University of Glasgow

XRED: PREPARING FOR IMMERSIVE EDUCATION

WORLD CHANGING GLASGOW

CONTENTS

INTRODUCTION

We are the Scoping Extended Educational Realities (SEER) research group within the University of Glasgow. Our team is made up of researchers in education, philosophy, XR technology and psychology, and this group has extensive experience in the deployment and use of XR technology in education. As a Glasgow-based research group, our expectations around education norms, funding, and decision-making, as well as our wider approach to writing this report reflects our experience working in this particular context. Our vision is reflected in our Illustrative Lesson, and our Case Studies give some background experience that informs our observations. We believe our findings are relevant across a wider range of educational environments than just our own.

Team

The SEER group was constituted in 2022 as a result of converging work among the members of the team. The group took on the aim to provide a rounded and well-balanced evaluation of the XR landscape in education. Our team is led by Professor Neil McDonnell who has expertise in Philosophy and in the development and deployment of XR Technology, especially in Education. Dr Lavinia Hirsu, Senior Lecturer in the School of Education, conducts research in emergent digital literacies, education-based responses to new technologies, the possibilities of storytelling and meaning-making with XR technology, as well as multilingualism and linguistic inclusion. Dr Gabriella Rodolico is Senior Lecturer in Science Education (Biology) at the School of Education, University of Glasgow. She has expertise in the implementation of innovative technology such as VR in Initial Teacher Education courses as well as experience of teaching in secondary school and Higher Education. Dr Sarune Savickaite is early career researcher specialising in immersive education, neurodiversity and cognitive psychology research. Dr Imants Latkovskis is a philosopher and XR lab manager at the University of Glasgow with first-hand experience of deploying XR provisions in higher education teaching. Dr Lysette Chaproniere is a philosopher specialising in disability and emerging technology.

Credo

We believe that XR technology will be transformative within education.

We believe that XR technology will become an integral component of our learning and working lives. As this technology is becoming embedded in various industries (e.g., healthcare, design and manufacturing, urban planning, etc.), the learners of today will need to become familiar with these technologies not only through their own learning, but also through the acquisition of skills and training that will make them competitive for present and future jobs that will use these technologies by default.

This transformation could arrive more quickly, more effectively, and more carefully with good decision-making today, and our aim is to catalyse the positive and responsible adoption of XR technology within education. We call such widespread adoption **XRed**.

Approach

Some scope setting is important here. This report does not aim to evangelise for XR technology in education, nor does it aim to act as a work of risk analysis. Rather, we have started by stating that we believe that XR will be transformative in education, and from that vantage point we aim to take a balanced and measured view about what could go well, what could go badly, and what we can do about it.

It is not possible to cover every topic that a reader might wish us to. For example, we will not cover issues around online child safety in detail – a hot topic for many, but one covered already in other work (Allen and McIntosh NSPCC report, 2023) and a topic which is not specific to XRed but applicable to the entire ecology of digital devices and technologies. We will not discuss AI either, despite believing that it will play a key role in the future we are considering. That is because we do not think we can predict precisely what that role will be, and an in-depth evaluation would be required which would detract from the focus of this report. Our assumption within this work is that AI will supercharge many of the issues we raise here.

We have focused our attention to those issues which we felt are the most salient for XR adoption and which are likely to have the biggest impact. We have identified these based on our experience as researchers and users of XR technology in different education settings and from literature reviews of current research-based evidence of the potential applications of XR and future developments on the horizon. We have consulted with education practitioners and accessibility specialists through a series of workshops. We have also held a round-table discussion with politicians, technologists and education sector specialists. We are grateful for their insights and we hope that our report provides the starting point of more sustained conversations, technological developments, and research in XRed.

This Report and the Whitepaper distilled from it form a pair of documents through which we identify Roadblocks, Opportunities, and Risks of XRed, and make distinct Recommendations for the XR Technology Industry, for Government, and for the Education Sector. The Whitepaper is the abridged briefing document focussing on the high-level takeaway messages. This Report is the fuller document where we lay out our case in more detail, provide Case Studies, an Illustrative Lesson, and a Glossary.

Roadmap

The report will begin with sections addressing the related questions of "What is XR Technology?" "What can XR Technology do?" and "What can XR Technology do for Education?". We will then present **Learning Untethered: Iron Age Scotland** - our illustration of a lesson set in 2035 using matured XRed technology. Next, we lay out what we consider to be the key Roadblocks, Opportunities, and Risks of XRed deployment. Many of the issues here are mixed: they have aspects which represent Roadblocks and aspects which represent Opportunities, and so we organise these by topic: Classroom Deployment, Pedagogical Deployment, Access, and Safety and consider both sides.

We will make recommendations along the way, but we will then expand them in their own section at the end. Our appendices will contain the Case Studies and Glossary that we refer to throughout.

This work was supported by funding from Meta, but the content, findings, and recommendations remain editorially independent.

WHAT IS XR TECHNOLOGY?

Extended reality (XR), sometimes also called immersive technology or cross-reality, is a collective term for a group of technologies which enable users to have novel experiences by leveraging space around them and delivering sensory information in a way that feels natural and uninterrupted. Immersive technology extends reality by intervening on the senses to convey and integrate information seamlessly into a user's perception of the world – be it the real world, a virtual one in its place, or a mixture of both.

When we engage with information using traditional technology, we are directly aware of the medium as something external to us. For example, when we read the morning news off our smartphone screen, or watch a cooking show on the TV, or play a racing game on a computer, we are directly aware that the experiences we are having involve interacting with an external device.

XR devices, on the other hand, are increasingly capable of bypassing this awareness by enabling experiences to be delivered in an immersive way – as if they are truly happening to us. The extent to which they succeed in doing this depends on the sophistication of the particular use case and the maturity of the technology.

This can be done in a way that wholly occludes a user's view of the real world and replaces it with an entirely computer-generated world – we call this **virtual reality (VR)**. For example, a user may put on a VR headset and suddenly find themselves on the steps of Machu Picchu. Because of the concerted effort of computer vision and a 3D games engine, when the user turns their head, or takes a step forward, the simulated environment adjusts to these movements, giving the user the feeling that they are really there, and allowing them to explore a representation of the Incan landmark without having to be physically present. When your movement like walking, crouching, jumping or bending is tracked, that represents six degrees of freedom (or 6DoF) VR – the most immersive variety.

Technology can also extend reality by adding to a user's view of the real world without replacing it – we call this **augmented reality (AR)**. A popular early example of AR was the mobile game Pokémon Go which allowed players to point their smartphone cameras to real world locations and interact with virtual characters that appeared as if they were there.

A more sophisticated example of AR would be a pair of smart glasses that would give the user information on things they were looking at using a heads-up display that would be seamlessly overlaid on their perception of the world. For example, a language learner could use an AR app to label objects around them using that language. A commuter could look up to the sky and read the weather forecast right off the clouds.

AR use cases of this level of sophistication are still perhaps a decade or so away for the average consumer. But the steady progress of research and development over the last few years has resulted in a way of achieving similar experiences using an intermediate kind of technology we call **mixed reality (MR)**. MR can deliver augmented experiences using VR headsets with high definition passthrough cameras.

Headsets like this can display augmentations in the real world mediated through a series of cameras on a VR headset – a much less lightweight solution than a pair of glasses, but effective, nonetheless. For example, an MR application could allow a group of learners to interrogate a shared internal combustion engine in a classroom as if it was floating in front of them. With the click of a button, the real world would fall away, and learners would be transported to an automotive factory floor, seeing the combustion engine being assembled in context. With another click of a button, the learners can be transported back to the classroom.

The terminology in this field has changed over time, and some instances of MR tend to be referred to as AR, and vice versa. We will use the collective term XR throughout this report to refer to at least one of these technologies, but we will distinguish between them when relevant. Our observations are not limited to the technology as it is today, but how we anticipate it will evolve – see Illustrative Lesson.

WHAT CAN XR DO?

XR follows in the footsteps of a range of past technologies which have made piecemeal progress in conveying increasingly complex information to users. However, XR represents a significant watershed in the progress that audiovisual technology has made in that XR devices enable a kind of interaction which is modelled on the way we naturally interact with the real world. Instead of watching a video recording of an erupting volcano, an XR user can find themselves right on the crater's edge and peak inside, even stand on their tiptoes as they inch closer to get a better look. Instead of reading about the distinguishing features of various dinosaurs, a user can don an XR headset and walk up to a virtual dinosaur as it's grazing on Mesozoic grass and get an immediate experience of its size, shape and presence in the world.

This sense of presence and immersion can offer countless opportunities not just for entertainment and storytelling, but as we will argue, for a wide range of educational experiences too.

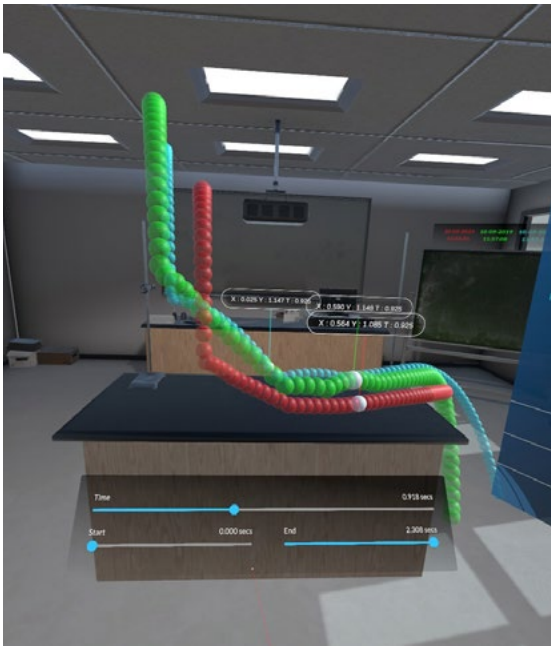
One of the core strengths of XR technology lies in its ability to construct realistic and plausible simulations. Another strength is that it allows users to engage with 3D content directly – that is to say, spatially. For example, a designer can bring their creation from a computer render to a virtual object in a matter of minutes. They can then interrogate this object in space as if it were a physical thing, rather than an interconnected series of 2D cross-sections animated onto a flat screen.

According to leading XR researcher and head of Stanford's Virtual Human Interaction Lab, Jeremy Bailenson (2018), XR simulations can be a worthwhile alternative to scenarios that would otherwise be Dangerous, Impossible, Counterproductive or damaging, or Expensive or rare. This is the DICE model for identifying apt use cases for XR technology.

For example, virtual firefighting or paramedic training can entirely remove the Dangers of injury while allowing trainees to practice life-saving skills under conditions that nonetheless feel realistic. An otherwise Impossible virtual field trip to the surface of Mars can illustrate abstract claims about the planet's geological features. A simulated conflict can give training mediators an opportunity to fail safely without Counterproductive real-world repercussions.

A virtual replica of a precious artefact can travel to audiences around the world without the traditional and prohibitive Expense of securely moving the real-world object.

But the power of XR does not end there. While the DICE model is helpful in organising some of the more striking features of scenarios that would benefit from a virtual simulation, we believe there are countless more opportunities for XR to transform education which will come out of thinking about the specific things XR enables teachers and learners to do.



WHAT CAN XR DO FOR EDUCATION?

The use of XR technology in the education sector presents a range of questions: What types of learning experiences are made possible with XR? What specific features and capabilities will have a transformative role in learners' experiences? What learning theories and frameworks apply to XR environments? In the sections below, we address these questions based on the research literature published to date. While we do not provide an exhaustive literature review, we do highlight critical aspects that we hope will inform decision-making based on existent research evidence. As the research community is building more knowledge on how we can best deploy these technologies for effective learning, we also draw attention to gaps in the literature and call for support for research to enable educators and learners to make the most of XR technology.

The transformative role of XR in education

We believe that learning experiences enabled by XR technology will change the ways in which individuals:

Experience and learn

XR technology enables learning environments where experiences are central to the process of knowledge-making. Being on the learning site and having the ability to interact, design, and feel are central to learning with XR, either in training situations, classroom-based contexts, or in any other location where learning can take place. From the educator's perspective, the possibility of experiencing learning through XR encourages new teaching and learning approaches.

Have access to learning via multiple modes, senses, and new types of interaction

XR technology can provide new opportunities for making knowledge accessible to different learners. Abstract concepts can be presented in concrete contexts (e.g., racial bias can be explored in a VR scenario), through different modes (e.g., learning maths by manipulating numbers and operations of addition, subtraction, etc.) and new types of interaction (e.g., gaze-activated knowledge).

Imagine and wonder

While we anticipate that the "wow" factor of XR technology will diminish as it is steadily integrated into everyday life, nonetheless, XR experiences will provide valuable contributions to the education landscape particularly because they will continue to stimulate the senses, foster imagination, and engage learners with a sense of wonder about the subject matter rather than the technology that supports it.

Enact learner autonomy and creativity

As XR experiences are guided by the user's controls, movements and embodied responses (e.g., gestures and gaze), XR technology gives the learner a high degree of autonomy in the direction of their learning process. This could potentially enable learning to be driven by curiosity and active engagement. The learner's autonomy can lead to creative and design-based actions which strengthen the users' learning experience.

Expand the boundaries of time, space, scale, depth and perspective

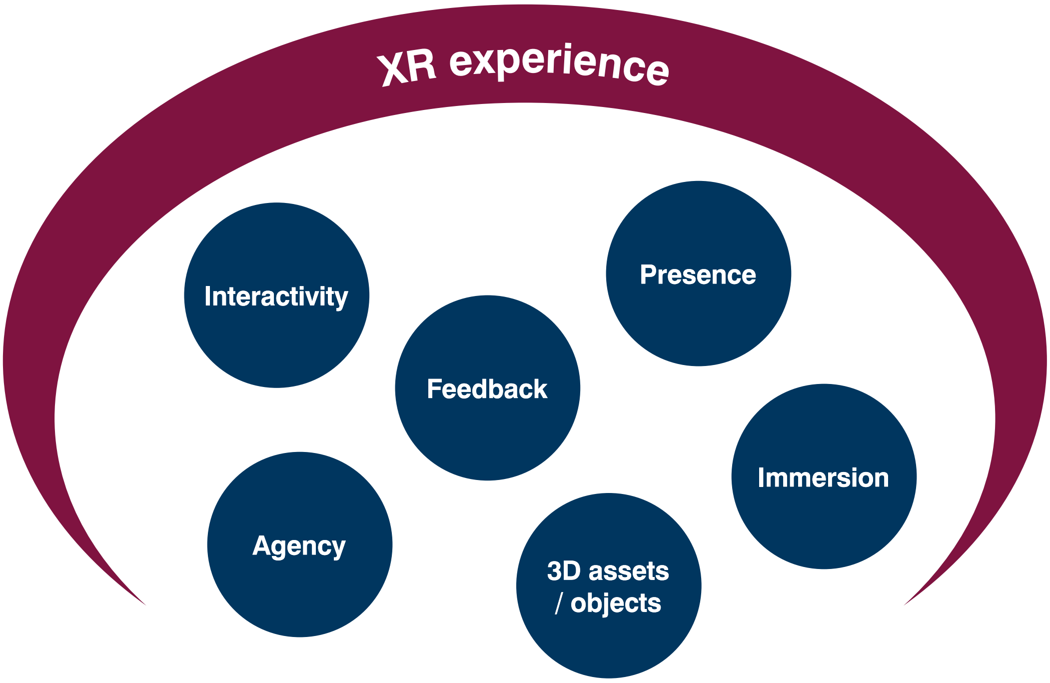
A robust integration of XR technology will lead to the expansion of learning possibilities across several dimensions, such as **time and space**, **scale**, **depth** and **perspective**. For example, XR can allow learners to navigate from real classrooms to virtual learning sites or explore a new city or neighbourhood with layered and on-demand access to its geography, history and socio-cultural heritage. Moreover, a VR lesson could enable a learner to move from the microscopic view of a cell to an in-cell experience. They could then explore an organism from its external appearance to its structural components and the cellular level of its parts, designing a product to its most minute detail. Finally, a learner could explore the plot of a novel by switching from one character's view to the next. XR technology need not take learners away from or outside of their learning spaces; we propose that XR technology expand, enhance and transform these spaces by adding valuable and powerful learning opportunities.

Have the freedom to fail safely and try again

XR experiences can be designed in such a way that learners experiment with the elements of their environment without risking breaking or damaging any of these components (e.g., a misassembled aircraft wing in VR can always be reset to its proper assemblage process without any damage to its constitutive parts).

XRed: Affordances

To fully understand the potential impact of XR in education, we need to consider the specific features of XR technology that may enable unique learning experiences:



Interactivity: interactivity refers to the degree of communication, involvement, and modifications the user can apply to the virtual environment in real time. In terms of VR education, for example, the Cognitive-Affective Theory of Learning with Media (CATLM) theory "articulates mechanisms for meaningful learning that may occur when learners directly interact with the instructional system (e.g., dialogue, control, and manipulation) in a multimodal learning experience" (Huang et al., 2022, p. 3).

Feedback: feedback can be delivered in multiple ways: as a physical experience such as visual feedback, proprioceptive feedback, as well as sensory feedback which may impact embodiment (Ding et al., 2018). Real-time feedback in XR could be coordinated through peer-to-peer engagement, facilitated by the teacher or by the integration of AI-assisted feedback.

Presence: the sense of physical presence or the psychological state of "being there" (Fowler, 2015) in a space that may include virtual elements fully (e.g., in a VR environment) or partially (e.g., in an AR experience). XR technology also enables co-presence, i.e., being in the immediate (physical and/or virtual) presence of others, which opens up the possibility for feedback and collaborative learning. Research in digital learning highlights that the concept of presence refers not only to the psychological presence in the digital environment, but also to teaching, social, cognitive (Garrison & Akyol, 2013) and learning presence (Wertz, 2022).

Agency: with XR technology, learners have different options to choose how they learn and/or decide their own learning pathway. They can self-direct by deciding how to engage with their learning environment (e.g., taking a sequence of steps to show awareness of a process). They can select the avatar that best represents their intentions and preferences, and they can have a higher degree of control over how much time they can spend with the learning content. Learning experiences in XR can be designed to support learner's autonomy and individualised experiences.

3D assets/objects: computationally constructed elements that populate the XR learning experience. These can be rendered visually in the environment or through any other type of output (e.g. auditory, kinetic, etc.).

Immersion: the principle of immersion refers to the psychological immersion of the user (the perceived sense of the user as being actively engaged with their environment), and the technological immersion (the technological capabilities of transposing the user into an enhanced environment including virtual elements).

Future developments of XR technology may enable or make salient new key affordances (see, for instance, the notions of "authenticity", "contextualisation" and "engagement" (MacCallum, 2022)). Research with a focus on the key characteristics and enabling features of XR will inform new pedagogical practices and future educational experiences. As XR technology continues to develop and facilitate new types of interactions, unique features will emerge and may have significant impact on learners' experiences. For instance, at the moment, 3D visualisations indicate a significant bias towards sight, i.e., learning experiences are primarily channelled by the ability to see the objects in one's XR environment. This approach can potentially leave visually impaired learners behind. Current developments in XR are looking into correcting this while expanding the sensorial range and creating learning experiences that use hearing and touch as equally important senses for learning. The integration of new gestures and body responses will also expand the ways in which users will be able to activate and engage with knowledge (e.g., through eye movement and gaze, aerial hand movements, etc.). Future research in these areas will be critical to determine how to create effective learning opportunities.

XRed: Types of learning experiences

What makes learning with XR particularly exciting is the wide range of learning experiences that can be applied in many different contexts and for different purposes. From visualising a difficult abstract concept to analysing the energy efficiency of a building by drawing on existent data points, XRed creates diverse opportunities for learning.

Embodied learning: The embodiment of learning refers to the idea that learning is not only a cognitive process occurring in the mind, but also a physical and rich sensory experience involving the entire body. In VR, for example, embodiment has been considered a "profound affordance" (alongside the "feeling of presence") which can foster agency due to the manipulation of 3D objects in the learning environment (Johnson-Glenberg, 2018).

XR affordances, discussed in the previous section, such as presence, immersion, interactivity, feedback and agency could constitute features of embodiment of learning. "Extended-reality (XR) environments open up tremendous opportunities for learners to connect new representational forms and modes of interaction to prior knowledge and experiences through embodiment" (Fortman & Quintana, 2023, p. 145). The possibility for learners to manipulate virtual objects, not only on a 2D screen, but in a 3D virtual environment, provides an authentic experience where learners' senses can engage with abstract concepts in a tangible, immersive way, with the caveat that "the gesture or movement should be congruent to content being learnt […]. One hypothesis is that when learners are activating congruent and associated sensori-motor areas, they may learn the content faster and in a deeper manner" (Johnson-Glenberg, 2018, p. 4).

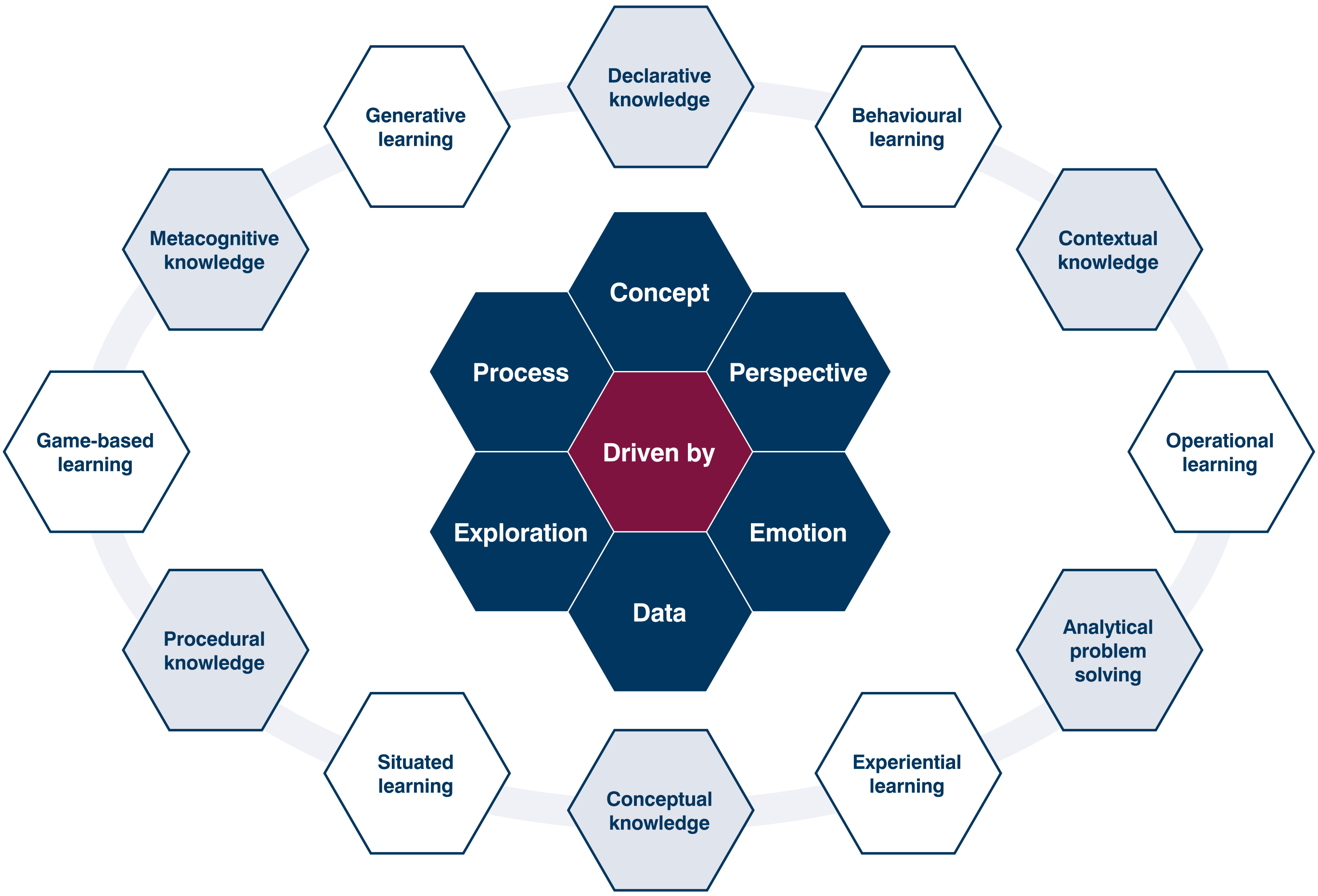
In addition, it is also worth noting that although embodiment is an individual process, it also "can be experienced as group phenomena that may lead to the development of communities of practice (CoP)" (Ziker et al., 2021, p. 57), and which in return could have a positive impact on learning and collaboration (Sánchez-Cardona et al., 2012).

XR experience-based learning

An XR lesson that takes into account the key features of XR technology can create one or more of the following types of learning experiences:

- **Perspective-driven:** the aim of the learning process is to provide the learner with different perspectives on a particular concept, situation or learning context;
- **Concept-driven:** the aim of the learning process is to explore a concept or set of concepts that are abstract or difficult to explain/understand through other learning approaches;
- **Process-driven:** the aim of the learning process is to help students understand the process behind a phenomenon or situation. Particular attention is paid to visualising and breaking down the stages or phases of that process to make it memorable and easier to understand;
- **Exploration-driven:** the aim of the learning process is to give students the opportunity to learn by experiencing a VR environment, by being present and engaging with the elements that make up that environment;
- **Emotion-driven:** the aim is to connect learning with emotional experiences and/or instil emotions (e.g., empathy) to strengthen the learning about certain concepts, phenomena or scenarios;
- **Data-driven:** the aim of the learning process is to use data and analytics to facilitate and realise new understandings of these sources of information.

XR experience-based learning could support different types of knowledge and learning processes. The below illustration provides a non-exhaustive range of examples (outer), any of which could feed into the different learning experiences (inner).



XRed: Learning theories and approaches

Innovative technologies have the potential to transform how knowledge is acquired, processed and used. They enable new ways of networking, constructing knowledge and interacting. Although existing learning theories might not be enough to explain the full potential of XR technology, it is essential to explore these to better understand how XR might contribute to the theoretical landscape.

In this section, we present some of the key learning theories applied in XR learning and teaching (adapted from Lee & Hu-Au 2021, Radianti et al. 2020, Stanney et al. 2023 and Siemens 2005). Most of these theories have been applied to other learning contexts and technologies so we would like to encourage researchers in the educational and the technological fields to explore the extent to which these theories converge with and apply the full range of XR affordances.

	Behaviourism	Cognitivism	Constructivism	Experientialism	Connectivism
Theoretical Stance	"Knowledge is a repertoire of behavioural responses to environmental stimuli" (Radianti et al., 2020) (environment-centred)	Knowledge is "actively constructed by learners based on pre-existing prior knowledge structures" (Radianti et al., 2020) learner-centred). Under this theory, Stanney et al (2023) propose other important theoretical concepts for XRed, such as Cognitive load theory, Component display theory, Conditions of learning theory, Embodied learning theory.	"Learning is an active, constructive process…". "Constructivists argue that the instructional learning design has to provide macro and micro support to assist the learners in constructing their knowledge and engaging them for meaningful learning". (Radianti et al., 2020) (learner centred)	"Learning as following a cycle of experiential stages, from concrete experience, observation and reflection, and abstract conceptualisation to testing concepts in new situations" (Radianti et al., 2020) (this process is conceptualised in the Kolb's cycle). It is worth mentioning that some studies consider Experiential learning theory under constructivism (Stanney et al., 2023), in addition to situated learning theory.	"Learning and knowledge rests in diversity of opinions. Learning is a process of connecting specialised nodes or information sources. Learning may reside in non-human appliances. Capacity to know more is more critical than what is currently known. Nurturing and maintaining connections is needed to facilitate continual learning." (Siemens 2005) (learner and network centred)
Role of learner	"Passive. Simply responsive to stimuli" Lee & Hu-Au (2021), "Learning is considered to be a passive absorption of a predefined body of knowledge by the learner" (Radianti et al., 2020)	"Active and central to the process in response to the external world" (Lee & Hu-Au, 2021)	"Active sense maker" (Lee & Hu-Au, 2021)	Active learners construct knowledge based on own experience.	"Learning also resides outside the person and is focused on establishing connections" (Lee & Hu-Au, 2021)
Teacher role	"The teacher serves as a role model who transfers the correct behavioural response" (Radianti et al., 2020).	"The learning motivation is intrinsic and learners should be capable of defining their own goals and motivating themselves to learn. Learning is supported by providing an environment that encourages discovery and assimilation or accommodation of knowledge" (Radianti et al., 2020)	"Constructivists argue that the instructional learning design has to provide macro and micro support to assist the learners in constructing their knowledge and engaging them for meaningful learning" (Radianti et al., 2020)	"The teacher takes on the role of a facilitator to motivate learners to address the various stages of the learning cycle" (Radianti et al., 2020). This is referred to the reflective cycle in experiential learning as described by Kolb et al. (2014).	"The teacher is one of the many sources in a knowledge flow and can help learners strengthen their abilities to "foster, nurture, and synthesise" different resources of learning to be able to explore different perspectives on pieces of information" (Siemens 2005).
XR education and design implications	"XR scenarios should support observing, imitating, and embodying modelled correct behavioural responses, as well as discovery and invention of new meaningful behaviours that enhance performance, be arranged such that the difficulty level elicits positive versus negative reinforcement, and provide feedback to motivate desired performance outcomes" (Stanney et al., 2023)	"Knowledge acquisition is a mental activity consisting of internal coding and structuring by the learner. Digital media, including VR-based learning can strengthen cognitivist learning design" (Radianti et., 2020). Under Cognitivism theory Stanney et al. (2023) identify the Cognitive Load Theory and mention that under this theory "XR learning scenarios should start with simple (as opposed to complex), primarily passive, observational tasks for which extraneous cognitive load is managed.	XR technology such as "VR-based learning fits the constructivist learning design […] (using pedagogical approaches such as) situated learning and experiential learning" (Radianti et al., 2020O) , e.g., hands-on science experiment (Lee & Hu-Au, 2021)	Google Expedition might offer a good example of how "the visual experiences offered by Google Expeditions enriched the classroom environment as the Expedition Guide and Explorers had developed a relationship where meaning was negotiated and constructed through questioning, rephrasing, accepting and disregarding information" with a teach-back pedagogical approach. (Parmaxi et al., 2021).	XR environments can be designed to bring together different sources of knowledge in various formats so learners can begin to build their knowledge in a networked and connected way.

Despite having so many different theoretical stances for learning, researchers recognise that "many of the definitions in use by these different disciplines, however, can be aligned with a common 'umbrella concept' of learning that can be applied across disciplines by considering learning simply as the processing of information derived from experience to update system properties" (Barron et al., 2015, p. 405). According to Chen et al. (2022), "Benefits of learning assisted by XR are reported, for example, increasing content understanding of spatial structure and function, facilitating learning of language associations, contributing to long-term memory retention, improving physical task performance, and increasing learning motivation and engagement" (p. 1).

A very important process in learning and teaching is to design learning opportunities that are based on empirical data with an alignment between theories of learning, learning goals and learning activities, as well as knowledge acquisition and assessment. The aligning process can be facilitated by learning frameworks as supportive conceptual models. While we recognise that there is no singular specific learning framework for XR in Education and more research is needed in this field, we also identified some examples of already existing learning frameworks which could highlight how presence, immersion, and interactivity could interplay between emotions and cognition in XRed. For example, the **Cognitive-Affective Model of Immersive Learning (CAMIL)** (Makransky & Petersen, 2021), or the **Cognitive-Affective Theory of Learning with Media (CATLM)** (Huang et al., 2022).

Particular attention is given to the **Cognitive Theory of Multimedia Learning (CTML)**, which highlights the significance of multimodal experiences and learning through the mental representations from words and pictures. This theory takes into consideration cognitive load and describes three types of processes: "extraneous processing, essential processing, and generative processing" (Mayer, 2014b, p. 60). The CTML theory has been recently studied alongside the implementation of generative learning strategies (discussion, reflections, journaling and so on) as successful framework for the implementation of VR-supported lessons (Parong and Mayer, 2018; Makransky, et al., 2021).

These frameworks are suitable for XR-supported learning; however, more research and technological development of XRed platforms could be informed by learning theories and frameworks that draw from different disciplines. To unlock XR's full potential, we need to continue and widen the base of learning theories and frameworks, their application and long-term evaluation to determine best and most effective learning practices.

The skills and abilities needed to be an effective learner today require innovation, creativity and in-depth learning. Knowing how to manage and organise information is equally important as having access to it, and integrating all these dimensions into current educational systems is crucial:

> *"Our educational and training systems are based on a model that was developed to meet the needs of the industrial revolution. They prepare and maintain people to fit an economic model of society. To a large extent, this is still the prevailing political mental model that drives educational policy. However, this model is no longer enough given our twenty-first-century world […]. Increasingly, we are seeing a system that emphasises standardisation and performance but not learning, creativity, or innovation. Instead, we need a system that creates and develops capable lifelong learners who have a rounded set of skills that prepare them for managing rapid change, with a concomitant desire to learn". (Blaschke and Haseln, 2015, p. 27)*

Looking at all aspects of the learning process will be essential, not only for developers of XR technology, but also for educators who will use these in different contexts. Too often, XR is chosen for its novelty or "cool" factor, but many studies and the practitioners we have consulted have raised concerns and challenges that need to be taken into account if we want to have a rounded and well-informed perspective on the impact of XR in education.

For instance, Makransky et al. (2019) found that VR designs often feature extraneous cognitive load–adding distracting elements (see foveated rendering in the Glossary) or unnecessary complexity which may ultimately hinder learning. Other researchers have observed that AR often requires too many complex tasks and manipulation, which may confuse learners and lead to discouragement (Alzahrani, 2020). In contrast to this, Savickaite (forthcoming) argues that the ability to remove extraneous stimuli can be helpful for neurodivergent individuals.

Conversations with practitioners have highlighted that the immediate future of XR needs to take into account the impact of these technologies on key aspects such as learners' cognitive load, control over biometric data, perpetuation of biases and the potential replication or exacerbation of inequities in society, perceptions of one's self-image in different real/virtual environments, to name a few (see Lee & Hu-Au (2021) for an extended list of ethical considerations). Educators and designers need to avoid a "silver bullet" view of XR as a promise or guarantee of better learning, but should rather adopt a much more nuanced, critical lens on how to achieve specific learning outcomes of interest.

XRed: Access to learning

In the research literature looking at XR in education, there exists a delicate balance between accessibility and exclusivity. The implementation of a single solution may enhance the accessibility of XR experiences for some users while simultaneously rendering them less accessible for others.

Customisable experience: XR developers can empower each user with the ability to tailor their XR experience according to their unique needs and requirements. This consideration gains particular significance in educational institutions where the selection of XR hardware is pivotal. Prioritising customisability in decision-making processes ensures that educational XR experiences cater to the diverse needs of learners, fostering inclusivity and equal opportunities for learning.

Selective simulation: Striving for a perfect match between the virtual and physical environments may not always be desirable. Instead, creators have the opportunity to craft experiences that break down barriers and provide access to spaces that might be otherwise inaccessible. For instance, a wheelchair user might face challenges in exploring historical buildings physically; however, an XR simulation might replicate this inaccessibility if it, quite unnecessarily, requires walking to move in the scene. In this context, the creators can simply remove the real-world barriers, offering an immersive experience that transcends physical limitations.

Haptics: While incorporating accessibility features in XR, developers and educators must navigate the complex landscape of conflicting accessibility requirements among different user groups. One promising avenue to enhance accessibility is haptics, a technology that can benefit not only blind and deaf individuals but also deafblind people by adding an additional sensory modality via which 3D virtual information can be relayed. Haptics also has the potential to enhance immersion for all users, making it a good candidate for universal design.

Neurodivergence: XR in education could be particularly transformative for neurodivergent individuals, such as those on the autism spectrum. VR in particular offers a unique advantage by allowing users to explore virtual environments before encountering them in the physical world, reducing anxiety associated with unfamiliar spaces (Mesa-Gresa et al., 2018). As mentioned above, XR may also offer a means by which extraneous stimuli could be removed, reducing stressors for some users in the learning context. The limited access to these technologies today, and limited research and development into accessibility provision, means that the potential benefits for neurodivergent and disabled individuals cannot yet be fully realised. When the technology is more available, neurodivergent learners may require additional time to familiarise themselves with XR technology before it can be effectively integrated into the classroom setting.

Co-design: the inclusion of disabled and neurodivergent groups in the design process offers an opportunity to make strides in accessibility through the participatory process of co-design. Inadequate community engagement poses a risk of overlooking the needs and preferences of marginalised groups and could result in the technology excluding those groups. Successful co-design offers inclusion in the process, from the initial stages of identifying their requirements to the subsequent design and development phases (Newbutt et al., 2023; Millington et al., 2022).

Accessibility is likely to be an important factor in the speed and success of XRed adoption. Today's versions of the technology are aimed primarily at those with typical hearing and vision, and that carries some inherent exclusion concerns for those with hearing or visual impairments. And yet eye-tracking technology and haptic integration in particular offer potential routes to developing XR into an assisting technology for a wide range of users. Making good on that potential is a challenge for those developing the hardware and software for XRed deployment.

XRed: Future Research

The research community has been responsive in testing, piloting and implementing XR devices in a range of settings. However, given the relative immaturity of these technologies, we are looking at the road ahead and we call for substantial research support as these technologies are adopted at scale and as we gain new understandings on how to integrate them effectively in different learning contexts. Support for future research is needed:

To design, test and implement learning theories and experiences that take into account the full range of XR affordances.

To review regularly the accumulated research evidence and enable cross-sectoral knowledge sharing in order to determine best practices and pathways towards implementation of XR at scale.

To address the challenges, concerns and risks related to XR technology. Research evidence should inform the (re)design of future learning experiences and environments from a bottom-up approach, taking into account the needs of learners and educators, as well as their expectations and capabilities.

To develop and integrate new technological features (e.g., AI applications) responsibly, transparently, sustainably, and ethically.

ILLUSTRATIVE LESSON: "LEARNING UNTETHERED: IRON AGE SCOTLAND"

Here we describe a potential lesson in 2035. The lesson utilises XR technology in the delivery of an integrated curriculum lesson within the wider topic of Iron Age Scotland[1].

Learning Module

Exploring the Iron Age through Experiential, Integrated, XR-Based Learning

Last week: A field trip to a local archaeological site in Scotland

The most interesting objects were fragments of Roman pottery at the Broch of Gurness in Orkney. During the trip, students used their XRed glasses – supplied to every pupil in the region as standard – to see what the dwelling would have looked like when built, and, using Lidar scan data, what remains of it underground and invisible beneath their feet. A shielding pupil took part virtually.

Task: locate a 3D printed replica of a fragment found at this site. The teacher had organised an AR hunt where AR clues guided them on the hunt and provided pupils with the experience required to build new knowledge on scientific methods in archaeology.

Key Concepts

Ambition
Outdoor and XR-enhanced learning

Equality
Every child has access to the technology

Distance
XR-enabled distance learning

Ambition
Scientific inquiry, mathematical thinking, designing techniques, engineering, problem-based learning, history and literacy

[1] This illustrates a lesson within a learning module designed to feature key educational changes and developments introduced in this report, not a step-by-step lesson plan or unit.

Learning Module

Today's lesson: Learn about the shape, material and purpose of the fragment found on the field trip

The teacher starts the lesson by recapping several concepts explored in the previous lessons and during the trip. The teacher uses several audio and e-books to build a story of how life was in the iron age.

The teacher summons the 3D models of the site and Lidar data in the middle of the room. The children sit in an arc around the room, with desks, coats, and bags kept to the perimeter to avoid trip hazards. Pupils can virtually interact with the objects by observing them from different perspectives, rotating them, and scaling them.

> *"Here is the fragment you found – well done, class! Today we are going to use this to find out about the shape, age, material and purpose of the pot it came from. We will see how archaeologists use science to deduce all of this from such little information!"*

Pupils virtually match the fragment to one of a series of virtual pots of different shapes and sizes showcased in their own environments. Each pupil sees the fragment in an ideal position for them but not what others see, or the match that their peers are attempting. Jessie is visually impaired and uses haptic input and AI-driven audio description of the virtual scene to join in the task. Fran isn't visually impaired but finds the haptics helpful too for accessibility.

The teacher leads a discussion of the pot shape the fragment belonged to and explains that the different shapes were used at different locations in history, which we know from other archaeological digs – each pot being shown to the class in its own rich immersive context.

A subtle vibration on the teacher's ring controller indicates a pupil wants to ask a question but is shy about speaking out in front of the class. The pupil is shielding at home and is virtually present today. He sends a private voice note to the teacher asking how we can be sure about the age of the pottery. The teacher is then able to raise the question with the entire class and summons a large molecule model into the middle of the class. A simplified Carbon-14 decay animated 3D sequence is shown, and is introduced to the pupils via accessible visuals that are available from a 3D resource library.

To explain the material composition of the fragment the teacher summons a terrain map of the local area to the middle of the class.

> *"Here is a map of our local area, and there is the dwelling we visited. Notice the depressions here." says the teacher, using a virtual spotlight to highlight. "These are evidence of flint mines and we know that flint and clay were used in this period for ceramics."*

The teacher then overlays a geological survey of the area to show where the clay is. This overlay was prepared with simple 3D editing software that was part of teacher training, and is supplied to educators.

Key Concepts

Equipping teachers
Literacy and history via alternative formats

Space & Health
Spatial safety

Equality & Ability
Immersive rich learning contexts

Ability
Universal design and haptic feedback technology

Ambition & Best Practice
Complex knowledge rendered accessible via multimodal learning experiences, multiple forms of feedback and controls

Distance
Distance learning

Expertise & Equipping Teachers
Ecosystem of resources

Expertise & Equipping Teachers
Ecosystem of resources

Time and bandwidth
Teacher training in 3D authorship

Learning Module

Some local landmarks are added to the terrain map and pupils are asked to work in groups to find the nearest source of clay to their school and estimate the time it would take to bring it back to make their own ceramic pot.

The terrain map does not show modern buildings or roads so the task is a challenge. Differentiation is available by layering on local landmarks, buildings and roads, and the pupil's own home to help orientate them. This is visible only to the pupil, and the data the system operates from is secured on-device along with other protected personal information, and any accessibility accommodations.

To aid concentration the teacher utters "holo off" and the class's XRed glasses stop performing anything more than the accessibility functions. Using the CAD software, pupils work in groups to create their own 2D designs based on the shapes and models they explored. When they complete the task, they utter "picture this" and "submit" so the teacher can see the pupils' work. The pupils can provide peer feedback, anonymously, individually or in groups, at the teacher's guidance.

The class are tiring as the lesson nears its end. The noise of chatter increases and it is time to wrap up the lesson. "Class attention," the teacher says, and progressive noise-cancelling and subtle visual nudges in the pupil's glasses help bring the class attention to the teacher without a raised voice being required.

"We know the shape of the pot we want to create, and we know where to get the materials. Next time we will sculpt some clay and experiment with different types and loads of available fuel to get the heat needed to bake the ceramic. On Friday we will source and prepare our ingredients, then cook our own Iron Age meal to learn about meal preparation, techniques and types of food in the Iron Age. We will then analyse its nutritional balance."

Key Concepts

Safeguarding & Data
Secure integration of personal data

Transition
Aligning the medium to the learning intention, transition

Standardisation
Classroom workflow standardised across platforms.

Classroom management
Guided attention tool

Best practice
Integration of knowledge with the use of physical materials and processes

XRED: ROADBLOCKS, OPPORTUNITIES, AND RISKS

We have set the scene for XR and its deployment in Education, and given an illustration of a potential future XRed-enabled lesson. In this section we consider the path to XRed under four headings: Classroom Deployment, Pedagogical Adoption, Access, and Safety. Under each we find the Roadblocks, Opportunities, and Risks which motivate our conclusions in the Recommendations section.

Classroom Deployment

Widespread XRed adoption requires that institutions, not just individuals, invest in the hardware, software, training and infrastructure (including buildings, connectivity and support/ maintenance skills). Here we outline considerations around the 'classroom' - which just means any place where teaching and learning takes place, and 'deployment' which means every aspect of establishing the technology infrastructure required for that.

Space

XRed will enable teaching in a wide range of non-traditional contexts but traditional teaching spaces are far too densely furnished and populated with learners to make immersive (VR) teaching practical except for a chosen two or three learners at a time. That is impractical with current class sizes.

Establishing dedicated space (Case Study 2) or co-opting multi-use spaces (e.g., a gym hall) are the present workarounds for the challenge of finding sufficient space for 6DoF VR teaching.

MR or AR teaching, on the other hand, can be deployed in existing contexts since the user can continue to see and interact with their real-world surroundings quite naturally. This is where the trade-off between immersion and isolation is to be observed: for highly immersive and transportative XRed you need considerable space for a whole class.

Takeaways:

Classroom flexibility; tech-assisted classroom management; improved distance learning; tech-assisted transitions.

Current classroom size layout; behaviour management barrier; on/offboarding friction; lack of XR expertise; hard/software standardisation.

Recommendations:

Develop an XRed apt Product – *Industry*

Build an XRed Ecosystem – *Industry*

Anticipate XR Adoption – *Education*

Classroom Management

XR-enabled teaching promises to be exceptionally absorbing for students, but that makes communicating with them and managing lessons and behaviour a different kind of challenge for educators.

According to an OECD report, the average class size in the UK has been around 25. In the US it is perhaps a little lower, but in China it could be upwards of 40. That makes deployment across even a single class logistically complicated with today's hardware (Case Study 2). In general, onboarding, offboarding, teacher interventions for behaviour or learning, technical support, and the sharing of equipment between learners are all particular challenges for XR deployment with current equipment.

At some point in the future, XRed classroom management could compare favourably to traditional classroom management challenges, perhaps by aiding focus and allowing more efficient and tailored teacher interventions (Illustrative Lesson). In the short term, however, XRed adoption is limited by the support overhead associated with onboarding, offboarding, and class communication. Hardware and software design that enables autonomous onboarding, and facilitates rather than hinders class communication, would remove one significant roadblock.

Transition

It is challenging today to transition from traditional teaching to an XRed intervention, and back again. Hardware, software, and familiarity improvements over time are expected to make XRed transitions smoother, but for now they remain a roadblock to current use and represent an opportunity for significant future improvement.

Distance

Distance learning has long served rural and remote communities; yet, during the pandemic it became clear that XR could bring great distance learning benefits to a far wider audience (VR-by-proxy). Remote learners can virtually co-locate with each other, or their teacher, and share 3D information and 3D experiences. One of the great promises of XRed is that it removes physical barriers between learners and their peers, their teachers, and extraordinary learning contexts (see Illustrative Lesson).

Expertise

Whilst many teachers may have experienced XR, very few will have used it in their teaching. Fewer still will have the niche 3D and development skills required to build lessons that fit their specific intended learning outcomes (see Best Practice below). This means that there is presently a significant lack of expertise to use XRed effectively in the classroom.

Standardisation

Current XR equipment is diverse, requiring different hardware, operating systems, controllers, platforms, cables, power, networking, and software across different potential XRed deployments. Standardisation in the industry is currently lacking but would lower the cost and risk of earlier adoption, and would make maintenance and support considerably more practical and scalable.

Pedagogical Adoption

Widespread XRed adoption requires that teachers embrace the technology, adopt and adapt it for their own needs, and embed it into their practice. The initial roadblocks to this can concern psychological barriers, lack of opportunity, lack of resources, and lack of time. The longer-term barriers concern making sure that the content is pedagogically and technologically *aligned* in the sense that the technology and intervention are in the service of the intended learning outcomes, rather than mere pleasing byproducts, and ensuring that educators adapt what and how they teach to the new possibilities. This deep cultural change will need time, patience and investment. It will likely change how we think about models of teaching and learning, as discussed above.

Ambition

We can teach different things with computers, the internet, tablets, and interactive whiteboards than we could before those technologies existed. The same will be true when educators and learners have access to a genuine 3D medium. If we think only about how to translate what is taught today into XR, then we miss the opportunity to expand the ambition of education with the vast new teaching possibilities that XR enables.

Best Practice

It takes time and careful effort to discover what does and does not work with new tools, and XRed will be no different. What we can aim for, however, is to develop best practice guidelines that recognise that XR creates a "wow" moment for users that can distract us from assessing the genuine and lasting pedagogical benefit of using the technology. If the XR intervention could have been a 2D app or a YouTube video, then there is a lack of meaningful alignment between the task and the technology used. If the cognitive load is increased by use of XR, but that increased load is not an intended or desirable aspect of the learning, then XR may not fit. More generally, if the capacities of the technology are not genuinely aligned with the intended learning outcomes, then the technology will not be serving a genuine pedagogical purpose.

Equipping teachers

Few teachers today could author their own XR experiences or develop their own 3D content. That means that XRed faces a roadblock in the production of curriculum-appropriate content. Tools, and platforms can be developed to create an XRed ecosystem in which educators can be empowered to create the content that their teaching needs. This could also open up new economic models around the content created and shared by teachers.

Time and bandwidth

If teaching is going to be transformed then the agents of that transformation —education practitioners— will need to have the time and bandwidth to develop the techniques, engage with research, develop best practice, and create content to make it effective. Such time and bandwidth are in short supply today and a clear barrier to adoption.

Takeaways:

- Vast new teaching possibilities.
- Best practice not yet defined; equipment, training, and resources limited; teacher workload.

Recommendations:

Build an XRed Ecosystem – *Industry*

Build the evidence base for pedagogical efficacy – *Industry, Government*

Adopt early and evolve – *Education*

Access

Widespread XRed adoption is hindered in the short term by the lack of access to XR equipment and platforms. For as long as it seems luxurious or frivolous, it will carry the stigma of something which is drawing resources from more urgent and deserving areas. The potential gains of XR education are extraordinary, however, and making them available as broadly as possible is desirable.

Cost

Undoubtedly, there are high costs associated with some XR deployments, but the cost barrier to XRed is perhaps overestimated. Extraordinary experiences are possible today on devices that cost around the same as an iPad, and iPads are widely deployed in education. The difference in the short term is that the proportion of teaching that XR can support is far lower than that which an iPad can. A mature ecosystem and broad existing content resources make the iPad deployment (Case Study 1) a better value proposition today than an XR equivalent.

Equality

If XRed offers substantial educational benefits —and we believe it does— then the cost of the equipment becomes an important equality issue too. If it is only the preserve of those who can afford their own, and if not all learners can afford it, then that means some learners will be left behind. This is anathema to many educators and policy makers.

On the other hand, remote teaching could be greatly enhanced by XR technology, making for a more equal educational experience for those who are distance learning, e.g. learners who are shielding for health reasons.

Ability

The issues around access to XRed are not merely financial, of course. XR technology is currently developed for the typical user: the sighted, the hearing, the mobile, the dextrous, and the neurotypical. Those with disabilities —be they physical, sensory, or neurological— have not been the primary focus of the development of XR devices to date. Some XRed uses will undoubtedly leave some learners behind, but the extraordinary power of XR technology to transport learners and to read and understand the physical environment on behalf of the user represents a great opportunity for XR technology to be an aid to users too.

Ecology

XR technology could negate the need for a great deal of waste in terms of travel to and erosion of sites, the virtualisation of experiments, prototyping, or any form of costly simulation. Those are clear routes to an ecological benefit from XR in general and XRed in particular.

XR hardware requires materials to produce, and electricity to operate. The servers that support networking, content streaming, and sharing also bring new environmental costs.

The net effect of these ecological benefits and costs is not clear, and will likely evolve over time. It requires careful attention and consideration as part of considerations around XRed rollout.

Takeaways:

- Access improvements for some; potential for environmental gains.
- New access barriers for some; current cost-benefit ratio; environmental costs.

Recommendations:

Research accessibility in XRed – *Industry, Government*

Adopt universal design for XRed – *Industry*

Develop an affordable XRed apt product – *Industry*

Research ecological impact – *Government*

Safety

Widespread XRed adoption requires a higher threshold for Safeguarding and Health and Wellbeing considerations, and considerations around Data Security, versus individually adopted XR entertainment uses. This is because institutions and teachers have a duty of care towards their learners, because the user data could be so sensitive (e.g., biometrics can often be inferred), and because many learners will belong to vulnerable groups, even if just by dint of their age.[1]

Takeaways:

- Tech-assisted safety; highly personalised experiences.
- New safeguarding, health, and data challenges; unknown long-term impacts.

Recommendations:

Develop a secure and private XRed apt product – *Industry*

Research impacts on perception, cognition, and behaviour – *Government*

Establish data handling protections – *Government*

Safeguarding

Education is an essential gateway for many learners and that means that opting-out is not as easy a choice as it might be for an entertainment user of XR. Moreoever, many young learners in formal education will have little or no say in the tasks they are expected to undertake in school. This significantly raises the bar for the requirements around safeguarding for XRed over other XR uses due to the lack of choice.

Of clear concern to many is the unregulated and unsupervised social dimension of nascent XR (Allen and McIntosh, 2023). As with the early internet, it will take time to develop the safeguards for this new medium, but the development of Learning Management Systems such as Google Classrooms, Showbie, and Moodle give us existing infrastructure and precedent to build on.

Health & Safety

Trips, falls, and collisions are problems that could be exacerbated when using VR devices, in particular, given the disconnect from the real-world environment. The sophistication around boundary (or guardian) systems is improving and problems in single person experiences are limited. Multi-person users in a single space, such as a classroom, represent a novel challenge.

On the other hand XR devices could use computer vision to help people avoid hazards in their environment, and sensors on devices could augment the valuable health information that wearable technologies such as fitness trackers already provide.

Data

Computer vision and eye-tracking technologies are key to the successful operation of many XR experiences, and may bring a wide range of benefits through the data they gather and interpret. And yet this powerful new sensing creates new data opportunities and vulnerabilities for those using the devices, and for those in their immediate environment. The stakes are especially high where the data can be interpreted to infer biometric and health characteristics.

Where this data is handled, who has control over it, and who regulates the data controller are all key questions around XR devices in general and XRed in particular.

The Information Commissioner's Office of the UK has already identified this as an area of focus within their *2022 Tech Horizons Report* and have issued updated draft guidance (2023) around the UK's General Data Protection Regulations in light of new technology developments. It appears that the European Data Protection Board, and the Office of the Privacy Commissioner in each of New Zealand and Canada are also reviewing their respective data protection regulations to make sure that they are flexible and robust enough to address these evolving data challenges.

Wellbeing

Age limits exist on XR headsets and there has been a recent reduction in recommended age from 13 to 10 by Meta. One concern is that the age limit is too high to benefit younger learners. Another concern is that it might not be high enough if there are significant developmental implications, or impacts on socialisation. Even the weight of devices on young learners' heads has been raised as a concern.

We do not yet know the medium- or long-term impacts of extended XR use on behaviour, cognition, or perception. Whilst there is no particular reason for alarm today, research is plainly required in advance of widespread XRed adoption.

[1] A recent report by Hines et. al (2023). offers an in-depth survey of Safety and Privacy issues concerning XR technology more generally.

XRED: RECOMMENDATIONS

Here we organise our recommendations by sector.

XR Technology Industry:

Build a product, build the path.

- We recommend that the XR Technology Industry build XRed products that are apt for classroom deployment. This requires that they enable safe and autonomous on/offboarding for classes and that they have integrated tools for classroom management to support educators, but it also requires that privacy and accessibility are not afterthoughts.
- We recommend that the XR Technology Industry build an XRed Ecosystem of standardised tools and platforms which allow educators to be trained and to be able to create content fit for their purpose.
- We recommend that the XR Technology Industry supports robust research into the demonstrable pedagogical benefits, and not mere "wow" or imagined gains, of XR use in education.
- When the evidence is strong, the products apt, and the ecosystem established, then the positive case for XRed will be compelling. Costs must be controlled to ensure the overall value proposition is too.

Government:

Anticipate, support and safeguard.

- We recommend that Government attends to the power of XR technology today before widespread adoption takes hold. Private interests and the natural evolution of the technology cannot be relied upon to safeguard XR users in general, but especially learners using XRed in mandatory or option-limited contexts.
- We believe that the Government's role is to support research which will inform strategy and regulation. Urgent research is required concerning the potential pedagogical benefits of XRed, the potential impacts on perception, cognition, learning, and behaviour of learners and educators, the potential accessibility implications (good and bad), the new data implications, and the net impact on our environment.

Education Sector:

Prepare, align, integrate, and lead.

- We recommend that the Education Sector anticipate widespread XRed and start early — now— in the process of preparing teachers, curricula, and classrooms for that future.
- We recommend that Educators engage with research and develop best practice guidelines. These should outline where and when there is alignment between learning outcomes and the capabilities of XR technology and identify where XRed can support new, ambitious, learning objectives that were not possible before.
- We recommend that educators develop techniques for transitioning in and out of XR within lessons, and integrate the technology into practice in an inclusive way.
- More generally we think that the Education Sector must take the lead to ensure XRed is built to enable and support those who know best: education practitioners.

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CASE STUDY 1 – GLASGOW SCHOOLS IPAD DEPLOYMENT

Glasgow City Council is responsible for the city's state school system and in 2019 invested in supplying every pupil from primary 6 onwards (age 10+ approximately) with their own iPad and younger learners getting access to class sets. A phased rollout of 52,000 iPads were deployed as part of a wider £300m investment in technology infrastructure.

Computer tablets akin to iPads had been part of Sci-Fi long before they existed as high-end entertainment devices, then as productivity tools in a wide range of workplaces, and then as an educational staple (at least in Glasgow).

XR devices were also present in Sci-Fi before they existed as high-end entertainment devices. They are not yet widespread productivity tools, though they are used in certain contexts (architecture and design, engineering, surgery). The iPad's path to widespread educational adoption in Glasgow may hold some lessons for those pursuing the same for XR technology.

Reception:

Criticism before the rollout of the devices centred on the high cost of devices (luxury versus essentials), questionable educational benefit, available software/content, classroom management and safeguarding concerns (distraction, inappropriate content), time and resource for teacher training, tech support and maintenance. (These echo the concerns practitioners have voiced about the adoption of XRed too.) Many of the points are covered or linked to in this teaching industry article from the time.

A key example that was relevant to the discourse was a "failed" prior iPad deployment in California. As part of the learning from that process, the Los Angeles school district resolved to ask four questions about educational technology deployment:

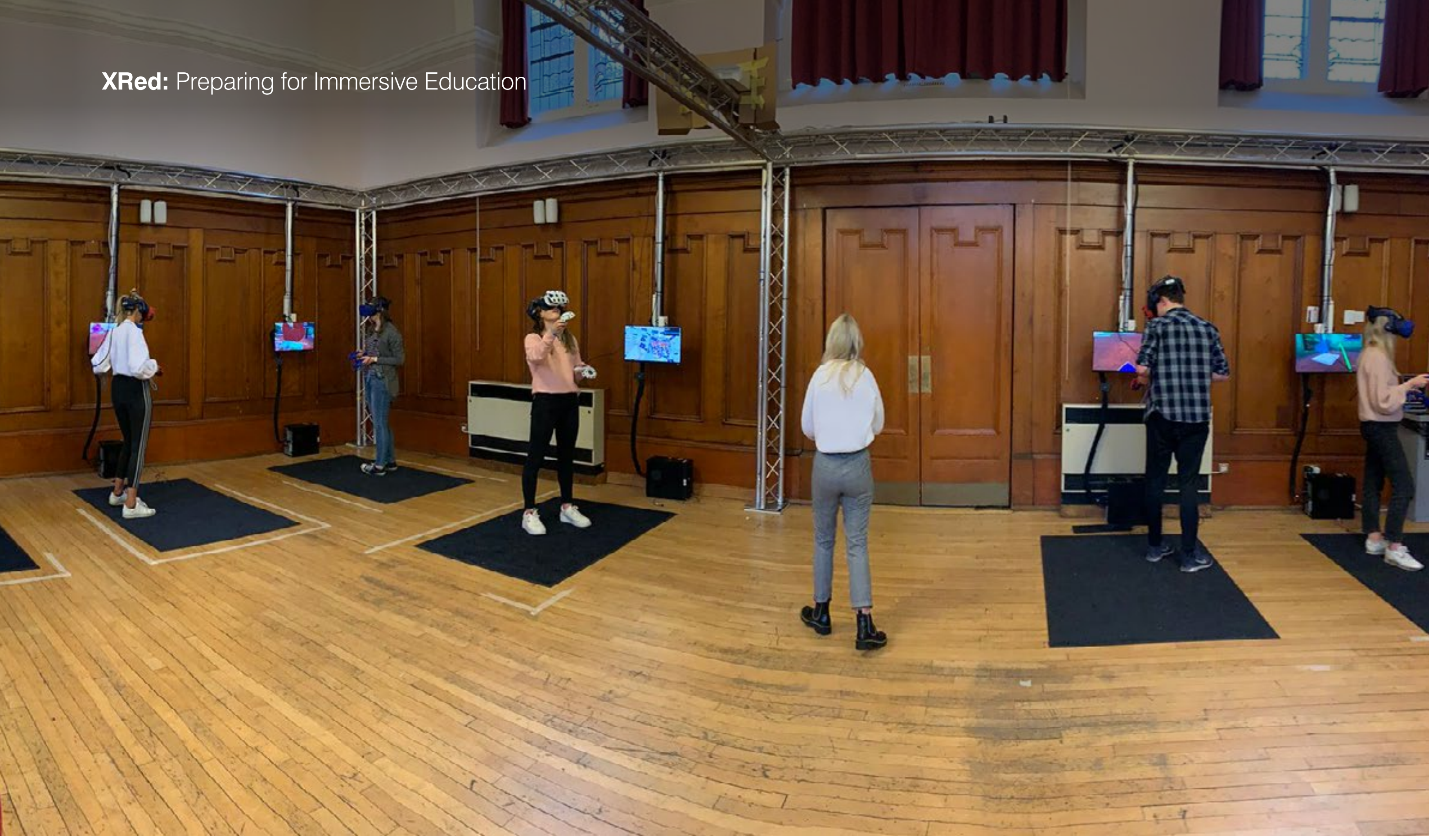
> *What will students learn? How will students learn? What resources will be needed? How will it work?*

The criticism levied at Glasgow and L.A. deployments, and the guiding questions about educational technology deployment, can be expected to be levied at the first wave of XRed deployment.

Rollout:

The rollout of iPads in Glasgow was at least partly informed by the lessons learned in California. Over a three-year implementation period leading up to deployment, Glasgow trained a selection of teachers to be digital tech champions in the teaching context (Digital Leaders of Learning) and worked to build a stable of curriculum-appropriate software/content with learning and teaching at the centre. Classroom management functionality was baked into the operating system of the devices allowing teachers to lock devices swiftly and easily, and share content to the board, or to learner's devices seamlessly. Support and maintenance were part of the overall contract procured. Favourable research was cited in defence of the putative educational benefits.

It is not our place to analyse or assess the success of the iPad deployment in Glasgow, but defenders of the importance of these iPads to teaching in Glasgow today are evangelical. We take this as an illustrative case study in the pursuit of responsible XRed deployment: the likely reception; the need for phased deployment and a lead up period of training and preparation; the need to keep focus on the learning and teaching outcomes.



CASE STUDY 2 – EDIFY AT THE UNIVERSITY OF GLASGOW

Project Mobius was a £1m collaboration between Sublime Digital (later: Edify) and the University of Glasgow to develop virtual reality teaching at scale. Innovate UK funded the R&D phase of the project (2018 – 2021) and the outputs include the Edify VR teaching platform and the Mobius teaching labs at the University of Glasgow.

Edify: Project Mobius started with an ideas competition within the University which asked teachers: assuming you had the equipment, the training, the support, and the right software what would you use VR to teach? The resulting ideas came from all across the University and variably harnessed different aspects of VR benefit: 3D objects handling, perspective of being in a place, the opportunity to go to impossible places or scales, to conduct dangerous procedures, or to make expensive and cumbersome teaching interventions more efficient. Ideas that leaned too heavily on the "wow" factor of VR, but did not align the unique selling points of the technology to the intended learning outcomes were not taken to the next stage. The ten initial winning ideas (several featured here) became the first apps to be built in the R&D phase and the lessons learned from developing and deploying them informed the creation of a Do-It-Yourself platform for VR lesson creation for teachers: Edify. This allows teachers with no 3D or coding skills to build their own lessons and to share with a wide non-VR audience through the VR-by-proxy tools within the platform.

Mobius labs: Whilst the teachers were asked to ignore the cost, equipment, support, and software development implications of their ideas, it was in fact a significant part of the R&D project to figure out how to deploy VR teaching at scale within a university context. The aim was to be able to take standard seminar or lab sized classes of 15 students simultaneously within one teaching hour. Two different approaches were trialled: Permanent PCVR (PC-powered VR), and pop-up standalone VR.

Permanent PCVR lab: This solution used the graphical power of dedicated computers and so required high end PCs (£2,500+) and tethered headsets (£500 - £1,200) to permanently occupy a space. Teachers could see what learners were doing by scanning monitors from the centre of the room and help where needed.

The estates implications of this were significant as at least 10m x 10m space was required to be wholly dedicated to this use. Rooms with low ceilings, pillars, insufficient ventilation, or uneven floors were not viable. In the end an off-campus solution was found in Partick Burgh Halls, around 10-minute walk from the main University of Glasgow estate. Issues around power, data, and fixings were exacerbated by the listed status of the building but were overcome through stage rigging. Initially a beacon system (Vive) for tracking headsets was deployed for stable tracking across sessions, but later inside-out systems were used due to interference between the beacons (Vive did not anticipate this kind of deployment and could not support it).

Native PCVR headsets (Vive Pro) created a smoother and more stable onboarding process than standalone VR headsets used in tethered mode (Quest, Vive Focus). The requirement for a Facebook account in order to use Oculus headsets in this way was unacceptable for educational deployment and ruled out the otherwise preferred hardware. This requirement was reversed by Meta in 2022 and Quest 2 headsets were used for this deployment in 2023.

As of 2023, 1,000+ students of the University of Glasgow are taught using Edify in this facility each year. Individual users also now have access to "Edify pods" in different schools in order to prepare and practice with the software before teaching.

Pop-up standalone VR lab: Standalone headsets allow a much cheaper and more flexible deployment as they do not require a tethered PC for every user. A wider range of spaces were viable for this deployment, and space could be occupied flexibly throughout the day – VR teaching in one hour, traditional lessons the next. To illustrate this flexibility, the student union bar was used for this deployment during the hours of 9am – 5pm, then equipment was packed away when the bar was being used in the evenings. Consumer headsets (Quest, then Quest 2) cost around £400, but for this deployment the enterprise edition (£800) licences were required.

Standalone deployment comes with significant drawbacks, however. First, the graphical power of the headsets were equivalent to that of a standard smartphone rather than a high-end gaming PC. This meant that apps had to be optimised to reduce graphics load and to remove functionality in order to run. Few of the original Mobius applications were suitable for such lightweighting, and it compromised the experience for the ones that could. Second, the onboarding of new users, and support for learners who needed help, was made considerably more difficult by the absence of a feed that would allow the teacher/technician to see what the user saw. If users could be guided on how to initiate a screencast then some support could be offered, but if a second person needed support then the whole solution became unstable. The enterprise software Oculus for Business was not fit for this deployment as individual users required the institutional PIN in order to initiate or cast their feed.

The lack of an apt hardware/software product for this kind of educational deployment moved the University of Glasgow to mothball this deployment in 2022.

Hybrid: It will soon be possible to use the power of PCVR and get some of the benefits of Standalone VR by adopting a hybrid solution. This involves PCs (or servers) delivering the graphical power to headsets wirelessly. Vive Business Streaming and Quest Link already offer this in principle, but network issues make the solution either unstable or unscalable in practice. Future XRed products may wish to support such a Hybrid solution.

Lessons learned:

The lessons learned through the University of Glasgow deployment can be seen in our identification of Roadblocks, Opportunities and Risks concerning: Space, Classroom management, Transition, Distance, Standardisation, Ambition, Equipping teachers, Time and bandwidth, Equality, Ability, and Health.

GLOSSARY

360 video – an immersive experience that is recorded using a camera that captures 360-degree input. This kind of immersive experience has limited interaction for the user as it consists of observation only.

Augmented reality (AR) – an immersive experience consisting of computer-generated augmentations which are seamlessly integrated into the visual field of the user, using either an HMD (see **head mounted display (HMD)**) or smart device screen.

Boundary (sometimes referred to as guardian) system – a safety feature that is built into VR devices which allows users to designate an area that is free of obstruction. When a user approaches the edge of this area, a visual indication is given (e.g., in the form of passthrough) to prevent the user from bumping into obstructions (see **passthrough**).

Cloud computing/edge computing – the delivery of computing services over a network, thereby disposing of the need for hosting bespoke computing resources on-site.

Computer vision – a field of computing science which enables computers to derive information from visual inputs and respond to those inputs, e.g., in self-driving cars.

Cross reality – alternative term for extended reality (XR) (see **extended reality (XR**)).

Custom virtual environment (CVE) – a 3D computer-generated environment built for a particular goal, such as virtual meetings, collaboration, or teaching.

Cyber sickness – a variant of motion sickness, which is induced by moving content on screens. In the case of XR, this may be induced by a mismatch between visually perceived motion and motion which is physically experienced.

Degrees of freedom (DoF) (3DoF vs 6DoF) – these refer to the number of ways an object can move through 3D space. 360 videos offer three degrees of freedom, as the user can rotate their head up/down, left/right and tilt it sideways. Computer-generated VR (see **virtual reality (VR)**) offers six degrees of freedom – in addition to the above, the user can also move forward/backward, laterally/vertically and up/down.

Extended reality (XR) – an umbrella term encapsulating virtual reality, augmented reality, and mixed reality.

Foveated rendering – an optimisation technique for concentrating rendering resources on the area where the user is immediately looking at, which is accomplished by in-built eye trackers which follow the user's fovea (i.e., the centre of their focus).

Games engines – software tools that enable developers to build 3D environments and interactions, used primarily for developing video games and, increasingly, for XR experiences.

Haptic technology – wearable technology which enables transmission of information to a user using tactile sensations such as touch, vibration or a feeling of resistance, e.g. through haptic gloves.

Head-mounted display (HMD) – a smart display device worn over the eyes of a user used for delivering a virtual, augmented or mixed reality experience.

Immersive technology – a cluster of digital technologies which deliver experiences to users in a way that feels like they are a part of the experience. This is usually thought to encompass augmented reality (see **augmented reality (AR)**, mixed reality (see **mixed reality (MR)**, and virtual reality (see **virtual reality (VR)**).

Interoperability – the ability of different systems, devices, or software applications to communicate, share, and work with each other effectively.

Lidar (or LiDAR) – an acronym of "light detection and ranging", a technology which enables scanning objects in 3D by measuring the time it takes light to reflect off their surfaces. Several smartphones today feature this technology, allowing users to create accurate 3D representations of objects and environments

Metaverse – the collective word for immersive experiences accessed via XR technology which enable users to interact with each other and the world around them. Also sometimes understood to be the next iteration of the internet, which will be distributed in 3D space.

Mixed reality (MR) – an immersive experience consisting of the mixing of elements from traditional virtual and augmented reality, for example, in the form of a passthrough view.

Passthrough – the experience of viewing the real world through a series of cameras on a virtual or mixed reality device. The concerted effort of passthrough and virtual augmentations results in mixed reality experiences.

PC-VR – a virtual reality experience powered by external computing in the form of a personal computer or server that is connected to the head-mounted display either via cable or network connection.

Smart glasses – wearable glasses capable of displaying information as part of a heads-up display, sometimes referred to as lightweight augmented reality.

Standalone VR – a virtual reality experience powered entirely by onboard computing resources of the head-mounted display (contrasted with **PC-VR**).

Universal design – the principled design of buildings, products or environments to make them accessible to all people regardless of age, disability, and other factors.

Virtual reality (VR) – an immersive experience mainly consisting of an entirely computer-generated environment which occludes the user's view of the world around them. Some VR experiences are not entirely computer generated and can contain video recordings (see 360 Video).

VR-by-proxy – the process by which a user shares in the experience of a virtual reality user, typically by casting a virtual camera feed from within the virtual experience to a 2D screen (such as PC, tablet, or phone).

XRed – widespread adoption of education delivered at least in part using extended reality technology.

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