The Need for Universal Design of eXtended Reality (XR) Technology in Primary and Secondary Education

Identifying Opportunities, Challenges, and Knowledge Gaps from the Literature

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Abstract. eXtended Reality (XR) provides new opportunities for immersive and engaging ways of learning in primary and secondary education. Educators and educational decision-makers, however, lack knowledge about the opportunities of this emerging technology. At the same time, XR technology lacks a fundamental universal design framework targeted at improving accessibility and usability for all, specifically for pupils with disabilities. In the following paper, we present the results from two selective and weighed literature reviews identifying: (1) opportunities, positive outcomes and challenges of using XR technology in primary and secondary education; (2) general advantages and limitations in terms of universal design, including barriers and possible solutions of XR technology for pupils with disabilities. The results show that utilization of XR technology in primary and secondary education is versatile, may positively influence learning outcomes in pupils, contributes to increase motivation, engagement, and interest. The challenges in implementing XR technology were mainly related to economic cost, health-related limitations, pedagogy, editorial limitations, and lack of universal design. Pupils with disabilities and varying degrees of abilities face challenges because there is lack of multimodality, practical issues when setting up or using devices, lack of interoperability and compatibility with assistive technology, financial costs, health-related issues, overreliance on gamification, and ethical considerations. In addition, most devices are designed for adults and not recommended to be used by children younger than 13 years of age. Future research needs to address development of guidelines including best-practice examples for increased accessibility and usability of XR technology, as well as advance the standardization and solidification of said guidelines into standards, regulations, and laws.

Keywords: XR, VR, AR, MR, Education, Universal Design, Accessibility, Usability, Primary and Secondary Education.

1 Introduction

Extended reality (XR) is an umbrella term that incorporates both virtual reality (VR), augmented reality (AR), and mixed reality (MR) [1]. Existing literature [2] highlights three main characteristics that enhance user experience making XR technology very suitable for primary and secondary education: (1) new ways of interaction, (2) high degree of immersion, and (3) information density of its content. Although multiple short-term studies involving ample types of XR-technology exist [3, 4], there are still significant gaps in the current research.

First, there is a general knowledge gap among educators and educational policymakers about the opportunities and challenges of this emerging technology in an educational setting. Even though many surveys about XR technology in education exist from a scientific or technological point of view, there are no comprehensive studies focusing on the interaction and correlation of educational curricula, technology, scientific methods, funding schemes, skill requirements, and universal design.

Second, there are gaps concerning the needs of pupils and teachers with cognitive, sensory, vocal, and physical disabilities and different degrees of cognitive and sensory abilities. Many aspects of XR technology, for example, are not accessible enough for users with common eye problems [5]. In general, the universal design of XR technology has not been sufficiently discussed, and there is a lack of guidelines, frameworks, and best-practice examples to address these problems [6, 7].

We attempted to close these gaps by conducting a selective and weighed literature review, in which we chose the most relevant literature of the past five years related to (1) the use of XR technology in primary and secondary education, and (2) universal design of XR technology including issues about accessibility and usability. We compiled a summary of the relevant research to date, identified new gaps, and highlighted opportunities for future research.

2 Methodology

The need for a literature review arose in conjunction with the development of an interview guide. The guide would be implemented for conducting group interviews with representatives from schools, municipalities, user organizations, and XR developers about the educational use of XR technology, and the universal design of the technology. We defined a search protocol based on the research by [8] and simplified it with suggestions by [9]. The protocol consisted of three steps: (1) planning the review, (2) conducting the review and selecting the articles, and (3) extracting and analyzing the data. During the planning phase, we defined research questions, inclusion criteria, as well as exclusion criteria, tested and selected relevant keywords, set up relevance assessment parameters including necessary requirements, and agreed on relevant search engines. We defined the following research questions:

1. What is the state of XR technology usage in primary and secondary education?
    - 1.1. For which courses in primary and secondary education has XR technology, e.g., VR, MR, and AR, been used?

   1.2. What devices are most used in primary and secondary education?
   1.3. What scientific design patterns and methods are deployed to evaluate the interventions? What kind of data is collected and how? How many participants participate in the interventions?
   1.4. What are the positive outcomes of using XR technology in primary and secondary education?
   1.5. What are the challenges and limitations of using XR technology in primary and secondary education?
2. What is the state of universal design of XR technology in the literature?
   2.1. How is universal design of XR technology, including its accessbility and usability, addressed in the literature? Who is promoting the universal design of XR technology?
   2.2. Who is researching and promoting the univesal design of XR technology?
   2.3. What disability groups are addressed in the literature?
   2.4. What are the general advantages of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities?
   2.5. What are the general challenges and limitations of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities?
   2.6. What barriers of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities does the literature address?
   2.7. What solutions for the previously mentioned barriers does the literature address? What general strategies for improved universal design of XR technology increase accessibility and usability for all, including people with disabilities?

We decided on both popular (Google) and scientific (Google Scholar) search portals. General inclusion criteria were literature from the past five years (2016 - 2021) including systematic literature reviews, state-of-the-art articles, opinion and position papers, doctoral theses, master theses, and gray literature. General exclusion criteria were commercial articles, advertisements, individual projects, and meta-reviews.

During the review and selection phase, we recorded the first fifty most relevant hits for each search string and compiled the results into a list containing the articles' title, year, and link. Then, we proceeded to read the abstracts of each article and checked whether the respective article passed the necessary requirements of the relevance assessment parameters defined in the protocol. Moreover, we skimmed the articles for compliance with the remaining relevance assessment parameters listed, awarding one point if the corresponding parameter was satisfactorily discussed. Then, we summed the awarded points for each article and sorted them in declining order, i.e., from highest to lowest score. Finally, we selected the articles with the highest scores.

We prepared and conducted two literature searches independently using two independent sets of search strings: (1.) A search about XR projects in primary and secondary education. The protocol parameters can be found in Appendix A. (2.) A search about accessibility, usability, and universal design of XR technology. The protocol parameters can be found in Appendix B. Originally, we targeted literature about the universal design of XR technology in primary and secondary education only. However, this resulted in a very limited number of papers. Thus, we decided on a more general approach for the universal design review.

3 Results

For the first search about XR projects in primary and secondary education, we conducted the first step of the literature search using Google Scholar as a search engine resulting in a list with 128 entries. In the second step, 53 of the articles passed the necessary requirements of the relevance parameters. In the third step, we applied the remaining relevance parameters and obtained 12 articles that had a score of 13 or higher. We eventually selected three articles with the highest scores of 15 (one article [10]) and 14 (two articles [2, 11]). One of the articles [2] was one of a three-part literature review series of which the other two [12, 13] ranked just one point below. One of the second-highest-ranking articles focused on MR including VR and AR while the other two articles focused on AR and VR individually. Thus, we chose to include the remaining two articles in the results as well resulting in a total of five articles [2, 10–13]. Thereafter, we identified educational courses, technology solutions, positive as well as negative effects of using XR technology in primary and secondary education, and reviewed scientific methods used to implement and evaluate XR-related projects in schools.

For the second search about accessibility, usability, and universal design of XR technology, we conducted the first step of the literature search using Google Scholar as a search engine, resulting in a list with 224 entries. In the second step, 129 of the articles passed the necessary requirements of the relevance parameters. In the third step, we applied the remaining relevance parameters and obtained 21 articles that had a score of 13 or higher. We eventually selected 14 articles: 3 articles having a score of 17 [14–16], 2 having a score of 16 [17, 18], 2 having a score of 15 [7, 19], and 7 having a score of 14 [6, 20–25]. Then, we summarized the general opportunities and limitations of XR technology for people with disabilities. Moreover, we extracted data about how UD is addressed in the literature and by whom. Eventually, we summarized barriers prevalent for people with disabilities and varying abilities categorized into cognitive, sensory (seeing-, hearing- and touch-related), vocal, and movement-related (both motor- and mobility-related) impairments as well as solutions for said barriers. Finally, we extracted general universal design strategies to make the technology more accessible and usable for everyone. In the following paragraphs, we will present our results according to each research question they relate to.

RQ1-1: For which courses in primary and secondary education has XR technology, e.g., VR, MR, and AR, been used?
VR technology has been used in, for example, environmental science, biology, geology, technology, mathematics, English language learning, and music [13].

AR has been used in Science, Technology, Engineering, and Mathematics (STEM), Humanities & Arts, Social sciences, Business & Law, Health & Welfare, Services & Others. AR is most often used in Science, Technology, Engineering, and Mathematics (STEM) subjects in primary and secondary education, specifically in formal science, natural science, physical science, and social science [12]. In primary education, formal and natural science are somewhat more predominant, whereas natural science and physical science are somewhat more predominant in secondary education [12]. Relevant science courses for AR have been, for example, mathematics, geometry, biology, ecology, physics, chemistry, geology, and computer science [11]. It has also been used in lab experiments and field trips [11]. In Humanities & Arts, AR has been used in language learning, visual art and painting appreciation, and culture and multiculturalism [11]. Less common were Social Sciences, Business & Law with library instruction, management and sales, and business, and Engineering, Manufacturing and Construction with automatics and robotics, laboratories, computer networks [11]. The least common use for AR is Health & Welfare and Services & Others [11].

MR has been used in formal science, e.g. mathematics, computer science, robotics, or information theory; in natural physical science, e.g. physics, chemistry, astronomy, biology, earth science like geography; and in social science, anthropology, archaeology, communication studies, economics, history, story-telling, or dramatic play [2]

RQ1-2: What devices are most used in primary and secondary education? The investigated articles cover all types of XR, i.e. AR [2, 10–12], MR [2], and VR [13].

There are four main technologies for VR used in education including (1) mobile VR like Samsung Gear VR or Google Cardboard, (2) wearable 360° spherical video-based VR, (3) room-sized 3D displays, typically with 2D or 3D projections on the wall, called Cave Automatic Virtual Environments (CAVE), and (4) head-mounted displays (HMD), e.g. Oculus Rift, Oculus Quest II, or HTC Vive, as well as hand-held displays (tablets, smartphones) [13, 26, 27]. The first two categories are most deployed in the classrooms whereas tethered HMDs with hand controllers are least commonly deployed [13]. Interaction is mostly done either by custom hand controllers, head movement detection through sensors embedded in the headset or through observation [13].

Devices used for MR are projectors projecting the augmentations on real objects, HMDs, barcode readers, large displays, monitors alone, or a monitor on a robot [2]. Many studies use embodied/authentic simulation MR as well as marker-based AR [2].

The interaction was provided by tangibles, AR cards, or motion-sensing devices [2]. Devices for AR technology used are (1) handheld devices like tablets (most common in primary education), and smartphones (especially for pupils with autism and intellectual disabilities), (2) computers combined with a (web)camera (most common in secondary education), (3) motion-sensing input devices (e.g. Microsoft Kinect), (4) head-mounted displays (HMD), (5) devices or screens mounted on the head (especially for pupils with hearing and vision impairments and autism), (6) glasses like Google Glasses, (7) large-screen projectors where stereoscopic projections can be combined with tracking cameras [10–12, 28–31]. Handheld devices are most common since mobile phones are very popular, followed closely by a PC combined with a webcam [11]. The trend towards handheld devices seems to be increasing [11]. There are several AR tracking strategies including (1) marker-based strategies, in which a camera and some type of visual marker trigger an event in the reader (QR, black-and-white pattern) [12]; (2) location-based strategies, in which GPS, digital compass, velocity meter, or accelerometer provides data about the user's location [12], and (3) markerless strategies, in which sensors accurately detect the real-world environment [12]. The most common software strategies are markers followed by location-based strategies. [10]. Marker-based AR is the most common strategy as it is considered as being effective, stable, and supported by a plethora of existing libraries [11, 12]. Location-based where position and orientation data of the device is used is the second most common. [11, 12]. Markerless AR where no marker is necessary is least common [11].

RQ1-3: What scientific methods are deployed to evaluate the interventions? What kind of data is collected? How many participants participate in the interventions?

Both quantitative, qualitative, and quantitative and qualitative methods combined are used to collect data [12]. Research methods are experimental studies like experimental-comparative methods or quasi-experimental studies, pure experimental study, user experience testing, usability testing, qualitative methods, literature reviews, single-subject design, transversal research, and mixed methods [10, 12, 13]. Other methods are mixed methods of qualitative and quantitative methods like qualitative-exploratory-case study, quantitative explanatory and causal research, quantitative-descriptive research, qualitative-exploratory-pilot case study [10, 11]. The most common research designs are explorative research methods or experimental comparative methods [2].

Tools used are questionnaires, interviews, surveys, tests, case observations, focus groups, surveys, case studies, and writing essays [2, 10–12]. The data is mainly collected with questionnaires, followed by interviews [11]. Less used methods are case observations, focus groups, and writing essays [11]. The data collected was of quantitative, qualitative, and mixed nature [2, 13].

Most studies take place inside the classroom [13]. The sample size of the scientific interventions is medium, and most commonly between 30/40 to 80/200 participants [2, 12, 13]. Some studies are low-sized with 30 or fewer participants, and very few were large-sized with more than 40 participants [10, 11]. The interventions are mostly short-timed, i.e. less than 50 minutes [13]. The intervention series are predominantly short-term and only a few long-term [11].

RQ1-4: What are the positive outcomes of using XR technology in primary and secondary education?

The following positive outcomes of utilization of XR technology have been reported: First, XR can influence learning outcomes in pupils, such as increased performance, gains, and feeling of achievement [2, 10–13]. Moreover, XR contributes to improvements in pupils’ social skills through collaboration, socialization, participation, and interaction [2, 10–13]. In some studies, improved language association has been recorded as well [12]. Third, XR technology has been associated with pupils’ improved self-image, including increased confidence, self-efficacy, and self-learning [10, 13]. Fourth, XR technology facilitates emotional reactions including enjoyment, general satisfaction, enthusiasm, and positive perceptions and attitudes towards learning [2, 10–13]. Fifth, XR technology is often reported to contribute to improvements in cognitive skills such as attention, memory, creativity, problem-solving [2, 10–13]. Likewise, XR technology is reported to increase motivation, engagement, and interest in pupils [2, 10–13].

RQ1-5: What are the challenges and limitations of using XR technology in primary and secondary education?

The studies have shown considerable challenges in multiple areas related to economic cost, physical space, health, pedagogy, editorial limitations, and universal design. First, XR technology devices tend to be more expensive than traditional education material. At the same time, XR devices, especially for MR and VR, can impose considerable space requirements for example for lighting and cable management [2, 10, 13]. Second, XR technology can be quite complex to set up and demand considerable training, at the same time there is limited qualification among teachers to utilize this technology [2, 10, 12]. Third, there can be health-related limitations in the form of so-called cybersickness where users experience for example nausea, as well as cognitive overload due to the sheer amount of stimuli user experience [13]. Fourth, the portfolio of available content tailored to individual national, regional or local curricula is still very limited [2, 10, 12]. Moreover, current XR technology is often very inflexible and does not allow adaptation or manipulation from one subject to another subject [2, 10, 12]. Fifth, XR technology lacks considerable research related to its accessibility and usability for pupils with common eye problems, physical and mental disabilities, or special needs [10, 32]. There is no robust framework to target general questions about the universal design of this emerging technology [33]. Sixth, there are considerable scientific uncertainties in existing studies as these often focus heavily on the novelty factor and acute results, leaving large gaps when it comes to long-term effects [2, 10, 12]. At the same time, there are challenges around limited sample sizes excluding any pupil with special needs, limitations on use of data collections tools, and comparing results between different curriculum subjects [2, 10, 12].

RQ2-1: How is universal design of XR technology, including its accessibility and usability, addressed in the literature to date?

Some of the articles present anecdotal cases, projects, and examples of barriers that people with disabilities might encounter, as well as solutions, or provide a compilation of helpful resources [21, 22, 34]. One article provides a thorough survey of concrete barriers of XR technology for people with disabilities [15]. Universal design of XR technology is addressed by providing some very general and loose guidelines or recommendations for developers [18–20, 23]. One of the articles revisits accessibility guidelines from other ICT areas, like WCAG 2.0 for websites [23]. A few articles provide very concrete and more standardized guidelines and examples [14, 16, 24]. Other articles discuss questions around universal design on a more general level [6, 7, 25].

RQ2-2: Who is researching and promoting the universal design of XR technology?

There are initiatives, communities, and workshops as well as research organizations that address accessibility, usability, and universal design of XR technology [7, 14, 17, 18, 24]. XR Access, for example, is an initiative dedicated to the promotion of universal design of XR technology by providing relevant resources addressing the topic, as well as organizing symposia where representatives from the XR community discuss barriers, solutions, and general frameworks associated with the universal design of XR technology [35–37]. Moreover, there is one working group and initiative by the World Wide Web Consortium (W3C) listing user needs and requirements for people with disabilities, which is the one attempt dedicated to a somewhat standardized process to date [14, 24].

RQ2-3: What disability groups are addressed in the literature?
We could find the following disability categories addressed implicitly or explicitly in the literature:

1. Cognition: [6, 7, 14–16, 18–22, 24, 25, 34, 38]
2. Senses
   a. Seeing: [6, 7, 14–16, 18–22, 24, 25, 34, 38]
   b. Hearing: [6, 7, 14–16, 18–22, 24, 25, 34, 38]
   c. Touch: [15, 16]
3. Voice: [7, 14–16, 18, 20, 21, 34]
4. Physical
   a. Mobility: [6, 7, 14–16, 18–22, 24, 25, 34, 38]
   b. Motor: [6, 7, 14–16, 18–22, 24, 25, 34, 38]

RQ2-4: What are the general advantages of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities?
XR technology can offer opportunities for virtual access and inclusion, compensations for disabilities, safe spaces, personalization, assistive technologies, and rehabilitation.

With XR technology, people with disabilities can experience inclusion and virtual access that would be inaccessible in the real world [15, 21]. Users can, for example, travel to places around the globe, at the same time as XR technology can offer new opportunities for remote working [15, 20]. XR technology can compensate for disabilities in the virtual world. In virtual worlds, people with disabilities can overcome visual, auditory, vocal, or physical limitations or gain extra abilities like flight or superhuman strength [15, 20, 22]. Virtual worlds can create empathy in people without disabilities by letting them experience the world through the eyes and body of a person with disability [21, 22]. There are, for example, simulations for blind, deaf, and wheelchair users [15]. XR technology can offer a safe space where people with disabilities can learn to cope with new sensory or physical disabilities, as well as people with autism, social anxieties, and other mental health challenges can experience comfort and safety [21, 22]. Virtual worlds can be personalized such that they accommodate for special needs of pupils, for example, by eliminating or reducing visual or hearing barriers and distractions [15, 22]. XR technology can be used as assistive technology for example by guiding visual tasks or providing captions for hard-of-hearing people [14, 21, 22]. XR can offer various opportunities for therapy and rehabilitation [20, 21]. In the virtual world, users can experience reduced social isolation, anxiety PTSD, or pain [15, 20, 21]

RQ2-5: What are the general challenges and limitations of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities?
General challenges are mostly related to the lack of multimodality, practical issues when setting up or using devices, compatibility with assistive technology, financial

costs, health issues, overreliance on gamification, and ethical considerations. XR technology, and especially VR and MR, is a multimodal medium, i.e. it has the capability of engaging multiple senses and functionalities like vision, hearing, and touch as well as motion and haptic control [6, 38]. However, the focus on the visual presentation of many XR applications, and the lack of multimodality, e.g. conveying the same information in multiple modalities through, for example, visual, audio, or haptic cues, impose barriers to people with disabilities [6, 15]. Moreover, many applications only allow one type of control, but it can be important to accommodate for and around assistive technology, controllers, sensors, and tether cabling for users with special needs, especially, people with visual, auditive, and physical disabilities [6, 14, 15, 18]. What is more, there are practical challenges associated with the setup of XR devices. Some users, for example, the elderly or people with cognitive disabilities, might encounter difficulties when setting up or learning how to use virtual reality due to the unfamiliarity or novelty of the technology [20]. Many users with disabilities report a lack of options and flexibility of integration with other hardware like keyboards, buttons, or paddles, as well as customization options that could benefit their specific special needs [14, 15]. In many cases, XR technology is not compatible with assistive technology (AT) that people with visual, auditory, or physical disabilities use [14, 15]. In some cases, manufacturers have implemented manufacturer locks that limit compatible software to one or a few specific brands or manufacturers [14, 15]. Likewise, there are significant financial challenges to XR technology. The cost of VR and MR equipment is often too expensive, as well as mobile devices capable of AR are often not feasible where the budget is limited [15, 22].

Furthermore, there are a few significant health issues connected to XR technology. VR devices might cause motion sickness, and vertigo [14, 15]. Thus, most manufacturers do not recommend their products for kids under the age of 13 [39, 40]. Finally, there are general challenges of ethical considerations related to for example virtual violence, bullying, virtual sex, and participation in the virtual worlds [20].

RQ2-6: What barriers of XR technology for pupils with disabilities and different degrees of sensory, physical, and cognitive abilities does the literature address? We will present the most common barriers for people with cognitive, visual, auditory, haptic, vocal, and physical disabilities.

Cognitive barriers are mostly rooted in differing mental capabilities, as well as bodily reactions to virtual stimuli. The literature lists, for example, cognitive barriers for users that have difficulties learning hardware in the form of new interfaces, input devices, or controls [20]. Other users with cognitive disabilities can encounter barriers in thinking, remembering, and concentrating especially where no breaks are allowed [15]. Moreover, sensory overload can exhaust users, and even cause seizures [15]. Lastly, some users can experience vertigo or motion sickness in the virtual world [20, 25].

The most common visual barriers are related to lack of multimodality, inaccessible elements of the user interface like menus, texts, or buttons, barriers due to color vision deficiencies, peripheral vision or decreased stereopsis, and hardware incompatibility with assistive devices. XR is to date a predominantly visual medium [22]. Thus, the negligence of an equally rich sound scape, and the lack of conveying visual cues and information to other senses like hearing or touch, e.g. multimodality, can decrease the experience for people with visual disabilities or make it completely inaccessible [14, 15, 20, 22]. Inaccessible user interfaces that do not provide labels or alt-texts for elements, and that do not allow resizing of text or choice of different color contrasts, can make menus and other important elements of the application inaccessible for people with visual disabilities [15, 20, 25]. Users with reduced or absent color vision or stereopsis, as well as users with peripheral vision can encounter significant barriers in the virtual world [15, 20]. Moreover, hardware incompatibility with assistive technology (ATs) like screen readers or magnifiers can impose significant barriers for people with low or missing vision that often rely on the use of these ATs when interacting with ICT applications and devices [14, 15, 20].

Most barriers for people with hearing disabilities are rooted in the lack of alternate modalities, hardware difficulties, insufficient sound design, and lack of communication alternatives. In some applications, there are no alternative modalities for visual cues or commentary, like the visual barriers described above [15]. Hardware interference with hearing aids or feedback can impose significant barriers for people with auditory disabilities [15, 20]. Insufficient sound design that does not allow localization of spatialized sound can make an XR application inaccessible [20]. Finally, the lack of communication alternatives like missing captions or sign language support can make communication in the virtual world impossible for people with auditory disabilities [15, 20].
Some users can have problems sensing haptic cues due to a lack of tactile touch or the capability to sense haptic sensations [15, 20].

People with vocal disabilities can encounter barriers where speech is used for interaction, but no alternative is offered [16].

Many people with physical disabilities can encounter barriers with XR devices that often require full-body interaction [21, 23]. More precisely, barriers for people with physical disabilities are often related to inaccessible controllers, energy and stamina requirements, and the inability to customize or personalize. Many papers point out the overuse of motion tracking solely based on non-disabled abilities and functions as one of the biggest barriers for people with physical disabilities [14, 15, 22]. Many XR controllers can be difficult or impractical to operate, especially where two hands are required [14, 15, 20, 21]. Likewise, many XR devices and controllers do not allow for personalization or customization accommodating for varying levels of reflexes, dexterity, range of motion, or finger strength [14, 15]. Moreover, many XR applications do not account for fatigue and pain, especially where they do not allow users to take pauses during the interaction [14, 15, 21]. Likewise, balancing in virtual reality can be challenging for people with physical disabilities [15]. Other barriers can be categorized according to different body parts. People with disabilities related to the head can encounter difficulties moving their heads to control or interact with a virtual world [15, 20]. Likewise wearing a VR or MR headset can be inaccessible for people with glasses, or when the headset is too heavy [15, 21]. People with disabilities connected to the arms and hands can have difficulties moving their arms or hands, as well as tracking hands for holding and griping [15]. People in wheelchairs can encounter barriers due to restricted movement and wire management that can get entangled in a power chair [15, 20]. Some XR applications do not accommodate for different heights of a user who is sitting in a wheelchair [14, 15, 20].

RQ2-7: What solutions for the barriers mentioned above does the literature address? What general strategies for improved universal design of XR technology increase accessibility and usability for all, including people with disabilities?
The literature addresses these barriers by proposing solutions implementation on the hardware/device level, as well as the software/application level.

Hardware/device solutions target especially input controllers as well as more flexible headsets. There are for example input controllers targeted at people with visual, auditory, or physical disabilities like white cane or braille displaying controllers, voice command, accessible input wheels, joysticks, mouses, or buttons [14–16, 18, 21–23]. Some papers present assistive technology for people with visual, auditory, vocal, and physical disabilities like screen readers, second screens, white cane controllers, or sound mixers [14, 15, 21, 22]. Additionally, software exists that targets people with visual disabilities that can be used as plugins with existing applications [5, 22].

Software/application solutions include the emphasis on in-game flexibility, personalization and customization, alternative communication means, improved multimodality, and increased accessibility of the user interfaces. Increased in-game flexibility can be obtained through the possibility of teleportation, observer-only mode, flexible time and reaction limits, focus indicators [14, 15, 20] as well as virtual aids that suggest corrections for errors, cues for depth-perception [14, 15, 20]. Personalization and customization should accommodate text size, color contrast, controller layout, height, and sound management [14, 20, 23]. Likewise, compatibility with assistive devices should be promoted [15]. Multimodality should accommodate for alternatives to visual or auditory information in form of text, descriptions, captions, vibrations, as well as complementing visual or auditory cues [14, 15, 18, 20, 21]. Especially, the focus on improved localized sound has been pointed out [15, 21]. Alternative communication means may include keyboard support, as well as speech-to-text, text-to-speech, and captions [14–16]. Finally, the importance of developing more accessible graphical user interfaces has been pointed out [15, 16, 21, 25].

As general solutions to increase the universal design of XR technology, the literature points out the need for research about its barriers and solutions, standardization, improvement of XR devices, and the inclusion of people with disabilities in the design and development process [6, 7, 14, 16, 23]. Research about barriers and solutions should include literature review and ethnographic studies [6, 7]. Especially the need for increasing accessibility and usability of XR devices and their controls has been pointed out [6, 7, 25]. The results of the previous two points should result in a standardized framework containing guidelines, checklists, and best-practice examples [7, 14]. An outline of such a framework exists already today [14]. Finally, users with disabilities should be included very early when designing and developing XR technology to increase the accessibility and usability of XR devices and applications [6, 7, 25].

5 Discussion

In the following sections, we will discuss the limitations of our chosen methodology, the results related to the educational use of XR technology, and the results related to its universal design.

To begin with, we chose a selective, weighed literature review rather than a systematic literature review because of time and resource constraints. Our first initial trial searches revealed that there were many papers and articles about individual projects. However, our focus was to get an overview of the state-of-the-art of educational use of XR technology and its degree of universal design. Thus, we limited our selection to those papers and articles that addressed all or most of the research questions defined above. Moreover, we weighed each paper according to whether relevant themes and topics were covered explicitly or merely coincidentally. For the education research that meant the inclusion of surveys that investigated both advantages and challenges, education subjects, methods, and technology in both primary and secondary education. Special points were attributed to papers that addressed accessibility, usability, and universal design explicitly. For the universal design search, that meant the inclusion of articles and papers that investigated concrete barriers for people with disabilities and their practical solutions, addressing the needs of multiple user groups, and discussing general frameworks for universal design of XR technology to increase its accessibility and usability for all. Points were deducted were only individual or few user groups, and where individual projects were addressed.

In general, our search revealed numerous articles about individual and singular projects. The educational search provided many scientific papers, whereas the universal design search revealed mostly popular, popular scientific, and gray literature as we will discuss below. Moreover, we discovered a plethora of existing systematic literature reviews of various focal points for the educational search. In contrast, we could not identify a significant amount of systematic literature reviews concerned with the universal design of XR technology or its accessibility or usability. Papers concerned with the UD of XR technology were almost exclusively opinion, concept, or scoping articles. Thus, our present paper is one of the first literature reviews covering these topics. However, there is a need for a more systematic review of the literature in the future.

Likewise, we decided on a general approach when extracting data from the articles as well due to our defined need of getting an overview. The papers related to the educational search, for example, contained a variety of data including individual projects as well as detailed descriptions of scientific methods and others. The universal design articles contained concrete examples of barriers for people with disabilities as well as singular projects providing solutions for these barriers. Since the main purpose of this selective and weighed literature was to inform an interview guide for group interviews with representatives from schools, municipalities, user organizations, and XR developers, we limited the extraction of data to the points described above. Thus, a future systematic literature review could cover more detailed data points like the categorization and systematization of barriers for people with disabilities and their possible solutions.

On the one hand, our selective and weighed literature review revealed the key opportunities, and challenges of XR technology in primary and secondary education.

One common thread that runs through many of the XR projects compiled in the surveys is the singular nature of the interventions with significant research gaps. Even though research exists about the advantages, and limitations of using XR technology in education, there is still a research gap related to the repeatability and objectivity of these results. Most notably, future research could benefit from increased standardization of research methods and increased visibility of concrete advantages and limitations of the technology. Moreover, projects involving XR technology in primary and secondary schools are often individual interventions separate from the regular curriculum focusing on one single subject and taking place with a limited group of subjects for a limited period. At the same time, the literature shows that the application areas of XR technology are extremely versatile covering areas from STEM, Social Science, Language Education, to Arts. We argue, thus, that research of XR technology as a mediator in primary and secondary schools has a dire need for diversification, integration, and additional and alternative reuse for multiple subjects simultaneously.

First, diversification of research should address multiple types of intervention, data collection methods used, sample size, intervention length, and the inclusion of more diverse subjects for the interventions. Many of the surveys we reviewed, for example, pointed out the need for more participants and a prolonged time for the interventions. Moreover, there is a need for the inclusion of pupils with disabilities that have been underrepresented in the literature so far.

Second, the integration of research means both the integration across multiple subjects and the integration with existing, more traditional teaching aids. Amit the vast range of possibilities that XR technology can offer, and that already exist, there is little correlation and intersection between individual projects. Likewise, many XR projects exist in a sandbox without any explicit connection or interactive interfaces to other teaching aids like books, physical models, or software. To exploit the full potential of and increase acceptance for XR technology, however, it is necessary to find a common ground for the individual projects, provide possible interfaces to interact and exchange information between projects, and investigate and highlight the opportunities and intersections of XR technology and the school curriculum.

Third, the integration of XR technology directly leads to the increased reuse of XR that eventually will increase the feasibility and sustainability of its technology. One major challenge reported in the literature is the cost of the technology. Even though costs for XR devices and applications have significantly decreased in the past years, many schools still struggle with the procurement of a still relatively young and unknown technology. Education budgets on both the national and local level have traditionally been very limited, and many schools have down-prioritized a technology with limited use and unknown outcomes like XR technology in favor of essential services and personal costs. As XR technology becomes more versatile, diverse, and better integrated, however, we argue that XR devices and applications could become a viable supplement to traditional teaching aids in the future. In addition to pedagogical opportunities, there might be yet unknown synergies as well. The possibilities in remote education, for example, have not been investigated so far. Providing engaging teaching experience for pupils that live in remote places or that cannot participate because of other reasons - one might think of pupils that are in quarantine during a pandemic not unlike the one we have seen in recent years - might lead to innovative and more inclusive ways for education.

On the other hand, our selected and weighed literature review highlighted the need for focused efforts to increase accessibility and usability of XR technology towards a significantly more inclusive and extended universal design of this emerging technology.

Our search results reveal that scientific research within the field of universal design of the technology is still limited. Whereas we found an impressive amount of scientific research articles addressing interventions of XR technology in primary and secondary education, there was only a very limited number of scientific papers concerned with the accessibility, usability, and general universal design (UD) of the technology. The most common types of scientific articles somewhat related to UD of XR technology were indeed usability studies of existing applications and devices. Many of those studies, however, did neither explicitly mention the inclusion of people with disabilities or address their needs. Moreover, there were some individual studies and reports investigating stand-alone solutions for specific user groups like toolboxes for people with low vision or special input devices for people in wheelchairs [5, 41]. A common finding of scientific studies or industrial reports was that research was missing a general, overarching framework or initiative to put needs, barriers, and solutions into correlation to each other. To put the experiences of multiple groups in context to each other makes sense since many people with disabilities can have multiple disabilities at once [42, 43]. At the same time, improvements for one user group might create synergies for other user groups and the public as well, a phenomenon often referred to as the “curb-cut effect” in universal design research [44]. Improving multimodality in XR, e.g. the process of conveying information to multiple senses simultaneously, could improve accessibility and usability for multiple user groups significantly. For example, providing auditory or haptic alternatives for visual information introduced for blind and low-vision people can significantly augment the experience for other user groups as well. Optimizing the graphical user interfaces (GUI) to accommodate people with screen readers might help users with other assistive devices as well. A more accessible GUI that accommodates for customization of font size, font color, color contrast and background noise reduction can benefit elderly people as well. Subtitles introduced for deaf or hard-of-hearing people can benefit both people with cognitive disabilities, as well as people that are in a physical environment with loud background noises. There is a need for research that investigates these synergies as well as communicates them to the public.

As we pointed out above, there was a noticeable lack of scientific research addressing the universal design of XR technology in a unified model. However, we could find an adequate number of articles in popular, popular scientific, and gray literature. Scientific studies that *do* address the UD of XR technology almost exclusively emphasize the need for more UD research [5, 6].

At the same time, the need for UD has not been unnoticed in the industry and communities involved in the design and development of XR devices and applications. There are communities of designers and developers of both XR hardware and software dedicated to tearing down barriers while increasing improvement with the accessibility, usability, and universal design of the technology. These communities take form as initiatives both explicitly dedicated to the inclusion of XR technology and subgroups of general XR associations, and working groups organizing, and arranging workshops and conferences from which they publish reports [7, 17, 24, 35–37, 45].

Moreover, we can witness the beginning of a standardization process under the direction of the World Wide Web Consortium (W3C) that has been a pioneer within the standardization of accessibility of websites, an effort that has been enshrined into both national and international laws and directives [14, 46–50]. However, this standardization effort has merely begun and lacks a more general and unifying approach addressing among others user needs of and requirements for several groups of people with disabilities. Many barriers for people with disabilities, and possible solutions for those barriers, have been investigated in one significant report by Lucasfilm's ILMxLab and the Disability Visibility Project [15]. We could not, however, find an independent, equally comprehensive, and peer-reviewed report in the scientific literature that would test the repeatability of their research, confirm or refute their findings, and fill in the gaps that have been pointed out by the report. Research that investigates barriers for people with disabilities and their needs, as well as solutions is very much needed to establish, develop, and promote a robust universal design framework for XR technology.

As mentioned earlier, there are some papers and initiatives outlining the general concepts of a universal design framework for XR technology [6, 7, 14, 16]. Besides the comprehensive compilation of user needs and requirements including descriptions of possible barriers for people with disabilities as mentioned above, there is a lack of practical guidelines and call for actions supporting designers and developers of XR devices and applications. Such guidelines are well established in other areas of ICT like the Web Accessibility Guidelines (WCAG) administered by the W3C or guidelines for inclusive game design [46, 47, 51]. Such guidelines often follow a structure that explains common barriers for affected user groups, compiles solutions of those barriers and provides use cases and best-practice examples on how the solutions can practically be implemented. At the same time, guidelines like WCAG 2.0 and WCAG 2.1 and checklists derived from these guidelines can be used as reference by user organizations, municipalities, supervisory authorities to investigate whether an ICT device or application contains some of the barriers or conforms to the best-practice examples presented in the guidelines to eventually examine the degree of accessibility, usability and universal design of the device and application. It has been shown that a system of audit and certification based on standards and guidelines is the most common means by which universal design is enforced in other areas of ICT [52]. Thus, there is a need for developing the existing guidelines for practical use by designers and developers of XR devices and applications, as well as user organizations and authorities.

6 Future work

Our selective and weighed literature review uncovered multiple opportunities for future research both scientific and practical, related to the use of XR technology in education as well as related to the universal design of the technology. There is a need for strengthening research on both the educational use of XR technology and its universal design. In general, there is a need for a more detailed, systematic literature review focusing on literature related to barriers of XR technology for people with disabilities, and questions around the accessibility, usability, and universal design of this emerging technology. Education research should focus on, for example, longitudinal studies, inclusion, and a combination of different and multiple research methods and data types increasing the sample size as well as including more pupils with disabilities. At the same time, future research should investigate the educational effects and impacts of using XR technology in the classroom as well as its integration with existing curricula and traditional teaching aids. Universal design research should focus on the identification, categorization, and systemization of barriers for people with different types of disabilities, as well as the development of solutions for these barriers. Moreover, future research should intensify the development of guidelines including best-practice examples for increased accessibility and usability of XR technology, as well as advance the standardization and solidification of said guidelines into standards, regulations, and laws. Lastly, there is a need for as strengthening, consolidating, and integrating national and international communities concerned with the universal design of XR technology, as well as raising awareness for, making visible, and promoting the need for universal design for people with disabilities and all people, to developers and designers of XR devices and applications, authorities, municipalities, educators, and the public.

7 Conclusion

This research shows that XR technology offers promising opportunities for primary and secondary education in most educational courses due to its representational fidelity and multimodality, as well as the possibility for a high degree of immersion, engagement, and interaction. Especially, the possibilities that come with the visualization of abstract concepts have been highlighted by many sources. At the same time, we reveal some significant opportunities for future research related to study design (the need for longitudinal studies, diversification of the scientific methodologies and the educational assessment), hardware development, cost reduction, as well as the need to improve teachers' digital skills, and finally the need to advance universal design of the technology. Further to this, our research reveals an urgent need for making XR technology more accessible and user-friendly to all people, including breaking down existing barriers experienced by people who have cognitive, sensory, and physical disabilities and varying cognitive and sensory abilities. Especially people with common eye problems, physical or cognitive impairments are partially or completely excluded from using XR technology today. Many sources emphasize the need of including representatives of these groups in the design process [5–7, 53]. Moreover, there is a need for a general discussion about the universal design of XR technology as a whole, resulting in guidelines, standards, or frameworks similar to those known from other areas of ICT like the Web Content Accessibility Guidelines (WCAG) for websites [23, 46, 47].

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Appendix A: Protocol parameters for the search about XR technology in primary and secondary education

Sources: We are including the first fifty hits of the search results in Google Scholar.
Inclusion criteria: We are using the general inclusion criteria described above. More precisely, we are looking for systematic literature reviews, scoping reviews, or survey articles about XR in primary and secondary education ("grunnskoler") including literature about XR OR Extended Reality, VR OR Virtual Reality, AR OR Augmented Reality, MR OR Mixed Reality, AND primary schools, secondary schools, elementary schools, middle schools, junior high schools
Exclusion criteria: We are using the general exclusion criteria described above. We excluded all papers that did not focus mainly on the technology part of XR technology. Moreover, we excluded papers that had the main focus on the following topics: (Senior) High school, and Higher education
Search strings (separated by ";"): ("extended reality" or "augmented reality" or "virtual reality") AND ("grunnskoler" OR "grunnskole" OR "grunnskolen"); ("extended reality" OR "augmented reality" OR "virtual reality") AND ("elementary schools" OR "elementary school") AND ("case study" OR "case studies") AND ("systematic literature review" OR "state-of-the-art"); ("extended reality" OR "augmented reality" OR "virtual reality") AND ("elementary school students") AND) AND ("education" AND "learning" AND "teaching") AND ("systematic literature review" AND "case studies"); ("elementary school students") AND ("extended reality" OR "augmented reality" OR "virtual reality") AND ("education" AND "learning" AND "teaching") AND ("systematic literature review" AND "case studies")
Relevance assessment: We awarded 0 or 1 point to each paper in each of the following relevance assessment categories:

- Does the paper address mainly AR, VR, or both (i.e. MR or XR). When the article addressed both, two points were awarded. (Necessary requirement.)
- Is the article a scoping state-of-the-art article, scoping article, or systematic literature review? (Necessary requirement.)
- Does the article discuss mainly primary and lower secondary school education? (Necessary requirement.)
- Does the article have clearly defined research questions?
- How many individual cases does the article address? None, one or multiple?
- Are the educational courses mentioned? When the article addressed more than one project, two points were awarded.
- Is the technology, e.g. devices, software, hardware, mentioned in the article?
- Are the benefits of XR technology mentioned in the article? Are the challenges mentioned in the article?
- Are barriers for people with different needs mentioned in the article?
- Is anything related to UU, accessibility or usability mentioned in the article explicitly?
- Are teachers' skills mentioned in the article?
- Are there explanations on how the outcomes have been assessed in the article?

Appendix B: Protocol parameters for the search about universal design of XR technology

Sources: We are including the first fifty search results in Google Scholar, and Google.
Inclusion criteria: W are looking for systematic literature reviews, scoping reviews, or survey articles about barriers, accessibility, usability, and universal design of XR technology including literature about XR OR Extended Reality, VR OR Virtual Reality, AR OR Augmented Reality, MR OR Mixed Reality, AND Universal Design, Accessibility, Usability, Barriers, Disability, AND Education, Learning
Exclusion criteria: We are excluding all studies that only mention universal design, accessibility, and usability peripherally, as well as usability or accessibility studies for individual projects whose results cannot be generalized.
Search strings (separated by “;”): ("extended reality" OR "augmented reality" OR "virtual reality") AND ("accessibility" AND "usability" AND "universal design") AND ("systematic literature review" AND "state-of-the-art"); ("extended reality" OR "augmented reality" OR "virtual reality") AND ("universal design” AND accessibility AND barriers) AND (disability OR disabled OR impairment OR disorder); (“extended reality” OR "virtual reality" OR "augmented reality") AND (accessibility OR usability OR "universal design") AND education AND (disability OR disabled); General literature search: ("virtual reality" OR "augmented reality" OR immersive) AND ("accessibility" AND "usability") AND (challenge* AND oportunit* AND need* AND barrier*); (“extended reality” OR "virtual reality" OR "augmented reality") AND (accessibility OR usability OR "universal design") AND education AND (disability OR disabled); (“extended reality” OR "virtual reality" OR "augmented reality") AND (accessibility OR usability OR "universal design") AND education AND (disability OR disabled) AND (challenge* AND oportunit* AND need* AND barrier*) ("upper limb" OR "upper body") OR ("lower limbs" OR "lower body" OR "wheelchair") OR (voice AND muteness) OR (blind OR “low vision”) OR (deaf OR “hard of hearing”) OR (cognitive OR intellectual OR developmental OR emotional); accessibility AND ("virtual reality") AND disability AND barriers; (barriers OR challenges) AND (VR OR AR OR XR) AND accessibility AND disability.
Relevance assessment: We awarded 0 or 1 point to each paper in each of the following relevance assessment categories:

- Does the paper address mainly AR, VR, or both (i.e. MR or XR). When the article addressed both, two points were awarded. (Necessary requirement.)
- Is the article a systematic literature review, scoping article, or concept/opinion article? Does the article represent comprehensive guidelines or a standard? (Necessary requirement.)
- Does the article address XR in education?
- Does the article address universal design?
- Does the article address the accessibility of the XR technology?
- Does the article address the usability of the XR technology?
- Does the article address the barriers of XR technology for people with disabilities?
- Does the article propose solutions to the previously mentioned barriers?

- Does the article address people with disabilities?
- Does The article address any of the following disabilities? Motor, Mobility, Voice, Senses (seeing), Senses (hearing), Senses (touch), Cognition