended realities lab for teaching mathematics. In P. Fotaris (Ed.), *Proceedings of the 15th European Conference on Games Based Learning*, 277–286. Academic Conferences and Publishing International Ltd.

Gómez, M. M., Saldis, N. E., Bielewicz, A., Colasanto, C. M., & Carreño, C. T. (2019). Comparative study of technological and communication means to improve the articulation between the secondary and university levels. *Virtualidad Educacion y Ciencia, 10*(18), 100–116.

Jaquith, T. (2016, August 17). VR, AR, and MR: What's the difference? *Futurism*.

Kiourt, C., Kalles, D., Lalos, A. S., Papastamatiou, N., Silitziris, P., Paxinou, E., Theodoropoulou, H., Zafeiropoulos, V., Papadopoulos, A., & Pavlidis, G. (2020). XRLabs: Extended reality interactive laboratories. In *CSEDU*, 1, 601–608.

Kosko, K. W. (2022). Pre-service teachers' professional noticing when viewing standard and holographic recordings of children's mathematics. *International Electronic Journal of Mathematics Education, 17*(4).

Lai, J. W., & Cheong, K. H. (2022). Adoption of virtual and augmented reality for mathematics education: A scoping review. *IEEE Access, 10*, 13693–13703.

Lee, H. (2020). A conceptual model of immersive experience in extended reality. *PsyArXiv*.

Lee, J., Ho, A., & Wood, E. (2018). Harnessing early spatial learning using technological and traditional tools at home. *Creativity and technology in mathematics education*, 279–302.

Lee, K. (2012). Augmented reality in education and training. *TechTrends, 56*, 13–21.

Li, X., & Taber, K. S. (2022). The future of interaction: Augmented reality, holography and artificial intelligence in early childhood science education. In S. Papadakis & M. Kalogiannakis (Eds.), STEM, robotics, mobile apps in early childhood and primary education (pp. 415–442). Springer.

Li, X., & Zaki, R. (2024). Harnessing the power of digital resources in mathematics education: The potential of augmented reality and artificial intelligence. In S. Papadakis (Ed.), *IoT and ICT for educational applications*. Springer.

Marr, B. (2019, August 12). What is extended reality technology? A simple explanation for anyone. *Forbes*.

McMillan, K., Flood, K., & Glaeser, R. (2017). Virtual reality, augmented reality, mixed reality, and the marine conservation movement. *Aquatic Conservation: Marine and Freshwater Ecosystems, 27*, 162–168.

Microsoft. (2023, January 25). What is mixed reality?

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems, 77*(12), 1321–1329.

Moumoutzis, N., Paneva-Marinova, D., Xanthaki, C., Arapi, P., Pappas, N., & Christodoulakis, S. (2020). Using the PerFECt framework to establish an onlife community for theatre in mathematics to teach principles of computing. In W. K. Chan, B. Claycomb, H. Takakura, J.-J. Yang, Y. Teranishi, D. Towey, S. Segura, H. Shahriar, S. Reisman & S. I. Ahamed (Eds.), *2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC)*, 1084–1085, IEEE.

Oliver, M. (2011). Technological determinism in educational technology research: Some alternative ways of thinking about the relationship between learning and technology. *Journal of Computer Assisted Learning, 27*(5), 373–384.

Oliver, M. (2013). Learning technology: Theorising the tools we study. *British Journal of Educational Technology, 44*(1), 31–43.

Palmas, F., & Klinker, G. (2020). Defining extended reality training: A long-term definition for all industries. In M. Chang, D. G. Sampson, R. Huang, D. Hooshyar, N.-S. Chen, K. & M. Pedaste (Eds.), *IEEE 20th International Conference on Advanced Learning Technologies: Proceedings* (pp. 322–324). IEEE.

Pearl, H., Swanson, H., & Horn, M. (2019). Coordi: A virtual reality application for reasoning about mathematics in three dimensions. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–6.

Qushem, U. B., Christopoulos, A., Oyelere, S. S., Ogata, H., & Laakso, M. J. (2021). Multimodal technologies in precision education: Providing new opportunities or adding more challenges? *Education Sciences, 11*(7), 338.

Rokhsaritalemi, S., Sadeghi-Niaraki, A., & Choi, S.-M. (2020). A review on mixed reality: Current trends, challenges and prospects. *Applied Sciences, 10*(2), 636.

Scavarelli, A., Arya, A., & Teather, R. J. (2019, June 18–21). *Circles: Exploring multi-platform accessible, socially scalable VR in the classroom* [Paper presentation]. 2019 IEEE Games, Entertainment, Media Conference (GEM), New Haven, CT.

See, Z. S., Ledger, S., Goodman, L., Matthews, B., Jones, D., Fealy, S., Har Ooi, W., & Amin, M. (2023). Playable experiences through technologies: Opportunities and challenges for teaching simulation learning and extended reality solution creation. *The Journal of Information Technology Education: Innovations in Practice, 22*, 68–90.

Taber, K. S. (2020). Mediated learning leading development – the social development theory of Lev Vygotsky. In B. Akpan & T. J. Kennedy (Eds.), *Science education in theory and practice: An introductory guide to learning theory* (pp. 277–291). Springer.

Taber, K. S., & Li, X. (2021). The vicarious and the virtual: A Vygotskian perspective on digital learning resources as tools for scaffolding conceptual development. In A. M. Columbus (Ed.), *Advances in psychology research* (Vol. 143). Nova Science Publishers.

Thorpe, M. (2002). From independent learning to collaborative learning: new communities of practice in open, distance and distributed learning. In *Distributed Learning* (pp. 131–151). Routledge.

Tomaschko, M., & Hohenwarter, M. (2019). Augmented reality in mathematics education: The case of GeoGebra AR. In *Augmented reality in educational settings* (pp. 325–346). Brill.

Verenikina, I. (2010). Vygotsky in twenty-first-century research. In J. Herrington & B. Hunter (Eds.), *Proceedings of EdMedia 2010: World Conference on Educational Multimedia, Hypermedia & Telecommunication*. AACE.

Videla, R., Aguayo, C., & Veloz, T. (2021, September). From STEM to STEAM: An enactive and ecological continuum. In *Frontiers in Education, 6*, 709560. Frontiers Media SA.

Walkington, C., Nathan, M. J., Huang, W., Hunnicutt, J., & Washington, J. (2023). Multimodal analysis of interaction data from embodied education technologies. *Educational technology research and development*, 1–20.