

Universally Designed Augmented Reality (AR) for the School of the Future

Making eXtended Reality (XR) technology inclusive for students with and without disabilities

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Abstract—Augmented Reality (AR), together with other technologies collectively referred to as eXtended Reality (XR), can offer opportunities in education for experiential learning and the visualization of abstract concepts. However, there is a lack of universal design and significant challenges for students with disabilities. In this paper, we present a case study of AR technology used in Norwegian schools to identify inhibitors and facilitators for the inclusive use of AR in education. We let students with and without visual and cognitive disabilities try out an AR app for books. The AR app would superimpose virtual 3D models and videos on the books similar to a pop-up book. Interviews with educators and a focus group session with developers identified opportunities, benefits, user expectation, best practices, challenges, and common pitfalls, as well as recommendations and concrete measures to address said challenges and pitfalls. Our study emphasizes the lack of support for assistive technologies, the over-emphasis on visual stimuli that can be hindering for students with visual disabilities, the significant demand of AR on cognitive capabilities, which might be challenging for students with cognitive disabilities, and the lack of awareness of and access to guidelines and best practices among developers. We suggest enabling compatibility with assistive technologies, increased multi-modality that engages hearing and touch, increased usage of visual explanations and elements like symbols and icons, in addition to collecting, organizing, and promoting existing and new guidelines for the universal design of both XR and AR. We argue that many of our findings for AR are relevant for other technologies gathered under the umbrella of XR, including Mixed Reality (MR) and Virtual Reality (VR).

Keywords - *Universal design; accessibility; usability; inclusion; eXtended Reality; Augmented Reality; Virtual Reality; Mixed Reality; XR; AR; MR; VR; education; learning; disability; barriers; solutions.*

I. INTRODUCTION

eXtended Reality (XR) is an umbrella term to describe Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) [1]. It has, for instance, been used in entertainment [2], industry [3], and education [4], [5]. XR has three main features beneficial for education, including new interaction methods, a high degree of sensory immersion, and high information density [4]. Previously, we examined the general state of universal design of current XR usage in Norwegian primary schools [5]–[8].

We conducted a literature review about different uses of XR, their opportunities and challenges, and we identified solutions to overcome these challenges and enhance the integration of XR in primary education [5], [6]. This review

shows that there are systemic and technical challenges that require improved pedagogical research and integration, skill-set and acceptance improvement among educators and decision-makers, infrastructure development for XR in schools, and development of funding and procurement schemes for the technology [8]. Further, there is a need for increased co-creation of XR technology, the identification of barriers for students with disabilities, the development of solutions for said barriers, the advancement of standardization of guidelines and best practices, and the development of methods to assess the degree of accessibility and usability of an XR device or application [7].

Moreover, we recruited informants among educators, decision-makers, representatives from civil-society organizations, and developers of XR technology [7], [8]. The participants emphasized the benefit of XR as experience based technology that can facilitate visualization of abstract concepts in an engaging and motivating way [7]. The informants also highlighted the need for making pedagogical benefits and limitations of XR better visible, including advice on utilizing opportunities XR technology offers, while mitigating challenges [8]. Especially the need for case study research and applicable solutions in schools has been emphasized. Likewise, there is a significant lack of research focusing on users and students with disabilities [7], [9], [10]. Last but not least, existing guidelines and best practices for digital user interfaces in general [11]–[13], and XR in particular [14]–[17], lack general recognition, acceptance, and compliance among developers [7]. The Web Content Accessibility Guidelines (WCAG) for accessibility and usability of digital interfaces, for instance, serve as standards in many national and international regulations for ICT [11]–[13], [18]–[20] but lack an adequate translation for XR technology.

In this work, we attempt to decrease the knowledge gap by presenting results from a case study that investigates the accessibility and usability of a concrete AR application used in Norwegian primary schools. We conducted user testing, interviews, and a focus group aimed at identifying opportunities and barriers of AR applications, and solutions to these barriers. The research involved students with and without disabilities, their educators, and AR developers.

In this paper, we first present the protocol for user testing and interviews, and its implementation. Then, we present the results of the user evaluations and interviews conducted in the fall of 2022 and discuss our observations. Finally, we conclude with suggestions for future research and improvements to the universal design of XR technology.

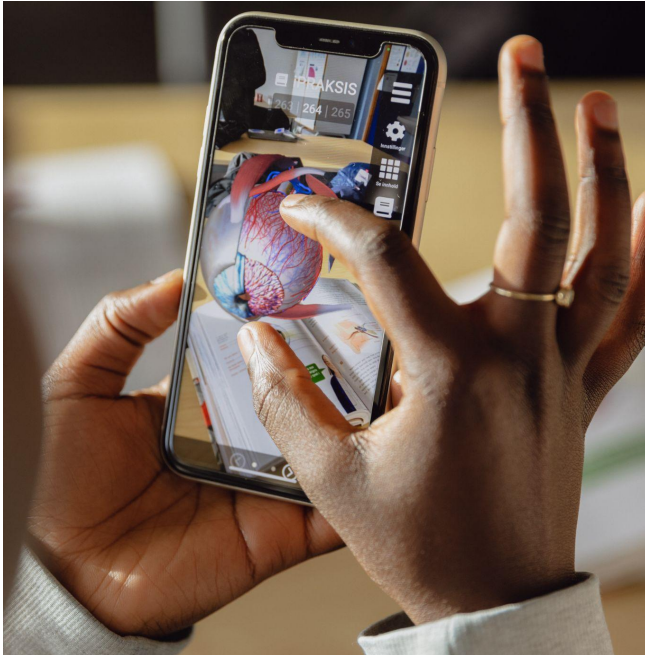


Figure 1. A student interacts with a virtual 3D model in the Ludenso Explore app on a smartphone. © Johanne Nyborg

II. METHODOLOGY & IMPLEMENTATION

Our accessibility and usability assessment was inspired by inclusive-design approaches and strategies for evaluation of design artifacts by focusing on user-centered evaluation, iterative processes, addressing the whole user experience, the integration of multidisciplinary skills and perspectives, and an iterative technical and formative evaluation [21], [22]. We used user evaluations by students based on a thinking-aloud approach as a primary research method. Here, we identified the key features of the AR application, and specified tasks that participants were asked to complete. A secondary method was focus group and semi-structured interviews engaging educators and developers [23], [24]. The protocols for the interviews consisted of guiding questions and conversation starters focusing on accessibility, usability, and universal design of AR in education.

In the current study, we evaluated an AR application for mobile devices called Ludenso Explore, developed by Ludenso AS (cf. Fig.1). The app is an extension to the science book *Solaris 9* used in Norwegian primary schools [25]. Ludenso Explore is similar to a traditional pop-up book in that students, after downloading the app, can gain access to various types of interactive content by scanning the pages of their book. Depending on the content, the app then shows an virtual interactive 3D model, a video that is superimposed on the paper page, or links to external digital learning resources on the publisher’s web pages (cf. Fig.1).

The user evaluations involved four primary schools in Norway during the fall/winter of 2022: Jordal ungdomsskole, Midstuen ungdomsskole, Holmen barneskole, and Greåker videregående skole. These schools represented a diverse range of students with and without

disabilities. In this study, we focused specifically on cognitive and visual impairments. A total of 34 students between 9 and 16 years, of both genders, participated. 15 children had cognitive impairments. The cognitive impairments can be categorized as ASD and developmental disabilities. Several of the students had personal assistants and teachers who also were interviewed. Three students had visual impairments. One student had a significant amount of remaining vision, another had limited remaining vision, and one student was completely blind. We also interviewed a teacher with severe visual impairment. During the user evaluations, the students completed the tasks defined in the protocol, using the AR app on their own phones or on the devices we provided. We asked them to comment aloud what they were doing and thinking as they completed the tasks, at the same time as we encouraged conversation with follow-up questions. The observations from these user evaluations were supplemented by conversations with 11 educators and three AR developers, which were conducted during one-on-one interviews and focus groups.

At least two researchers were present for each user evaluation. One researcher conducted the evaluation by presenting tasks, supporting students and asking questions. The other researcher focused on observation and notetaking. We did not take any recordings during the evaluations to preserve the students’ privacy. After the evaluations, each researcher transcribed observations from the experiments, and conducted a thematic analysis of their notes and summarized identifying themes to extract the most relevant and important points. Both researchers discussed their respective data sets. Finally, they summarized and compacted the findings across all evaluations combined.

III. RESULTS

Here, we present benefits and pedagogical opportunities, as well as user expectations and best practices, followed by systemic and practical challenges, and common technical and functional pitfalls. Further, we provide organizational recommendations, and concrete measures to improve universal design of AR. We grouped observations into sections. Each category is summarized in bold font, followed by detailed explanations and examples.

A. Pedagogical Opportunities and General Benefits

AR can engage students with the curriculum in novel and more practical ways. AR can effectively illustrate abstract ideas and “obscured” objects, like atoms or planets, replacing the need for physical models. AR can enhance practical knowledge compared to text or 2D sketches.

AR typically captures students’ interest and attention better than traditional learning materials, leading to increased interest, motivation, and engagement. This increased engagement and motivation might be related to the use of new technology and the fact that many students are highly responsive and significantly drawn to tablets and mobile apps. Likewise, AR can provide various gamification elements that stimulate engagement. At the same time, research questions the long term effect of XR technology in light of the so-called novelty effect [4], [10].

Consequently, AR might add variation to the learning process that can lead to positive learning effects, such as enhancing cognitive skills like comprehension and cooperation. For instance, AR allows for interactive exploration, enabling students to move around and zoom in on models, which can result in a better learning experience and increased understanding. AR may invite students to cooperate around the virtual content, and to learn from each other when navigating the app.

AR, on par with other digital learning aids, can provide benefits for the organization and distribution of curriculum materials. Organizing the curriculum digitally has the advantage of consolidating various resources in one easily accessible place for all students. Educators can more flexibly choose and use learning resources in the classroom.

AR has the potential to increase inclusion, if accessibility of AR technology is properly addressed. Compared to the challenges of adapting analogue learning aids in the past, AR can offer more flexible and easier adoption, as long as universal design is addressed from early on in the design and development process. In general, digital learning aids including AR could more easily be adapted for screen readers than traditional paper books. Likewise, AR could provide interfaces for assistive technology like hearing aids and alternative input/output devices. However, this requires developers to be aware of users with disabilities and address their needs satisfactorily.

AR serves as a suitable learning alternative for those who prefer visual and less text-based approaches, such as students with dyslexia, ADHD, or learning difficulties.

B. User Expectations and Best Practices

Users anticipate seamless and efficient user experience while utilizing an app, including installation, general usage, and scanning and tracking of virtual content. The students in the study appreciated a simple and convenient installation process of an AR app that can be downloaded from app stores like Apple's App Store or Google Play. They also appreciated robust and reliable tracking of AR content, particularly 3D models.

Users respond positively to user-friendly interfaces with intuitive and familiar functions and elements. The students appreciated quick and easy access to digital content, such as videos and 3D models. The students appreciated an interface that is easy to understand and intuitive, with comprehensive buttons and tabs. Choosing the right default is also essential. Many students, for instance, preferred watching videos in full screen. Likewise, they appreciated features like auto-play combined with intuitive muting of the video.

An intuitive navigation within the AR app was positively received. This includes navigation of AR content based on functionality known from other apps like zooming in and out using pinch gestures, along with familiar icons for full screen, muting and other functional elements.

Users prefer a variety of interactivity options with the virtual content. Many students preferred the option to access and freely interact with virtual content like 3D models by choosing it from a digital library instead of using

image recognition or AR markers that restricts them to the literal confines of the paper book. Also, many students preferred using the standalone function for 3D models, i.e. the possibility to place 3D models in the physical room without connection to the physical paper book.

C. Systemic and Practical Challenges

AR might encounter technical and practical challenges in schools. There might be limited access to necessary hardware and reliable online access with sufficient capacity in schools. Also, limited physical environments can hinder AR use in practice, like overcrowded classrooms with restricting space to move around in.

Lack of digital skills and experience with AR among educators and students might be a challenge. AR requires technical skills, posing a potentially steep learning curve for users, particularly older teachers who may struggle or are reluctant to adapt. Students with disabilities might lack the necessary skills to use AR devices.

Insufficient universal design of digital learning tools, including AR, is likely to negatively impact accessibility for students with disabilities.

There is a lack of awareness of and expertise in universal design of AR among developers and decision-makers in schools and authorities. The awareness and knowledge about accessibility and usability among developers can be improved. The participating developers were partially familiar with general programming guidelines for accessibility and usability [26]–[28]. Even though national and international legal requirements exist [18]–[20], [29], these are not widely known to developers.

Some developers were aware of WCAG [11]–[13] but reported that their knowledge about them was very superficial and not embedded in any organizational or structural routines. When presented with surveys of barriers [9], [15] and accessibility guidelines for gaming and XR [9], [14]–[17], the participants were not aware of them.

Universal design is by some considered costly and conflicting with aesthetics. The developers were concerned that limited resources and restrictive development budgets in AR companies may lead to situations where universal design is neglected. The developers in the study also reported a lack of demand for universal design of AR applications by decision-makers in schools, education boards, and authorities.

Focus on visual presentation of the virtual content can be a challenge for some students. AR predominantly embraces visual aspects, limiting its suitability for individuals with visual impairments or cognitive challenges. It is our impression that sensory and auditory elements, such as sound effects and tactile feedback, are not adequately addressed in today's digital learning tools, including AR.

AR and other digital learning tools may distract students. Students may be distracted from other apps. Potential noise issues can occur when multiple students use the digital learning tools simultaneously, for instance by playing video simultaneously.

D. Common Technical and Functional Pitfalls

Some apps may have technical challenges related to its stability, performance, unexpected behavior, or erroneous tracking of virtual content that can disrupt the user experience, together with unreliable devices and the lack of cross-platform compatibility. An AR app might freeze and exhibit unexpected behavior, requiring restarts. Some students reported that their device went into sleep mode while watching videos. Other students reported that some AR apps might be incompatible with newer versions of iOS or Android, limiting its usability.

Many students reported that they experienced unreliable tracking behavior in many AR apps. Some students struggled to choose the best camera position and angle for proper scanning of the AR markers. Other students experienced challenges due to heterogeneous illumination conditions or physical distortions of the AR markers.

Some apps lack tutorials, explanations for specific features and functions, intuitive presentation of functions, and sufficient feedback functionality. An AR app might lack suitable guides or tutorials, especially for users new to AR. The students in the study inquired explanations of AR and its possibilities in general, and how to navigate an app's features in specific.

Navigating the interface of an AR app and understanding its elements and functions might prove challenging for some users. Some functions might not be explained sufficiently. Some students might not understand features like muting, full screen mode when indicated by icons only. Features like choosing 3D models from a library instead of scanning might be particularly difficult for and feel non-intuitive to students with cognitive impairments.

Apps might lack feedback after particular functions have been completed, either successfully or failed. An AR app might not provide proper feedback on functionality, like downloading content, leaving users uncertain about successful or failed downloads.

Some apps lack localization for the country in which the app is deployed. An AR app targeted for Norwegian schools that is only available in English can pose difficulties for younger users or users with cognitive disabilities who may not fully understand the language.

AR apps might not conform with universal design requirements and common accessibility guidelines. An AR app might not adhere to commonly used accessibility guidelines [13], [16]. The most common missing measures include alternative ALT text for images, support for screen readers, proper semantic markup, adjustable text sizes, audio descriptions for videos, and keyboard navigation.

The content of an AR app might be unsuitable for students with cognitive impairments. Videos may be too complex or delivered at a fast pace, posing difficulties for reading and comprehension.

Motion-based navigation of 3D content can be challenging for students with and without disabilities. Visually impaired students might encounter challenges, as well as any students in small classrooms. Physical devices,

such as tablets, may be challenging for young or physically impaired users due to their weight.

E. Organizational Recommendations

There should be an effort to increase awareness of and expertise in universal design of AR among developers, educators, and decision-makers. Educators and decision-makers in municipalities need increased expertise in and awareness of accessibility, usability, and universal design of AR at all levels including development, testing, and procurement. Awareness can be raised by revisiting literature about barriers of XR technology and their solutions [5], [8], [9], [15], [16]. Likewise, training for developers and decision-makers should focus on universal design of ICT and digital inclusion in general, considering how universal design requirements can be integrated with modern and effective development and production.

Schools should consciously demand universal design of digital learning materials and content, including AR, as a mandatory requirement by referencing existing legislation and live it in practice, too.

Research on the cost-benefit of universal design in AR should be conducted and shared with stakeholders. Especially, the hypothesis that universally designed AR is more beneficial and cost-efficient than AR without UD should be investigated.

Priority should be given to the development, organization and distribution of guidelines, best practices, evaluation methods, and action plans. All digital learning materials and content should comply with national and international legal requirements and standards for universal design of ICT [18]–[20], [29]. Existing guidelines for universally designed programming, XR, games, and user interfaces should be distributed and promoted among developers [12]–[14], [16], [17], [26]–[28]. Relevant guidelines and best practices for AR and XR should be organized and highlighted for the production of XR applications (cf. sec. F.).

More research on the needs of and challenges for XR users with disabilities and the solutions to said challenges is needed. More resources and literature targeting the universal design of XR in general and AR specifically should be developed for vendors of XR technology and content.

Companies should create and implement concrete plans on how universal design is integrated in their development and production of products and services. Automated accessibility and usability tests, e.g. contrast checks, should be available for developers. Checklists, recommendations, and best practices tailored to XR and AR should be created.

Development should include user testing throughout the entire planning, implementation and testing stages of the production process, making the app as flexible, robust and glitch-free as possible. Developers should deploy an agile development process with multiple iterations of planning, execution, review, and retrospective [30]. In this process, bugs and performance issues can be uncovered and then fixed. From the planning stage to pre-release, the app should be tested by actual students with and without disabilities.

F. Technical and Practical Measures to Increase Universal Design of AR

Robust and stable scanning of the markers or image recognition should be a priority, as well as stable and robust tracking. This includes accommodating various exterior conditions related to lighting, surface texture and structure, as well as a variety of possible user interactions. The AR app should be compatible with the latest versions of operative systems like iOS and Android.

Efforts should be made to enhance the usability and user-experience of an app by facilitating access to documentation and tutorials, including a feedback mechanism and highlighting important functions. Comprehensive installation instructions and documentation should be available to users. Tutorials and explanatory texts/illustrations for AR in general and specific app features should be provided. Instructions and information about pedagogical possibilities and the functionality of AR in education should be provided to teachers and decision-makers. A feedback mechanism should be provided throughout the installation process and app usage that allows users to report bugs or send in suggestions.

The most common functions should be easily understandable. Existing features like unmuting videos or standalone 3D models should be highlighted and provided with clear explanations.

Internationalization and localization in the primary country language should be made available. The language used in texts should be kept as simple as possible for better comprehensiveness.

AR content should be available in offline mode, including 3D models, video snippets, and audio files.

Developers should revisit the presentation of text, speech, and non-textual elements by offering textual and non-textual alternatives to support students with visual and cognitive impairments. An AR app should incorporate both text and visual representation for its AR content, elements and functions including explanatory descriptions and illustrations [15]. On the one hand, AR apps should increase the use of non-textual elements like symbols, icons, images, graphic elements, and images of 3D models to support students with cognitive impairments. On the other hand, all functional visual elements should have explanatory and descriptive text alternatives. If support for screen readers is yet unavailable, a text-to-speech feature can be considered.

Efforts should be made to conform with existing standards, guidelines, and best practices. An AR app should be designed according to the latest WCAG [12], [13], in particular the following success criteria :

- Support for keyboard navigation and screen readers (cf. Guidelines 2.1 and 4.1).
- Captions and audio description, or a text alternative for all videos (cf. 1.2.2 and 1.2.3).
- Text alternatives for all visual elements (cf. 1.1).
- Recommendations for distinguishable elements including the use of color, contrast, text size, dynamic adaptation, and text spacing (cf. 1.4).

An AR app should be designed according to W3C's XR user requirements [16], including the following guidelines:

- Adaptation to various assistive aids and output devices (cf. 4.1, 4.8, 4.13, and 4.14).
- Alternative navigation options include using voice commands and providing alternatives to motion controls (cf. 4.2, 4.5, and 4.9).
- The option to personalize content for students with cognitive challenges (cf. 4.3).
- Establishing safe spaces and time limits to prevent overwhelm and exhaustion (cf. 4.11 and 4.12).
- Allowing interaction speeds for among other text, video, and audio (cf. 4.15).
- Captions for audio-visual media (cf. 4.19).

Developers should follow best practices aiming at programming in general [26]–[28], and XR technology and games in specific [14], [17].

AR and XR equipment and apps should accommodate special needs, both physically and programmatically. Support for assistive technology and alternative input and output devices should be implemented. AR and XR equipment should be lightweight and work on a variety of screens and devices [15]. Compatibility with common assistive technology should be enabled, including screen readers or text-to-speech tools for users with low vision, hearing aids for those with a hearing impairment, voice or gaze command and wheelchairs with motor or mobility impairments [9], [15]. Note that the most common aids are regular glasses that should be compatible with all AR and XR devices [31]. Alternative input devices are keyboards, computer mouses, customized controllers or buttons, whereas alternative output devices include additional external screens, customized headphones or refreshable braille display [9], [15].

Compatibility with these aids should work both programmatically and physically. Programmatically, by providing an interface or API for these technologies, e.g. screen readers, input or output devices. Physically, by not interfering with or hindering usage of assistive technology, e.g. hearing aids, wheelchairs or glasses. Moreover, it is important for all digital information to be available and accessible with and without assistive technology, e.g. through text alternatives for screen readers.

Compatibility with screen readers like VoiceOver / TalkBack for students with visual impairments should be prioritized. Likewise, navigation within the interface and the virtual world through alternative input devices should also be prioritized.

Developers should enhance the multi-modality of the virtual content. AR content should be presented through various modalities, i.e. engage multiple senses simultaneously, such as hearing and touch [15]. AR content should be expanded through modalities such as sound, vibration, 3D-printed artifacts, and tactile display units. Different modalities should also be considered for user interaction, including auditory elements like sound effects, vibrations, and tactile feedback. We advise employing user preferences for modalities, combined with profiles for personalized experiences.

Presentation of the virtual content without tracking should be available. There should be the possibility for a purely virtual representation of 3D models within the app through a so-called “stand-alone” mode. This would allow exploration without scanning book pages, tracking markers, or placing models in the classroom.

Navigation within the virtual content should be possible without motion control through on-screen buttons. Navigation through various control methods, such as buttons, keyboard, motion control, gestures and voice commands should be available. Navigation without motion control should be available through plus and minus buttons for zooming, buttons to rotate 3D models, or buttons to view the inside of models by zooming inside. Rotation should be possible along all axes, i.e. the x-, y-, and z- axes.

The AR app should have a certain level of tolerance for input errors when it comes to navigating the 3D models. There should be designated areas on the screen where fingers and palms can be placed without triggering unintended gestures.

AR apps should consider including more interactive features and educational content that is available both online and offline. AR apps should incorporate more interactive elements, such as opening/closing parts of models and displaying dynamic processes or animations. Gamification elements such as progress indicators, levels, challenges, rewards, competitions, etc. could be included. A collection of educational tasks that can be used outside the curriculum and without internet access could be provided.

Measures to address distractions should be implemented. AR and digital learning materials should limit potential digital distractions. Features like locking the app or disabling the exit button for students can be considered. Notifications from other apps, particularly social media, should be disabled during app usage.

Age and skill-set, e.g. reading and abstract thinking, recommendations for using the learning tool should be provided in the description of an app and its content.

IV. DISCUSSION

The current study validates previous observations and introduces new findings regarding AR and other XR technologies in education. Although we have focused on AR, many of the findings can be applied to Mixed Reality (MR), Virtual Reality (VR), and other digital learning aids as well. AR shares many similarities with other digital learning aids that rely on tablets or mobile phones, as they utilize the same underlying technology. Thus, many of our findings are relevant for other tablet, mobile or computer apps as well. Moreover, the differences between AR, MR and VR technologies are blurred. For these technologies are often placed inside a “virtuality continuum”, also referred to as eXtended Reality, with a completely real environment on one end and a completely virtual environment at the other end [1], [32]. Thus, most findings for AR are transferable to other XR technologies. The barriers associated with the necessary hardware, for instance, become more apparent in VR and MR than for AR, as both VR and MR require more extensive and immersive equipment. Thus, barriers related

to virtual worlds and the demands placed on the user's abstraction and spatial sense become more apparent, as the level of immersion increases for MR and VR compared to AR. Likewise, the dominating focus on visual aspects is relevant for all XR technologies. In future research, we recommend investigating multiple types of XR technologies, while indicating which findings are most or least relevant to each respective type.

Positive outcomes mentioned in literature could be confirmed, such as increased motivation, collaboration, interest, and experiential learning [5], [8]. Further, our study confirms practical challenges mentioned in the literature related to space and illumination limitations of the physical environments, availability of XR devices and Internet-availability in schools, along with the need for improved digital and XR skills among teachers, decision-makers and students [5], [8]. In previous research, educators reported the lack of educational AR content suitable to national curriculums and daily routines in schools [5], [8]. We addressed this challenge in the current study by evaluating an AR solution tailored to the Norwegian science curriculum. Nevertheless, participants in this study pointed out that there is still a need for more content in other subjects.

The insufficient representation of students with disabilities during the development and testing of XR technology [5] is addressed in this study by including students with disabilities. Generally, this inclusion might lead to improved user experience for all students: Simplifying the user interface, integrating icons and graphical elements, and adding sound and vibration effects might benefit students with and without disabilities alike. This synergy is commonly referred to as the “curb-cut” effect [33], [34]. Thus, future research could investigate how integrating students with disabilities in evaluations including other minority groups, such as those with hearing, motor, and mobility disabilities, as well as people with chronic conditions, could provide various benefits.

The study further confirms the lack of accessibility and usability of current XR technology [5], [7]. Barriers include the absence of support for assistive technology like screen readers, alternative input/output devices, glasses, hearing aids or wheelchairs, and the complexity of virtual content for users with cognitive disabilities [5], [7], [9]. Without adjustments, AR and XR are little suited for people with cognitive disabilities and largely unusable for students with visual disabilities. We particularly suggest making sure that the app is compatible with and does not hinder the use of assistive technologies. Furthermore, we suggest exploring alternative modalities such as sound effects, vibrations, (physical) 3D-printed artifacts, and tactile displays to enhance accessibility. Examples of such solutions are a white cane with auditory and tactile feedback in VR [35], or a toolbox with improvements for users with low vision [36]. Additionally, incorporating icons, images, and graphical elements may be helpful for students with cognitive challenges who lack linguistic capabilities and the ability to process abstraction. An example of this is using pictograms and icons for users with cognitive disabilities [37].

Our findings from the interviews with developers of XR technology echo previous findings [5]. Companies are often aware of universal design to some extent but lack the necessary resources and tools to enhance the accessibility and usability of their technology. Developers may also not be aware of barriers faced by users with disabilities or lack the expertise to adequately address these barriers. Existing guidelines and frameworks from other ICT areas [11]–[14], [17], are often not adequately communicated. Additionally, developers express the need for easily accessible and usable best practices. The participating developers noted that many customers do not prioritize increased universal design, which may lead to a lack of emphasis on universal design on the management level. Developers of systems should be made aware that several directives and legal regulations already exist that require the universal design of digital learning aids [18]–[20], [29].

Therefore, we suggest increasing the awareness of and expertise in universal design among developers, designers and decision-makers responsible for procuring digital learning resources in both the private and public sectors. This can be achieved by promoting existing guidelines, visualizing concrete barriers, providing specific solutions to these barriers, and offering practical best practices. Additionally, guidelines from other areas like programming or video games [11]–[14], [26]–[28] should be reviewed for their relevance to XR technology. Likewise, we argue that WCAG, originally developed for websites, is also relevant for XR through the integration of WCAG 2.0 and 2.1 in national and international legislations for ICT in general and digital learning aids in specific [12], [13], [20].

At the same time, AR companies should incorporate dedicated procedures for universal design in their development and evaluation processes. This may include automated or manual checks for accessible and user-friendly user interfaces, testing for compatibility with ATs, and regular user trials involving students with and without disabilities. Similarly, decision-makers, educators, and buyers of digital learning solutions should demand and test for compliance with universal design requirements. The referenced guidelines and standards for user interfaces, video games, programming, and XR applications in this paper, provide some examples of what XR developers can use during the development process, and to which decision-makers can refer for requirement specifications.

Last but not least, our findings demonstrate the consequences of inaccessible learning resources used in schools, as well as the potential for improved integration if universal design is adequately addressed. Inaccessible digital learning resources can easily result in knowledge gaps, with students who lack essential knowledge struggling to keep up when more advanced topics are introduced. Students with disabilities, particularly those with visual impairments and cognitive challenges, are especially vulnerable to these difficulties. However, AR can serve as a suitable alternative for learners who rely less on text-based approaches, such as students with dyslexia, ADHD, and other learning disabilities. These findings align with findings from previous research we conducted [5].

V. CONCLUSION

In this article, we presented a case study that explores the universal design of Augmented Reality (AR) technology in educational settings. We believe that the findings will also be relevant for other technologies under the umbrella of eXtended Reality (XR), such as Mixed Reality (MR) and Virtual Reality (VR). Central to the assessment is the evaluation of an AR-based pop-up-like book designed for primary schools in Norway. User evaluations and interviews were conducted with students, including those with disabilities, educators, and developers to assess the opportunities and benefits, user expectations and best practices, challenges, and common pitfalls of using AR in educational materials. The study especially identified barriers faced by students with visual and cognitive disabilities. Furthermore, we provided recommendations and concrete measures to improve the integration of AR into the primary school curriculum and enhance its accessibility and usability for students with and without disabilities.

One significant challenge highlighted is the heavy reliance on visual stimuli in AR, which may pose difficulties for students with visual disabilities. Another challenge is the complexity and virtuality of AR putting a significant demand on the cognitive capabilities of the students, including spatial visualization ability and the concept of virtuality. This makes AR challenging for students with cognitive disabilities, especially in cases where the app lacks both visual and textual explanations. These challenges should be addressed by employing different approaches, such as incorporating alternative modalities like sound and tactile feedback, utilizing visual explanations, enhancing engaging symbols and icons to captivate students' interest, and offering textual descriptions as alternatives for visual content. Consequently, these improvements could enhance the accessibility and usability of AR technology for students with and without disabilities alike.

Moreover, many students with disabilities rely on assistive technology, like screen readers, hearing aids, glasses or wheelchairs. Developers need to ensure that the AR application, including its operation, is compatible with these technologies, both physically and programmatically.

Finally, we recommend raising awareness of and expertise in universal design among developers and decision-makers in private companies and public institutions. This can be achieved by gathering best practices, consolidating existing guidelines for AR and XR technology, adapting relevant guidelines from other ICT areas, and making these guidelines easily accessible and widely distributed to developers and designers.

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