European Commission

HEALTH AND EDUCATION XR

EXTENDED REALITY: OPPORTUNITIES, SUCCESS STORIES AND CHALLENGES (HEALTH, EDUCATION)

Final report

VISIONARY ANALYTICS

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Abstract

The overall objectives of this study are to describe the state of the art and to provide an assessment of the strengths and weaknesses of the use of extended reality (XR) technologies in the healthcare and education sectors. The study employs a mixed-methods approach based on desk research, surveys, interviews, case studies and sectoral workshops. The study begins by identifying XR affordances in the healthcare and education sectors, coupled with examples of European XR tools and applications. In addition, it identifies barriers associated with the wider adoption of XR in Europe. These relate to market conditions, technical limitations, research gaps and policymaking issues. Furthermore, the study analyses the European XR market, including: a) a presentation of the status quo and an exploration of future market potential; b) a vertical breakdown of the market by European players and their business models; and c) an investigation of technological standards in relation to XR. Lastly, based on the results of this analysis, the study provides a set of recommendations in terms of policy interventions and potential research and innovation areas.

Résumé

Cette étude a pour but de présenter les dernières avancées technologiques et de fournir une évaluation des forces et faiblesses de l'utilisation des technologies de réalité étendue (XR) dans les secteurs de la santé et de l'éducation. Cette étude utilise une approche mixte basée sur des recherches documentaires, des enquêtes, des entretiens, des études de cas et des ateliers sectoriels. Elle commence par identifier les possibilités de la technologie XR dans les secteurs de la santé et de l'éducation, et propose des exemples d'outils et d'applications de la XR en Europe. Par ailleurs, l'étude identifie les obstacles à une adoption plus large des XR en Europe. Ces obstacles sont liés aux conditions du marché, aux limitations techniques, aux lacunes de la recherche et aux questions d'élaboration des politiques. En outre, cette étude a analysé le marché européen des technologies XR, y compris : a) la présentation du statu quo et l'exploration du potentiel futur du marché ; b) une ventilation verticale du marché par acteurs européens et leurs modèles d'entreprise ; c) une enquête sur les normes technologiques en rapport avec les technologies XR. Enfin, sur la base des résultats de cette analyse, l'étude fournit une série de recommandations en termes d'interventions politiques et de domaines potentiels de recherche et d'innovation.

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- Page 47, picture in the box, source: Okanovic, 2022
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Introduction

The objectives of the study are to describe the state of the art, and to provide an assessment of the strengths and weaknesses of the existing research results linked to the use of extended reality (XR) in health and education. In addition, the study identifies and presents success stories on how XR benefits the education and health sectors, as well as engineering, logistics and manufacturing. Moreover, the study also investigates how XR can help in the daily life of vulnerable groups, as well as the challenges they face when using these technologies. Lastly, the study includes a market analysis of XR applications in Europe. Based on this analysis, recommendations are provided with regard to policy interventions and potential areas for research and innovation at EU level that might best exploit the opportunities and benefits XR technologies can offer to individuals and European businesses.

Scope

The technological scope of the study covers augmented reality (AR), virtual reality (VR) and mixed reality (MR), collectively referred to as XR. However, both research (e.g. H2020 projects on these subjects) and market (e.g. market research reports) contexts usually refer to XR in general, or AR and VR in particular. Thus, the study focuses either on XR technologies collectively, or AR/VR technologies specifically. However, where necessary (e.g. for the purpose of clarity in the success stories), MR is referred to with a careful specification of what it entails in each particular case.

In terms of sectoral scope, this report largely focuses on the application of XR in the health and education sectors. While we use the term ‘cross-sectoral’ in the report, we refer to issues that are cross-sectoral to the health and education sectors, unless otherwise stated. Other sectors are covered only to a limited extent when drafting the success stories and in the surveys.

When it comes to target groups, the study focuses on XR for the population as a whole, but pays specific attention to the following vulnerable groups:

- Children and adolescents with special needs.
- Persons with disabilities, including (i) people with physical disabilities including those with neurological diseases; and (ii) people with mental health disorders.

Geographically speaking, many academic articles do not refer to particular locations (e.g. EU borders); research objects and communities are global. However, the tender specifications focus on research conducted in the EU27. Hence, there is a focus on literature, examples and other data from the EU27, while other relevant literature not specific to the EU27 territory is also considered.

Methodology

The study mostly focuses on secondary data (e.g. available literature). The study findings are further supported by primary data collected during the field research stage of the project (including interviews with key stakeholder groups; XR researchers and representatives of XR companies; success stories; and sectoral workshops). More specifically, the following methods were used in this report:

- **Desk research focusing on the following:**
    - Collecting background information on the XR industry in Europe, deepening our knowledge of selected aspects and filling the information gaps remaining

after the interviews. Desk research was the main method used to analyse the research data. The list of sources used is presented in Annex 2.

  - The roles and dependencies of technologies, complemented with expert input from members of the project team as well as from interviews with solution providers.
  - Mapping of companies operating within the European XR market.
  - Analysing existing reports from market research companies concerning the size and forecasting for the XR industry.
  - Analysing official statistics and publicly available annual reports to enrich estimates and forecasts from the market research.
  - Analysing specific companies operating within the European XR industry.

- **Two online surveys:**
  - A survey of XR company representatives and XR researchers/academics was conducted between 16 November 2021 and 24 January 2022 to gain deeper insights into the state of the market, barriers and opportunities, as well as other topics within the context of XR application. In total, the survey received 129 responses (106 complete and 23 partial). The survey targeted respondents working in the health and education sectors, and thus 41% of respondents work in these sectors – although it must be noted that almost half of this 41% also work in other sectors.
  - A survey about XR education programmes offered by higher education institutions in Europe was conducted between 04 April 2022 and 29 April 2022 to gain deeper insights into the education landscape. Of a total of 33 responses, 16 were complete and unique responses.
- **Interviews** were conducted to deepen the knowledge accumulated through the desk research and to fill in any remaining information gaps. A total of 79 interviews were conducted. Table 1 below provides a breakdown of the interviews, by target group and project deliverable.
- 11 **case studies** of European XR companies across different vertical market segments to illustrate the different types and business models of European XR players. These case studies are based on desk research and interviews with company representatives. The case studies are presented in the form of boxes in Chapter 2.
- **Success stories were developed of XR companies** in the sectors of health (AMA); education (Varjo); engineering and manufacturing[1] (Holo-Light); and logistics and manufacturing (TeamViewer) (see Annex 3).
- **Sectoral workshops on health and education sectors** were held. A health sector workshop was held on 20 May 2022, and had 11 participants. A workshop on the education sector was held on 10 June 2022, and had 27 participants. Both workshops yielded information and informed the recommendations to address the current barriers in the field and maximise the potential impact of XR.

[1] However, applications are also possible in automotive, healthcare/medtech, construction and architecture, aerospace and defence, process industry, training and education.

Table 1. Interviews conducted during the project

Group of interviewees	Number of interviews implemented					Total
	Task 1 Exploratory	Task 2 (health)	Task 2 (education)	Task 3 (success stories)	Task 4 (market data analysis)	
XR company representatives (e.g. CEOs, CTOs)	2	5	4	14	16	41
Academics and researchers in the field of XR	2	2	5	0	0	9
Practitioners and industry representatives	2	8	5	0	0	15
Policy makers/government officials (e.g. people working in the area of social insurance)	2	0	4	0	0	6
Representatives of end-users of XR technologies (esp. vulnerable groups, but also others such as teachers)	1	6	0	1	0	7
Total	**9**	**21**	**18**	**15**	**16**	**78**

Source: Visionary Analytics, 2022.

Structure of the report

The first chapter of the report presents an analysis of the applications and affordances of XR technologies in health, education and the other sectors covered in the success stories. It focuses on describing areas of application for XR, their economic and social impact, the barriers to be addressed, relevant policy actions, and regulations and business actions, as well as gaps in XR research in the health and education sectors. The second chapter describes the overall landscape of the European XR market, focusing on an overview of market size, analysis of different market segments by vertical market breakdowns, and a qualitative overview of the direct economic impacts in different EU XR market segments. Lastly, the report details the study's conclusions and presents recommendations.

1. Analysis of the applications/affordances of XR technologies in selected sectors

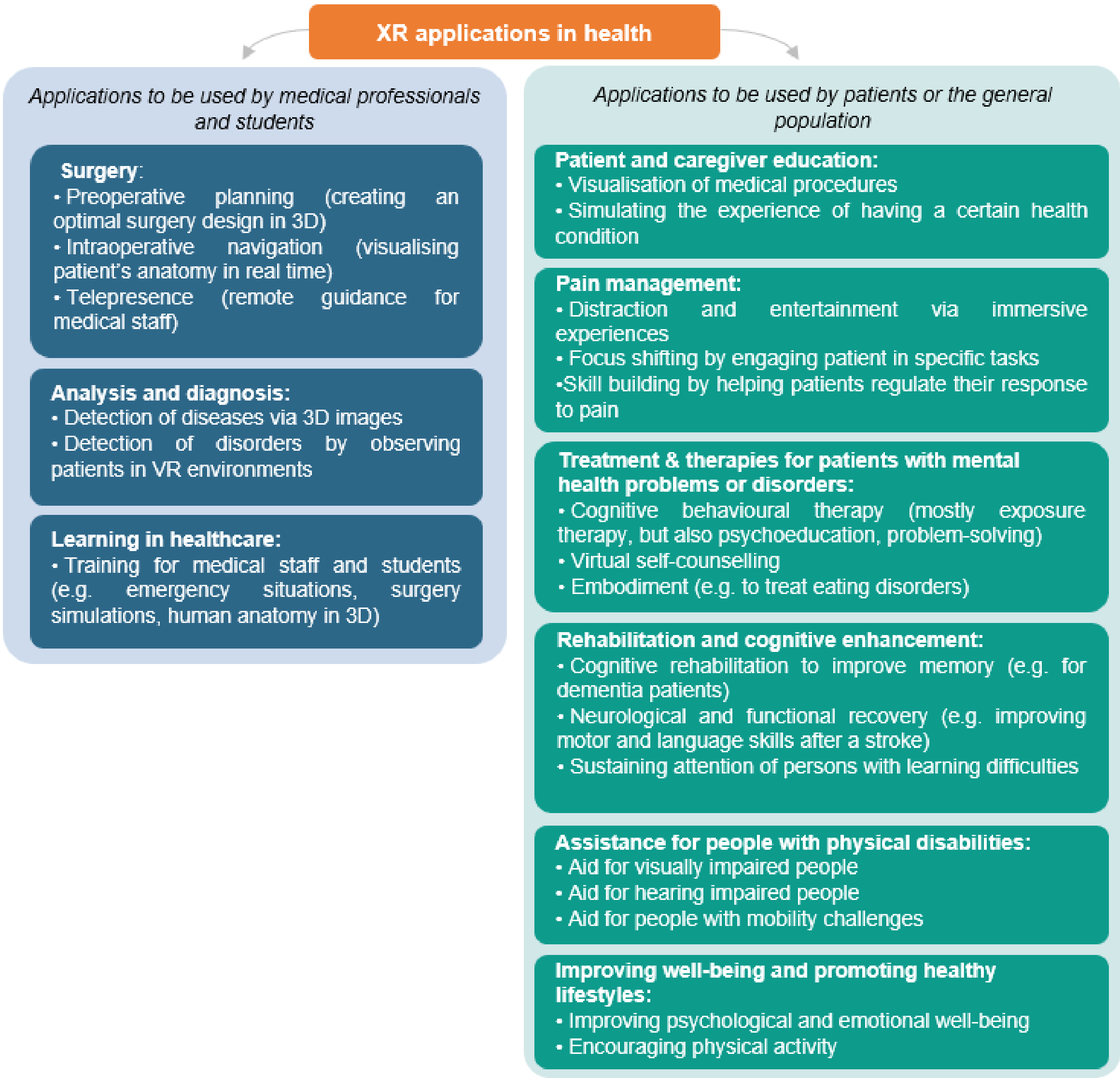
1.1. Use cases for XR technologies in selected sectors

This section presents the applications and affordances of XR technologies in health and education sectors. In addition, it presents applications of XR in other sectors covered by the success stories analysed as part of the study.

1.1.1. Health sector

XR-based applications for health can be broadly categorised in two separate areas, depending on their user group (see Figure 1).

Figure 1. Applications of XR technologies in the health sector



Source: Visionary Analytics, 2022

This chapter analyses each of these areas of application and their potential to contribute to better health care.

Applications to be used by medical professionals and students

Surgery

XR offers many opportunities for surgeons to improve their performance during procedures, reducing human and surgical errors while improving surgical efficiency (Barteit et al., 2021; Chan et al., 2021).

First, XR is highly beneficial to preoperative planning, as the ability to view in 3D may help surgeons or radiologists to assess a patient's condition more accurately before undertaking a surgical procedure. Conventional 2D scan data (such as CTA or MRA images) can be transferred into 3D environments such as AR, VR or holograms (MR). In the case of cancers, it can help to analyse the position, shape and size of a tumour with greater precision (Alfonso-Garcia et al., 2020; Douglas et al., 2016; Wellens et al., 2019). Implantology and plastic surgery may also benefit from XR. For instance, VR can be used to identify facial asymmetries and create an optimal presurgical design, possibly in consultation with the patient (Zhu et al., 2017). Accurate and realistic medical models can be included in XR using popular medical imaging software. For example, *OsiriX* allows 3D medical models of real human bodies to be created from a collection of 2D images in the DICOM format[2]; these models may be further included as interactive components in VR and AR applications.

Second, AR and MR can improve intraoperative navigation. A surgeon can intraoperatively access anatomical information on the patient and overlay virtual holographic elements in real time onto the actual superficial anatomy of the patient while they are on the surgical table. In spinal surgery, AR may assist surgeons in placing screws by enabling them to visualise the patient's anatomy and pre-planned drilling trajectories using an AR visor (Elmi-Terander et al., 2018). By overlaying visual information onto the operative field, AR and MR (e.g. holograms) eliminate the need for external monitors, reducing context switching and associated cognitive load and performance errors. During simpler procedures, medical staff can benefit from AR systems such as *AccuVein*, which projects a map of a patient's veins before injection. Improving the precision of injections may be especially useful in paediatric wards, as children tend to fear such procedures (Usclade et al., 2021).

Another aspect enabled by XR is telepresence. Head-mounted VR and AR displays offer great potential in surgery due to the possibility of remote communication and telemonitoring (Hamacher et al., 2016; Khor et al., 2016). For instance, *Microsoft HoloLens, Magic Leap* and *Google Glass* enable medical teams to collaborate remotely by sharing point-of-view data during surgery. Hands-free image capturing via voice commands is especially beneficial during surgery to maintain sterility and avoid infections (Shluzas et al., 2016). Moreover, this technique can be applied in extreme conditions, such as treating combat trauma injuries or performing emergency surgeries, where less experienced surgeons can be guided remotely by more expert colleagues (Andersen et al., 2017). The ability to simultaneously analyse the same data (e.g. 3D medical images) may also aid preoperative planning by reducing the number of meetings needed by medical teams.

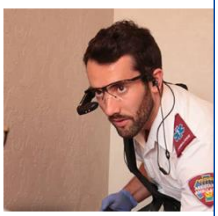
Example of *XpertEye* use in surgery

Smart glasses using AMA's *XpertEye* software are very useful during a procedure to implant an aortic prosthesis. During this procedure, technical medical assistance may be required at certain crucial points in the intervention (e.g. to precisely determine the delivery area and reduce the risk of error). Outside technicians can watch the procedure remotely and provide advice in real time. The surgeon can receive indications and alerts providing details and images on the feedback screen of their glasses.

Source: Visionary Analytics, 2022, based on AMA video "XpertEye Essential use case - Dr Kaladji" https://www.youtube.com/watch?v=PobiWJHYn64&ab_channel=AMAXPERTEYE;

Example of the use of *XpertEye* software for emergency care at the University Hospital Centre in Nantes

University Hospital Centre in Nantes, France collaborates with technology company *AMA* to provide emergency services through the use of smart glasses featuring AMA's *XpertEye* software. Hospital staff are able to view in real time the off-site procedures conducted by emergency responders. According to hospital practitioner Dr Martinage, the use of smart glasses with *XpertEye* enhances rapid evaluations, especially those requiring visual examination: traumatology, neurology, dyspnoea, rash dermatology, and so on. As a result of remote visual examinations, emergency medical dispatchers can convey knowledge in real time



[2] DICOM is an international standard for medical images and related information. It defines the formats for medical images that can be exchanged with the data and quality necessary for clinical use.

and choose the appropriate means of transport, depending on the urgency of the situation. Furthermore, it allows emergency responders to keep their hands free and receive precise directions to conduct certain procedures. According to Dr Böeffard, a specialist in adult medical-surgical emergencies, the use of *XpertEye* may also help less skilled or experienced emergency workers to provide care – for example, those lacking obstetric skills[3] in the event of a complicated home delivery. In addition, the use of *XpertEye* allows the emergency services in Nantes to gain a better understanding of the different types of situations faced by emergency services, and to optimise the response they provide.

Source: Visionary Analytics, 2022, based on AMA Whitepaper "Bringing the digital revolution to healthcare: eHealth applications and use cases" https://info.amaxperteye.com/ebook-bringing-the-digital-revolution-to-healthcare; AMA video "Use Case XpertEye Advanced - SAMU 44" https://vimeo.com/404656613

XR/AR-assisted analysis and diagnosis

XR offers greater accuracy and efficiency than conventional techniques, and can thus be applied in medical analysis and diagnosis.

First, XR can be applied in the **detection of diseases**. By offering improved high-resolution 3D microscopic images of patients' anatomy, XR can enable a better understanding of data and diagnostics (Aziz, 2018; Calin Riley-Missouri, 2019). A more accurate diagnosis simultaneously leads to a more accurate and appropriate treatment for the individual patient. XR can, for example, be used to analyse cardiovascular anatomy to diagnose congenital heart disease[4] (Goo et al., 2020); detect small intracranial aneurysms[5] non-invasively (Liu et al., 2018); analyse tissue (e.g. blood cells, cancer tissues); and protein organisations and interactions in 3D images (Calin Riley-Missouri, 2019; Chen et al., 2019).

Use of VR for the diagnosis and study of cancer tissue

VR could revolutionise the diagnosis and study of cancer tissue. This could be achieved through the microscopic assessment of tissue samples. VR labs can provide doctors with more detailed scans of breast cancer tissues. VR enables the analysis of individual tumour cells in a more detailed fashion and helps doctors to more clearly identify which cells are cancerous, which have genetic variations, and how advanced a tumour is. In addition, data on tumour cells can be shared more easily than with microscope slides. This means that doctors do not have to go through the process of obtaining their own samples in order to study cancer, but can quickly access, compare and analyse samples that have been taken by colleagues all over the world.

Source: Visionary Analytics, 2022, based on Robitzki, 2019; University of Cambridge, 2019

Second, XR can be applied to analyse and diagnose patients while observing them in virtual environments. For example, XR can be used in the analysis and diagnosis of **visual processing capabilities**. VR devices can help to tackle the difficulties of testing human visual conditions, by providing a mechanism to reliably assess the core visual functions with standardised stimuli (Foerster et al., 2016). The lightweight head-mounted display covers the patient's entire visual field, and excludes factors stemming from external test conditions (Foerster et al., 2016). When assessing the patient's visual capabilities, the patient is fully immersed and not distracted by outside factors, so that the doctor can precisely record/monitor the patient's visual processing components. VR headsets have been found equally reliable to a standard cathode ray tube computer screen in delivering diagnostic tests for the assessment and diagnosis of elementary cognitive functions (Foerster et al., 2016). Similarly, VR has also proven helpful in quantifying the level of ocular suppression in amblyopic[6] patients. Whereas conventional clinical tests only detect the presence or absence of such suppression, VR facilitates an approach that quantitatively calculates the level of suppression during an image recognition task (Panachakel et al., 2020).

[3] Skills in relation to pregnancy, childbirth and the period of the first six weeks following childbirth.
[4] Congenital heart disease refers to a range of birth defects that affect the normal operation of the heart.
[5] Intracranial aneurysm is a cerebrovascular disorder in which weakness in the wall of a cerebral artery or vein causes a localised dilation or ballooning of the blood vessel.
[6] Amblyopia is a reduced vision in one eye. The weaker eye often wanders inward or outward. Amblyopia is caused by abnormal visual development early in life.

In addition, XR can be applied to analyse and diagnose various **mental health, neurological and cognitive disorders**. In these cases, it is often hard to offer patients real-world scenarios in which the relevant behaviours can be assessed. In addition, conventional clinical interviews and questionnaires can often lead to biases (van Bennekom et al., 2017). XR offers a safe platform to recreate real-life situations in virtual environments through interactive virtual simulations in which the behaviour and reactions of patients can be observed and recorded accurately. Thus, XR offers non-invasive, non-pharmacological and easier-to-use interventions for diagnosis (García-Betances et al., 2015). For example, XR could be used to analyse and diagnose addictive disorders, phobias, social anxiety disorders and post-traumatic stress disorders, psychosis and schizophrenia, attention-deficit or hyperactivity disorders, autism spectrum disorder, eating disorders, obsessive-compulsive disorder, dysexecutive syndromes[7] (see the box below for an example), spatial navigation disorders, Alzheimer's disease and Parkinson's disease (Cogné et al., 2017; Dechant et al., 2017; García-Betances et al., 2015; Orlosky et al., 2017; Segawa et al., 2020; University of Cambridge, 2019; van Bennekom et al., 2017).

Use of VR for the diagnosis of dysexecutive syndromes

The Spanish company *Nesplora* has developed multiple products to perform neuropsychological assessment through virtual reality. One of its products, Ice cream, is designed to assess executive functions in people over 8 years of age. The test takes around 30 minutes in a virtual environment in which the subject has to serve customers with ice cream, respecting certain criteria. The test evaluates the person's planning skills, working memory, processing speed and cognitive flexibility. Development of the product has received funding under the Horizon 2020 programme.

Source: Visionary Analytics, 2022, based on https://nesplora.com/en/producto/executive-functions-ice-cream-en/

Learning in health care

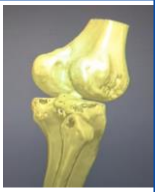
XR offers additional possibilities for training in medical skills, and growing evidence shows that XR can improve learning in health care (Logeswaran et al., 2021; Zweifach & Triola, 2019). The application of XR in health care education promotes experiential and collaborative learning, situated cognition and connectivism. Multiple learners can explore environments with greater freedom than when using traditional methods, with potentially better knowledge transfer to the real world. These benefits address the needs of medical educators (Logeswaran et al., 2021). For example, XR gives surgical trainees the opportunity to gain realistic experience in a 3D operating room, as well as creating opportunities to study 3D models of human organs. Thus, it can help medical students to study the anatomy of a patient or be educated on preoperative planning – a crucial part of surgery (Ayoub & Pulijala, 2019; Hamacher et al., 2016; Kordali, 2021; Sánchez-Margallo et al., 2021). Furthermore, XR in health care education has been proven to enhance privacy and reduce embarrassment while learning, as students can practise on virtual patients (Mäkinen et al., 2020; Saab et al., 2021). This allows students to practise real-life clinical procedures without risking patients' safety. Lastly, XR systems usually give users useful feedback and allow them to practice medical simulations as often as they like (Ebner et al., 2019; Hamacher et al., 2016).

As yet, the adoption of XR in medical education remains low due to the cost of implementation, faculty acceptance in terms of long-term value, tools for educators to assess learners' performance, and the integration of such tools into learners' curricula (Zweifach & Triola, 2019). Nevertheless, the restrictions imposed during the COVID-19

[7] Dysexecutive syndromes refer to dysfunction in executive functions, such as planning, abstract thinking, flexibility and behavioural control.

pandemic boosted the use of XR and demonstrated the potential of XR learning platforms to facilitate skills acquisition by learners in clinically realistic, repeatable scenarios (Ong et al., 2021).

Examples of XR application for learning in health care



XR can be used in the general education of medical students. For example, *SimforHealth*, a VR system developed in France, offers students 35 medical settings in which they can practise real working conditions. The Finnish company *Adesante* has also developed the application *SurgeryVision*. This application allows users to view magnetic resonance imaging (MRI) and computerised tomography (CT) images in a stereoscopic 3D format, helping them to study human anatomy and anatomic abnormalities more effectively.

Multiple XR products have been developed to train for medical emergencies. One company based in Germany has developed the basic life support learning system *Vireed Med*, which educates health care staff on cardiac massages with haptic feedback, as well as advanced life support and dyspnoea[8]. In the Netherlands, Schola Medica has introduced a VR emergency care education system called *THRIVE* for its trainers and trainees. Using this VR training system, trainees engage with realistic scenarios that ensure that they follow the correct steps in an emergency. This contributes to the trainees' medical professionalism and their self-confidence in real-case scenarios.

Source: Visionary Analytics, 2022, based on https://simforhealth.fr/en/about-us/, https://www.surgeryvision.com/medicalstudents, https://www.vireed.de/, https://aixr.org/insights/thrive-vr-medical-training-with-volumetric-professionals/

Applications to be used by patients or general population

Patient and caregiver education

Learning in health care through the use of XR is not solely intended for medical staff and students, but also for patients and/or caregivers.

XR demonstrations of medical procedures offer patients greater self-efficacy, awareness, confidence, coping skills and health literacy, which leads to better doctor-patient relationships (Kordali, 2021). The project of a virtual hospital[9], for example, helped pregnant women virtually visit the maternity department of the hospital to cover the patient journey in advance and reduce labour-related anxiety. In addition, multiple telehealth solutions involving XR technologies have recently been developed that empower patients to understand their own care (Ong et al., 2021). VR can also improve patients' understanding with regard to giving informed consent for surgical procedures such as tumour removal. It can help them understand the nature and purpose of the proposed procedure, including potential risks and benefits (Perin et al., 2021).

In addition, XR can be used to **simulate the feeling of living with a certain medical condition**. Caregivers often experience psychological distress due to the illness of a family member. XR can be used to improve understanding and empathy in caregivers, as well as to educate and inform the public. For instance, VR interventions can simulate the experience of having dementia (Wijma et al., 2018) or the difficulties of having vision impairment (Jones et al., 2020).

Pain management

Immersive experiences can alter **pain perception,** and can be used to alleviate acute and chronic pain such as that associated with burns, phantom limb[10], cancer-related pain, or even labour contractions. Scientists agree that VR may be an effective non-

[8] Dyspnoea is shortness of breath.
[9] https://www.poppr.be/projects/virtual-hospital-uz-leuven
[10] Phantom limb is the perception that a limb that has been removed or amputated is still present in the body and performing its normal functions.

pharmacological, non-invasive complementary adjunct or alternative analgesic technique (Ahmadpour et al., 2019; Cieślik et al., 2020; Guarino et al., 2017). Ahmadpour et al. (2019) describe three mechanisms for VR analgesia:

1. **Distraction**: VR applications distract and entertain. Embodiment in the virtual world and blocking out noises from the physical world can overpower and diminish a person's ability to respond to neural signals. By doing so, immersive experiences (e.g. 360-degree videos) may result in patients perceiving less pain. This may be particularly effective in paediatric patients.
2. **Focus shifting**: VR applications systematically shifts the patient's focus on to virtual objects. Pain and stress can be minimised by engaging patients in specific tasks of tracking moving targets while requiring them to recall certain information (a more engaging/activating approach than distraction). According to one study, burn patients who actively engaged with a VR game experienced significantly less pain during wound care, compared with patients who received passive distraction by watching the game (Jeffs et al., 2014).
3. **Skill building**: VR applications mediate pain management. This may help patients to build the capacity necessary to regulate their responses to painful stimuli and to become agents in their own care (e.g. interactive games to encourage patients to exhale deeply to avoid hyperventilation during painful procedures). Ahmadpour et al. (2019) note that VR skill-building mechanisms in relation to VR analgesia, are so far the least well explored. In addition to simply wearing a VR headset, Spiegel (2020) describes biofeedback-enabled introspection (enabled by monitoring sweat levels, blood pressure, breathing rate and other bio signals), which can teach patients to control their levels of stress, pain and anxiety.

VR-based clinical hypnotherapy to manage pain and anxiety

Developed by Belgian scale-up company *Oncomfort, Digital Sedation* is a non-pharmacological option for anxiety, pain management and sedation delivered to patients through therapeutic virtual reality sessions. The sessions use clinical hypnotherapy techniques to bring the patient into a state of dissociation. Following clinical studies of more than 2,000 patients to demonstrate its efficacy, the *Digital Sedation* software is now CE-marked as a medical device. It is already available in several European countries for use in anaesthesiology, interventional cardiology, interventional radiology, obstetrics and gynaecology, oncology pain management, paediatrics, surgery, dentistry emergency, geriatrics, urology and burns units. In the future, the platform will expand beyond acute care and surgeries to allow patients to reduce their need for medication to manage a wide range of symptoms during their medical journey.

Source: Visionary Analytics, 2022, based on https://www.oncomfort.com/en/

Treatment and therapies for patients with mental health problems or disorders

Exposure therapy is perhaps the most well-known use case for VR in the treatment of mental health disorders. Exposure therapy is a cognitive behavioural therapy (CBT) technique with a strong evidence base in the treatment of anxiety disorders, behavioural and substance use disorders and post-traumatic stress disorder (PTSD). It involves gradual and repeated exposure to feared stimuli, with resultant changes in the patient's cognitions, behaviours, emotional and physical responses. However, some *in vivo* exposure therapies are challenging to implement (patients may refuse treatment out of fear, it may be difficult to arrange exposure within the therapist's office, etc.). Immersive VR can help to overcome these issues by allowing a patient to be sufficiently exposed to the feared stimuli, but in a safer and controlled environment. A VR-based alternative is therefore more acceptable and potentially more effective. Therapists can choose specific VR content and personalise it for the patients, as well as monitoring and guiding patients to engage with the content and manage their anxiety (Boeldt et al., 2019; Wiederhold and Miller, 2018). Potential use cases for VR exposure therapy include the following:

- Eating disorders can be treated by presenting patients with virtual food to help reduce food craving and anxiety (Riva et al., 2021).
- Treating substance use disorders and behavioural addictions (nicotine, cocaine, alcohol, cannabis, gambling addictions, etc.). By exposing patients to specific cues, VR benefits both the assessment (e.g. through eye-tracking and heart rate monitoring) and treatment of such disorders (Segawa et al., 2020). VR can provoke cravings and help people to learn to control them. Even unsupervised behavioural tasks using VR can help to achieve positive results – for instance, finding and crushing cigarettes in a game-like setting can help to get rid of a smoking habit (Pericot-Valverde et al., 2014).
- VR has proved effective in the treatment of persecutory delusions and other psychoses, often caused by schizophrenia. In a clinical study (Freeman et al., 2016), patients could test out predicted threats in relation to persecutory delusions by dropping their safety-seeking behaviours in VR social environments. VR cognitive therapy led to large reductions in patients' delusional convictions and real-world distress. With the help of VR-based cognitive behavioural therapy, people with paranoia can walk virtual streets and otherwise participate in VR social environments and learn to interpret external cues more appropriately (Pot-Kolder et al., 2018).

Although there is ample evidence to support the efficacy of VR in the area of anxiety disorders, far less research has been conducted on VR interventions for depression (Lindner et al., 2019; Nilufar et al., 2021). While it is relatively easy to present the user with a virtual equivalent of the phobic stimulus to enable exposure therapy, more nuanced CBT techniques are required for the treatment of depression. Some discussion and several clinical trials have been undertaken to translate CBT techniques such as psychoeducation and problem solving into VR. A clinical study involving adolescents explored how a single-session immersive VR intervention teaching a growth mindset – the belief that personal traits and attributes are malleable, as opposed to fixed – may contribute to reducing depressive symptoms (Lee et al., 2019). However, the results of this trial are not yet available[11]. Traditional anti-depressive treatments such as behavioural activation and physical activity, cognitive restructuring (identifying and modifying cognitive patterns that contribute to a depressed mood) and social skills training may also be translated into the VR modality in the future (Lindner et al., 2019).

Virtual self-counselling is increasingly gaining relevance in the treatment of people suffering from anxiety, depression or PTSD (Spiegel, 2020). Such AI-guided systems are becoming more sophisticated. For example, a team of bioengineers created a VR program that both elicits and automatically recognises emotions using brain waves and heart signals (Marín-Morales et al., 2018). Although virtual humans are not an ideal substitute for real humans, a study on war veterans showed that some patients were more willing to reveal their PTSD symptoms to a virtual human than to a real human (Rizzo et al., 2016). Another approach is to combine VR with biofeedback (such as heart rate monitoring) and neurofeedback, which enables the person to be aware of normally unconscious physiological activity. This can bring about positive results (a person can learn to self-manage their level of stress or anxiety) (Bermudez i Badia et al., 2019).

Another emerging technique is **embodiment**, which allows users to take on a virtual body that is different from their physical body. It allows the individual to modify their stored negative memories of the body and to reorganise multisensory integration processes to treat eating disorders. Asking patients to model their perceived body image using a VR avatar[12] and comparing it with both their actual body image and their ideal one can help to treat body illusions. Despite the relatively large amount of research carried out, VR has not

[11] https://clinicaltrials.gov/ct2/show/study/NCT04165681
[12] Avatar is a visual representation of a person or character in a virtual environment.

achieved a high volume of routine clinical practice in the treatment of eating disorders (Riva et al., 2021). However, being embodied and taking ownership of a virtual body can also affect implicit attitudes and perceptions. For example, it may help overcome gender or racial bias (Schulze et al., 2019).

Rehabilitation and cognitive enhancement

XR interventions can be useful for people with neurological conditions. Such interventions include therapies for persons affected by progressive neurological decline, such as mild cognitive impairment (MCI) or dementia; for persons recovering after a stroke or a traumatic brain injury; as well as for individuals (especially children) with neurodevelopmental disorders. These use cases are described in detail below.

While researchers continue to seek a cure for **MCI and dementia** (especially its commonest form, Alzheimer's disease) in the hopes of a breakthrough, technological innovation can play a significant role in managing the disease and reducing its progression. XR can become a tool for **cognitive rehabilitation**, a form of nonpharmacological therapy intended to improve everyday memory. VR systems and applications seek to provide treatments for navigation and orientation, face recognition, cognitive functioning and other instrumental activities (García-Betances et al., 2015). Moreover, using VR for both stimulation and relaxation can result in decreased stress, reduced aggression and improved interactions with caregivers for people with cognitive decline (Tabbaa et al., 2019). A recent meta-analysis of VR interventions for patients with cognitive impairment showed small-to-medium effects on physical fitness, cognition and emotion. It must be noted, however, that the sample sizes in most of the studies analysed were small, and their methodological quality was low (Kim et al., 2019).

Virtual reminiscence therapy platform for dementia patients

LookBack is a platform for virtual reminiscence therapy which transports people with dementia to places of personal significance and memorable experiences to trigger memories. By using a combination of 360-degree filmed environments, VR reminiscent scenarios and *Google Street View* panoramas, the platform provides a versatile and immersive form of reminiscence therapy[13]. It also enables caregivers and family members to easily create tailored playlists and itineraries for immersive experiences. This allows a more personalised experience for the patient. The platform was developed in consultation with researchers from the University of Oxford by *Virtue Health.*

Source: Visionary Analytics, 2022, based on https://aixr.org/insights/how-virtual-reality-can-transform-dementia-care/; https://www.virtue.io/lookback/

VR and AR therapy offers many benefits to promote **neurological and functional recovery**. Generally, XR-based rehabilitation can be used for:

- **Improving motor function.** XR appears to be a safe and effective intervention for improving arm function and activities of daily living for persons with acquired damage of the central nervous system due to a stroke, traumatic brain injury, brain tumour or infection, as demonstrated in a growing number of clinical studies. VR or AR-based neurorehabilitation therapy can be more entertaining than regular exercises, which may improve user motivation and engagement. Furthermore, well-designed environments could evoke sensations or illusions, thereby activating corresponding neural circuits and facilitating neural plasticity (Gorman & Gustafsson, 2020; Ku & Kang, 2018). Lastly, so-called 'exergaming'[14] using VR can be used for motor development, especially among children with neurological motor disorders. For instance, head-mounted displays allow users to be fully immersed into their

[13] Reminiscence therapy is a life review therapy that is often used to treat severe memory loss or dementia.
[14] Exercising while gaming.

environment and can enable them to visualise and compare two views – their actual movement and the simulated one – in a similar manner to conventional mirror therapy[15] (Gorman & Gustafsson, 2020).

- **Improving language.** Persons with acquired and recent damage of the central nervous system (such as stroke patients) commonly develop aphasia, an impairment of the ability to comprehend and formulate language. Persons with neurodevelopment disorders also often struggle with speech. Several studies have explored possible uses of XR for language rehabilitation in cases of aphasia. Patients can, for instance, meet in a virtual world and communicate by asking to pass a virtual item to each other. In this way, one patient has to verbally request an object, while the other has to understand the request and give the requested object (Grechuta et al., 2019). Such applications may potentially speed up language rehabilitation. It should be noted, however, that systematic reviews of XR treatments in cases of aphasia demonstrate inconclusive results due to small sample sizes and the poor methodological design of studies (Cao et al., 2021; Repetto et al., 2020).
- **Training in the use of new prosthetics or robotic limbs.** XR offers an interactive goal-oriented training platform to train patients in the tasks expected to be accomplished using the prosthetic. For example, amputee patients with new leg prosthetics can train in locomotion in a lab-controlled XR environment, before using the prosthetics at home or outdoors (Porras, 2021).

VR-based solutions for motor rehabilitation

MAGIC-GLASS is a VR-based solution for upper limb motor rehabilitation, designed for post-stroke treatment. The solution uses a consolidated mirror therapy[16] approach in a VR environment, thus providing the patient with an improved rehabilitation experience. *MAGIC-GLASS* uses a portable VR device and a set of adaptive serious games, along with further communication features, plus remote monitoring carried out by clinical staff. Hence, the rehabilitation can be performed at home. The system and the method used by *MAGIC-GLASS* are unique and patented. After successful clinical trials, the solution is available and being sold to customers in Italy, Norway and India. The solution was developed by Italian start-up *Tech4Care* in cooperation with Ulster University in Northern Ireland and *miThings* in Sweden. The development of the solution was supported by the Horizon 2020 programme within the framework of the MAGIC PCP and INNOLABS projects (grant agreements no. 687228 and 691556).

CSE Entertainment, a developer of VR, interactive fitness games and devices from Finland, offers another rehabilitation tool – *rehabWall*. The tool uses VR glasses, a balance board, touchscreen, and motion sensor. It offers various exercises designed for physiotherapy and occupational therapy. *rehabWall* can be used either alone or with the assistance of a health professional. It also allows health professionals to monitor in detail the patient's progress with the exercises. In addition, *rehabWall* offers content that is suitable for users with disabilities; the tool's height is adjustable, making it possible for wheelchair users to use *rehabWall* with ease.

Source: Visionary Analytics, 2022, based on https://www.tech4care.it/magic-glass/; http://www.magicglassvr.com/en/; https://digital-strategy.ec.europa.eu/en/news/virtual-reality-games-improve-rehabilitation-tech4cares-journey-idea-market-thanks-pcp; https://www.cse.fitness/en_US/rehabwall

Sustaining attention is another therapeutic use for XR, which is particularly relevant for persons with learning difficulties and neurodevelopment disorders such as attention deficit hyperactivity disorder (ADHD) or autism. Exergaming or serious VR games can eliminate

[15] Mirror therapy (MT) is a rehabilitation therapy in which a mirror is placed between a patient's arms or legs so that the image of a non-affected limb in motion gives the illusion of normal movement in the affected limb. This setup stimulates different regions of the brain relating movement, sensation and pain (Thieme et al., 2018)
[16] Mirror therapy is therapy in which a mirror is used to create a reflected illusion of an affected limb in order to trick the brain into thinking that movement has occurred without pain, or to create positive visual feedback on a limb's movement.

distractions and hold an individual's attention and concentration for a longer time by providing specific stimuli. VR games can also offer rewards for certain behaviours, making them effective tools in the rehabilitation of children with ADHD (Bashiri et al., 2017). Interest is also growing in the use of AR to assist children and adults on the autism spectrum. This interest has been encouraged by the success of *Brain Power,* a neuroscience tech start-up based in Cambridge, UK, that developed an **AR smartglasses system** to help people with autism spectrum disorders (ASD) learn what other people are feeling, as well as paying attention to people's faces, improving reading and conversation skills, and reducing repetitive motor behaviours and underlying stress[17]. In doing so, it helps individuals to remain engaged with their physical environment (Sahin et al., 2018).

Multi-sensory environments that incorporate XR can help an individual with sensory issues learn to regulate their brain's negative reactions to external stimuli by developing coping skills for these experiences. As a result, spending some time to explore a sensory room may have calming effects, improve focus and contribute to motor and cognitive skills development (Bell, 2019). For instance, having a sensory room at school is especially helpful for children with cerebral palsy, as it noticeably increases their range of motion.

Assistance for people with physical disabilities

Currently, the use of XR as an assistive technology[18] is still at the experimental stage. XR is mainly used as a tool for rehabilitation and training (e.g. to regain motor function or learn how to move around using a wheelchair), rather than an accessibility tool for persons with disabilities to independently learn, communicate or function in everyday life. Inherently, VR is meant to be immersive, taking the user away from his or her real surroundings. AR technology, on the other hand, aims not to replace but to enrich real-world experiences, and thus demonstrates potential to make daily living easier for people with physical disabilities.

AR technology can provide **aid for visually impaired or blind people.** Relatively speaking, this is the most well-researched and consumer-ready area in terms of assistive technologies (Amini et al., 2020; Ehrlich et al., 2017; Fox et al., 2019; Huang et al., 2019). AR offers potential help to persons with blindness or visual impairment through:

- **Sight enhancement and machine vision**. With the help of machine learning, a camera built into wearable devices can be used to magnify and/or read out text, recognise and enhance faces, watch television, etc. Some commercially available solutions are listed in the box below.
- **Navigation support and obstacle avoidance***.* For example, the widely available *Microsoft HoloLens* can generate a digital 3D replica of the user's environment and thus recognise nearby objects (such as bus stop signs). In a similar manner to a white cane, audible alerts can be used to notify the user about obstacles in the environment. However, using current technology, such systems only work smoothly indoors or in pre-scanned environments due to poor scanning in sunlight and low processing speeds[19]. On the other hand, non-wearable solutions exist that can help users navigate unfamiliar outdoor environments, e.g. the *Microsoft Soundscape* app uses 3D audio cues to enrich ambient awareness via a smartphone and earbuds[20].

Examples of AR-based sight enhancement and machine vision solutions

OxSights, a company based in Oxford, UK, offers custom-made smart glasses that can instantly enhance vision. Intelligent functionality allows the user's eyes adapt to light, as well as discerning

[17] https://brain-power.com/about/
[18] According to the World Health Organization, assistive technology is an umbrella term covering systems and services related to the delivery of assistive products and services. Assistive products maintain or improve an individual's functioning and independence, thereby promoting their well-being. Hearing aids, wheelchairs, communication aids, spectacles, prostheses, pill organisers and memory aids are all examples of assistive products.
[19] https://arvips.squarespace.com/
[20] https://www.microsoft.com/en-us/research/product/soundscape/

between faces, objects and text, with zoom and image enhancements to maximise vision. Another popular wearable device, *OrCam,* simply attaches to conventional glasses, and conveys visual information audibly (e.g. it can read out the text from a book). *Orcam* is available in more than 20 languages.

Source: Visionary Analytics, 2022, based on https://oxsightglobal.com/; https://www.orcam.com/

Although no solutions are known to commercially available solutions as yet, AR could potentially assist hearing impaired people. Current hearing aid technologies cannot match the user's needs in complex everyday situations such as conversation with several persons at a party. Since 2020, however, researchers at Facebook Reality Labs have been exploring how to combine beam-forming technology, deep learning, noise cancellation and AR to improve audio pickup for individuals in noisy environments[21]. A recent paper describing this work (Mehra et al., 2020) emphasises the ability of AR technology to render individual "digital objects". By leveraging current advances in AI and machine learning such systems could allow better separation between speakers, noise cancellation and signal enhancement in problematic listening situations.

Lastly, AR platforms could provide support to people facing **mobility challenges**. Assistive technology such as eye-typing has existed for more than 20 years, and has dramatically improved quality of life for people with severe physical disabilities. Today, eye-tracking technology can be incorporated into AR devices to help individuals control and communicate with home appliances remotely (Tang et al., 2015). For instance, a pilot study was carried out to test an eye-tracking system integrated into AR glasses for the autonomous management of electric beds and electric wheelchairs by patients with severe functional impairment (Bona et al., 2021).

Improving well-being and promoting healthy lifestyles

Perhaps one of the most popular uses of XR technologies is to encourage a healthy lifestyle and improve the physical and psychological/emotional well-being of the general population. In contrast to the XR affordances described above, these use cases are not usually targeted at people with specific health conditions, and can be enjoyed by anyone (although they may be especially beneficial for certain vulnerable groups). For instance, some XR products have been designed to enhance engagement with common indoor exercise activities such as climbing and jumping[22].

XR (especially VR) applications can **improve psychological and emotional well-being** by helping people to relax, relieve stress and anxiety, or simply improve their mood. For instance, Icelandic company *Flow* offers individuals and organisations a VR meditation tool, which immerses the user in natural scenes from Iceland[23] (see further examples in the box below). VR systems may also help in countering loneliness and depression, improving connectedness and stimulating brain activity among older adults in assisted living communities (Lin et al., 2018).

[21] https://g3ict.org/headlines/facebook-to-develop-augmented-reality-glasses-to-enable-persons-with-hearing-impairment
[22] https://valomotion.com
[23] https://www.flow.is/

Examples of VR apps to improve psychological and emotional well-being	
The Swedish company *Virotea* offers meaningful virtual journeys[24]. *Virotea*'s services are used mainly within the domain of social support and are tailored to the needs of elderly care as well as support and services for persons with certain functional impairments such as lumbar spinal stenosis (LSS). The services offer meaningful activities through which recipients of care can individually or collectively experience and discover places from all over the world, without having to leave their rooms.	*Flowborne VR* is a meditative biofeedback breathing game developed in Germany. The game is designed to run on a mobile, all-in-one VR headset. Notably, an integrated VR hand controller is utilised as a sensor to detect respiration-induced movements of the diaphragm, meaning that the person's breath is used as a game controller. A longitudinal evaluation study provided evidence of improved diaphragmatic breathing and breath awareness and positively influenced participants' level of relaxation, perceived stress and symptoms of burnout, as well as boosting relaxation-related self-efficacy.
Source: Visionary Analytics, 2022, based on https://virotea.com/en/	Source: Visionary Analytics, 2022, based on https://flowborne.com/virtual-reality/; (Rockstroh et al., 2021)

XR can encourage physical activity, especially since some people find it hard to find the time or motivation to get the recommended amount of exercise every day. For example, overweight children are better able to tolerate walking on a treadmill in a virtual environment than they are the same physical effort in traditional form (Baños et al., 2016). While exergaming is available using digital hardware such as *Wii* (not produced since 2013) or the Xbox Kinect (not produced since 2017), VR can provide an even more engaging immersive environment for exergaming techniques (Bond et al., 2021).

In many cases, XR tools simultaneously bring about positive effects in terms of both physical and mental health. For instance, location-based AR games, such as Pokémon GO, were shown to provide virtual socialisation, sustained exercise, temporal routine and mental structure during the COVID-19 pandemic (Ellis et al., 2020).

1.1.2. Education sector

XR-based applications for education can be categorised into two areas, according to their intended use (see Figure 2). The first area for the application of XR is categorised according to the aims of the intervention (e.g. procedural training, the development of soft skills, awareness raising). The second area relates to instructional approaches (e.g. the use of XR for visualisation, virtual trips, and storytelling).

[24] https://virotea.com/en/

Figure 2. Affordances of XR technologies in the education sector

XR affordances in education

Affordances of XR by the aims of intervention

Procedural training:
- Development of hard skills required for different occupational areas (e.g., aviation, maritime, military, firefighting, security forces) by practising in a virtual environment

Soft-skills development:
- The application of virtual scenarios and virtual platforms to develop students' communication, problem solving and conflict management skills

Raising awareness:
- Using VR simulations to raise students' awareness about environmental issues and ethnic racism

Art and designing:
- Using VR tools to explore works of art (e.g., visiting museums, buildings)
- Using VR spaces to design/ create virtual works of art

Computational thinking:
- Application of XR-based video games and simulation of problematic situation to develop students' computational thinking skills

Collaboration:
- Applying virtual collaborative environments to promote virtual co-working by students
- Use of virtual collaborative environments to promote engagement and develop communication skills of people with autism
- Practice in virtual laboratory with virtual assistance

Physical training:
- The application of XR technologies in physical education (PE) improves the quality of education, stimulate students' interest in sports and physical activity, and develops students' athletic and motor skills

Learning/practising languages:
- XR technologies facilitate the language learning process and improve learning performance, increase engagement, motivation and satisfaction with the language learning process

Affordances of XR by instructional approaches

Visualisation:
- Visualisation using XR allow learning materials to be presented in a 3D environment; this may create opportunities for virtual interaction and simulation as well

Virtual field trips:
- A virtual field trip is a (semi-)guided experience, allowing the users to go on an exploration of the world through both time and space

Storytelling and/or annotations:
- Digital media platforms and interactivity for narrative purposes, either for fictional or non-fiction stories

These affordances can be applied at different educational levels, including:

1. Primary and nursery education
2. Secondary education
3. Vocational education and training (incl. apprenticeships)
4. Higher education
5. Adult learning
6. In-company training

Source: Visionary Analytics, 2022

This chapter analyses each of these areas of application, their potential to improve education, barriers to their development and uptake and, where possible, an indication of their economic and social impact (including their impact on vulnerable groups). At the end of the chapter is an overview of the policy context of XR in education, together with examples of the measures that companies selling XR-enabled products and services take to mitigate or prevent various types of risks (health, data protection, privacy etc.).

Affordances of XR by the aims of the intervention

Procedural training

The potential use of XR for procedural improvement is considered the widest area of application for XR in the field of education (Artese, 2020; BAA training, 2021; Bahadoran, 2021; Bellemans et al., Boel et al., 2021; Di Natale et al., 2020; 2020; Fussell & Truong, 2020; Hamilton et al., 2021; 2020; Maas et al., 2020; Radianti et al., 2020). XR technologies are particularly useful in situations where real-life training is either too expensive or dangerous. XR helps to save costs and ensure the safety of trainees by providing simulated scenarios for training activities. In this section, we present six examples of procedural training in which XR technologies are applied.

XR has been used extensively in **aviation** training, as it allows the simulation of real flight by integrating advanced aviation training devices (Dehais & Peysakhovich, 2018; Fussell & Trinon, 2019; Truong, 2020). These solutions develop the technical skills required for pilots more effectively[25] and without any risks to safety[26] compared to traditional training methods (Bernard et al., 2022). In a similar vein, resistance to stress and skills for emergency situations can be nurtured by simulating dangerous flight scenarios (Bahadoran, 2021). Examples of such XR solutions are shown in the box below.

XR for aviation training

- *Varjo*[27] (Finland) integrates MR into a live-virtual-constructive (LVC) training solution for fighter pilot training, used by the Finnish Air force since 2018.
- *KLM Royal Dutch Airlines*[28] (Netherlands) has developed VR training for pilots who fly Embraer aircraft short-haul for its subsidiary company Cityhopper.
- *VRpilot*[29] (Denmark) is a VR solution for professional flight training, offering VR applications for both commercial and private use.
- *Flight Simulation Training Device (FSTD)*[30], developed and built by VRMotion (Switzerland), is used for rotorcraft pilots, with a focus on risky manoeuvres. It is the first VR-based solution certified by the European Union Aviation Safety Agency (EASA).
- *Vi-MRO*[31] (Belgium) is a training module for aircraft technicians within the Interreg project Educavia. It was developed by the VIVES aviation research group.
- *VR Hub*[32] (Germany) is a VR-based training hub for flight attendants, introduced by Lufthansa in 2019.

Source: Visionary Analytics, 2022, based on Mihai-Alexandru Cristea, 2020. Image source: https://www.pilotcareernews.com/klm-selects-l3-for-boeing-787-full-flight-simulator/

XR tools can also be applied in training programmes for **train** crews. XR-based solutions not only teach users how to operate new trains, but also explain rail classes and grades along with developing the necessary skills involved in being a crew member (Aylward et al., 2021; Mallam, 2019; Markopoulos, 2020). Examples of such XR solutions are shown in the box below.

[25] https://www.auganix.org/klm-cityhopper-introduces-virtual-reality-training-for-pilots/
[26] https://varjo.com/blog/case-finnish-air-force-the-future-of-pilot-training-with-a-live-virtual-constructive-solution-in-mixed-reality/
[27] https://varjo.com/blog/case-finnish-air-force-the-future-of-pilot-training-with-a-live-virtual-constructive-solution-in-mixed-reality/
[28] https://www.auganix.org/klm-cityhopper-introduces-virtual-reality-training-for-pilots/
[29] https://vrpilot.aero/wp-content/uploads/2022/03/VRflow-brochure-2022.pdf
[30] https://www.easa.europa.eu/newsroom-and-events/press-releases/easa-approves-first-virtual-reality-vr-based-flight-simulation
[31] https://www.vives.be/nl/onderzoek/smart-technologies/vi-mro-virtual-reality-maintenance-repair-overhaul
[32] https://www.lufthansa-aviation-training.com/virtual-reality-hub

Applications of XR in the training of train crews

- *VISCOPIC*[33] (Germany) uses 3D representations of switches that are projected into virtual space using AR glasses. Trainees can explore the infrastructure from all angles and develop skills as maintenance technicians. The project is an integral part of the DB Netz AG qualification landscape.
- *Engaging Virtual Education (EVE)*[34] (Germany) uses VR glasses to teach crews how to operate the wheelchair lifts installed on ICE4 trains to help safely lift wheelchair users on to the train. This training has been offered nationwide by Deutsche Bahn since 2018.
- *NXRT* (Austria) offers a train driver simulator as well as rail infrastructure and rail operation training using VR and MR. NXRT uses MISHBILD technology for an enhanced experience.
- *Sim Factor* (Poland) createsVR-based driver training software. Its Smart Simulator, Full-Cabin Simulator and Mobile Simulator provide immersive environments.

Source: Visionary Analytics, 2022, based on Mihai-Alexandru Cristea, 2020, https://www.nxrt.io/, and https://simfactor.pl/?lang=en

In addition, the use of **VR** simulators in **maritime education** and training makes the maritime training process cheaper, safer, more immersive, compact and accessible for trainees compared with traditional configurations, while not requiring substantial investments or specific literacy skills (Mallam et al., 2019; Makransky and Klingenberg, 2022; Markopoulos and Luimula, 2020; Renganayagalu et al., 2022). Moreover, the use of VR in maritime training creates an opportunity to train both the technical (hard) skills that are required for various professional positions and operations (e.g. operating and controlling the ship) and non-technical (soft) skills such as those for navigation, bridge operations, traffic services, communication and more (Mallam et al., 2019). Due to the aforementioned benefits, maritime simulators are widely used in the training process for seafarers by maritime companies and accredited institutions, including maritime universities and academies (Mallam et al., 2019; Markopoulos and Luimula, 2020).

Examples of XR use in formal maritime education

Aboa Mare Maritime Academy and *the Novia University of Applied Sciences* (Finland**)** carry out in-depth studies on the application of XR technologies in maritime education and training. In particular, Aboa Mare Maritime Academy develops remote operation simulators and XR-based training technologies. In addition, Aboa Mare Maritime Academy, together with Novia University, actively participates in ASTP (Arctic Simulator Training Program) projects that aim to improve simulation tools for icebreaking and winter navigation with integrated pedagogical tools for instructors and students.

SLIM-VRT[35] (Self-learning integrated methodology-virtual reality tool) was a European-level project aimed at creating a VR-based training tool applicable to the maritime sector. The tool allows trainees to build the necessary technical skills, experience real conditions at sea, and develop the soft skills required in case of emergencies.

The world-class *Centre for Simulator and Maritime Training (CSMART*[36]*)*, operating in the Netherlands, provides training for maritime personnel using Transas technology solutions (including navigational and engine room simulators, such as classroom stations, and virtual missions).[37]

[33] https://www.viscopic.com/en/
[34] https://www.deutschebahn.com/en/Immersive-technology-6935112
[35] https://cordis.europa.eu/article/id/85358-maritime-training-through-virtual-reality
[36] https://safety4sea.com/carnival-opens-simulation-and-training-center-in-netherlands/
[37] https://www.csmartalmere.com/portfolio/

Source: Visionary Analytics, 2022, based on Aboa Mare, 2022; Markopoulos et al., 2019.[38]

Another well-known application of XR is in the training of **armed forces,** which can be used to develop the fighting abilities of individual soldiers or small combat groups by simulating a real vehicle, real soldier, or real combat scenarios. More specifically, this type of training develops the combat command and decision-making skills of the armed forces by realistically simulating 3D battlefields and using a VR-based system to analyse tactics (Liu et al., 2018). In this way, XR can be used to overcome the limitations of traditional military training programmes such as the time and cost inefficiencies resulting from large-scale warfare and strategic exercises (Artese 2020; Liu et al., 2018).

Examples of XR use in formal training programmes for armed forces

The Austrian Armed Forces[39] (Austria) apply VR technologies in training, using 3D reconstructions of urban and other scenes. This solution allows trainees to move freely within a virtual environment, trains them in local knowledge, and develops skills through operational planning and manoeuvring exercises.

The German Armed Forces[40] (Germany) have signed an agreement to use Virtual Battlespace 3 software in their training processes. This software provides soldiers with the opportunity to engage in tactical training and rehearse for missions in an immersive virtual environment.

The General Tadeusz Kościuszko Military University of Land Forces[41] (Poland) uses Virtual Battle Space 3 (VBS3), provided by the Polish Academy Command and Staff Trainer (PACAST). This virtual battlefield simulator allows soldiers to practice in a virtual environment and learn how to react and make the right decisions in real battlefield situations.

Other examples of VR-based military training come from the armed forces in the UK,[42,43] Belgium[44] and Belarus.[45]

Source: Visionary Analytics, 2022, based on various sources.

The application of XR in training for the police and other **security forces** is another example of XR-based procedural training (Harris et al., 2021; Fejdys et al., 2022; Michela et al., 2022; Saunders et al., 2019).

VR training solutions for security personnel

One of the relevant EU-level projects in this field is *SHOTPROS,*[46] which develops a human factor-rooted training curriculum involving VR training solutions that provide practical training for decision-making under stress and in high-risk situations[47], thus improving the performance of European police. The *SHOTPROS* training scenario includes VR-based simulations of operational environments, which are generated through a number of different methods, including conventional desktop computer games or the use of immersive VR and AR tools together with haptic/thermal vests (providing vibration, temperature and pressure feedback to learners) (EC Cordis, 2018).

Together with Virtual Reality Training Solutions (VRTS), *OneBonsai* (Netherlands) has developed VR solutions to train security personnel to cope with challenging situations. *OneBonsai* has

[38] Additional examples:
Kilo Maritime: https://www.kilo-solutions.com/maritime-vr (UK)
Maritime VR: https://kanaalz.knack.be/business-communities/z-defensie-het-leger-ontwikkelt-vr-toepassingen-via-triple-helix-model-03-11-21/video-normal-1797195.html?cookie_check=1650465514 (BE)
[39] https://www.vrvis.at/en/research/research-topics/extended-reality-xr
[40] https://www.army-technology.com/news/newsvirtual-battlespace-3-software-4459971/
[41] http://www.polska-zbrojna.pl/home/articleshow/33123?t=Army-3D#
[42] https://short-cgi.com/vr-military-training/
[43] https://avrt.training/military/
[44] https://vr-training-solutions.be/bienvenue/?lang=en
[45] https://otr.eu/vr-ar-military/
[46] https://shotpros.eu/the-shotpros-project/
[47] Ibid.

prototyped both hardware and software that enable users to engage first-hand using a realistic, high-performance VR experience.

Source: Visionary Analytics, 2022, based on www.onebonsai.com

XR is also widely used in **firefighting** training. In particular, the application of XR in training for firefighters reduces the risks to safety of serious injuries and great stress. XR helps to simulate a real fire, ensuring both effective and safe practical training. In addition, it provides an opportunity to create an endless number of learning scenarios that can develop many different practical skills (Bellemans et al., 2020; Grabowski, 2021)). For example, Firefighting simulation software, developed under the *BRIDGES* H2020 project, allows trainees to practice using a simulated emergency involving a plane (after an accident during take-off or landing).[48]

Development of soft skills

XR technologies can also help to develop transversal (soft) skills (e.g. communication, critical thinking, problem solving, leadership, teamwork), the importance of which is rising substantially in the context of increased labour market competitiveness (Federica et al., 2021; Kic-Drgas, 2018). In this section, we present some examples of the application of XR in formal education and training for the development of soft skills.

In general, XR-supported training leads to **higher achievement** in soft skills development compared with traditional training methods (Bastos, 2021; Dahl, v2021; García et al., 2016). The results of clinical tests indicate that VR-based training ensures a faster learning process, higher confidence among learners in their acquired skills, and a deeper focus on learning (eliminating multi-tasking and distracting issues) (Lepaya & Parable, 2021). Moreover, XR-based learning is also cheaper (the cost usually does not increase with the number of trainees) and allows trainees to maintain social distancing if necessary (Lepaya & Parable, 2021). For this reason, formal educational institutions at all levels can apply XR tools that provide an opportunity to build soft skills in a more efficient and engaging manner (García et al., 2016).

The use of **virtual scenarios** is a popular area of XR application in soft skills training (Carlton, 2018; Pirker & Dengel, 2021). Using XR tools, educators create virtual scenarios (stories)[49] and assign related tasks to learners. These can include collaboration, problem solving and conflict management activities (Carlton, 2018). Research in this area shows that this learning approach has a positive impact on the learning process and on the achievements of learners (including communication, leadership, conflict management, collaboration, critical thinking, and creative skills), who are engaged in a more effective and enjoyable manner. XR-based learning also addresses the widespread problem of classic role-plays, which can make students feel ashamed and fearful of making mistakes with real-life consequences (Carlton, 2018). Thus, XR tools foster students' empathy and openness to learning, and help to achieve better learning results.

Example of an XR-based game for soft-skills development

Students at Jönköping University (Sweden) explored the effects on performance of VR-based games in team-building workshops, compared with non-VR-based methods. For this purpose, researchers selected the game *Keep Talking and Nobody Explodes*, which required collaboration, communication, and teamwork to defuse a virtual bomb. The results

[48] https://www.bridges-horizon.eu/firefighters-training-simulation/

[49] Virtual scenarios (VS) are a valuable educational tool that allow learners to engage in realistic learning activities that directly relate to situations encountered in the workplace. The use of scenarios provides a safe environment in which learners can develop their decision-making skills without fear of making mistakes, as well as providing them with rich narrative feedback to explore their decisions and the accompanying consequences. VS can be applied to almost any discipline and can empower learners to feel more confident by giving them an opportunity to build up valuable experience in dealing with the challenges associated with their chosen field.

showed that the VR-based game fosters communication and collaboration between students and empowers all participants to focus on the tasks in hand. This compares favourably with non-VR methods, in which the positive effect was limited.

Source: Visionary Analytics, 2022, based on Sekwao and Modlin, 2018; https://keeptalkinggame.com.

Another example of the application of XR, **virtual platforms**, allow the teaching, tracking and evaluation of students' teamwork and critical thinking skills in a virtual professional environment (García et al., 2016). The operation of these virtual platforms (e.g. the Evalsoft system[50]) is based on a blended learning approach that uses game and role-playing elements and applies problem-based and collaborative learning strategies. When using virtual platforms, students work collaboratively in teams to perform tasks set by teachers and receive feedback (including feedback on the results of the tasks, teamwork and leadership skills) on completion of these tasks. Research indicates that virtual platforms facilitate the learning and development of teamwork skills; thus, students can achieve better results than in a real classroom (García et al., 2016; Nesenbergs et al., 2021).

A further example of the use of XR for soft-skills development

ConVRself™[51] (Spain) is software that allows trainees to develop their communication and problem-solving skills. The software involves two 3D virtual avatars: a personalised 3D avatar of the user, who explains the problematic situation, and that of a counsellor. After the problem is explained, the roles are switched, and the talker becomes the counsellor. This provides an opportunity for students to hear their own story from an outsider's perspective, and to provide possible solutions, which affects the way a person thinks and works with challenges.

Source: Visionary Analytics, 2022, based on Virtual Bodyworks (n.d.).

Despite the positive effects of applying XR tools to the development of soft skills, such technologies are used only rarely in educational institutions. The reasons for this include: i) insufficient digital skills on the part of educational institution personnel (noted especially in Eastern Europe [Bucea et al., 2020]), thus creating the necessity for training sessions, workshops and/or certification programmes targeted at teachers and other related personnel[52]; ii) the high costs of XR technologies (Bucea et al., 2020), which could be solved through additional funding, as well as via professional recommendations to ensure well-informed decisions with regard to the purchasing of technologies[53]; and lastly, iii) a lack of research in this area (Dahl, 2021), which leads to insufficient exploration and dissemination of the positive effects of XR tools on soft skills development in the long term, which might encourage educational institutions to apply XR more frequently.

Raising awareness

In this section, we will introduce the ways in which XR technologies are used to educate students about environmental issues (McGinity, 2018; Nelson, 2020; Nikolaou, 2021; Theodorou et al., 2018) and racism (Tassinari, Aulbach & Jasinskaja-Lahti, 2021; Ziker, 2021).

XR technologies can help to teach students about **environmental issues** and build **environmental awareness**. For example, students can apply AR features using their

[50] García, M. G., López, C. B., Molina, E. C., Casas, E. E., & Morales, Y. A. R. (2016). Development and evaluation of the team work skill in university contexts. Are virtual environments effective?. International Journal of Educational Technology in Higher Education, 13(1), 1-11.

[51] https://www.virtualbodyworks.com/homepages/convrself

[52] The observation was made during the workshop.

[53] Ibid.

smartphones by pointing the camera at a target image (a QR code) to display a 3D model on their phone's screen. Such 3D models can visualise current environmental issues (e.g. global warming, deforestation, air or soil pollution), explain their causes and provide recommendations for mitigation. In addition, the use of VR headsets and virtual scenarios also provides an opportunity to create realistic images of environmental disasters (the box below presents one particular example).[54] The purpose of such applications is not to moralise, but rather to raise awareness and explain how each person can contribute to positive environmental changes (Paule, 2020), as well as to reinforce students' cognitive performance (Azis, 2019; Nelson, 2020; Theodorou et al., 2018).

XR use to develop environmental awareness

The smartphone app *Klimaklar Esbjerg* (Denmark) combines images from the phone's built-in camera with AR to show the effects of climate change right where the user stands within the boundaries of the Danish city of Esbjerg. The app was designed as part of the city's climate and risk management plan and aims to better engage its citizens with the local climate agenda.

Source: Visionary Analytics, 2022, based on https://virsabi.com/klimaklar-esbjerg/

XR tools can also be useful in increasing students' **awareness of racism and reducing racial discrimination** (Hasler, 2017; Tassinari, Aulbach & Jasinskaja-Lahti, 2021; Ziker, 2021). This can be achieved by students participating in a gamified simulation in which they assume the role of a student who faces racial bias while studying. In this way, learners can learn first-hand about negative experiences and difficulties while studying related to racial discrimination. Participants can wear 'VRZ360 – The Antiracism Glasses'[55] for a more realistic experience[56] (see box below). Research into the impact of such awareness training reveals that engagement with such virtual experiences reduces racial bias and increases students' empathy towards ethnic minorities (Bertrand et al., 2018; Hasler, Spanlang & Slater, 2017; Roswell, 2020) and/or students with disabilities[57].

Use of XR to raise awareness of racism

Bodyswaps (UK) is an award-winning soft skills training platform via which students can practise and develop their communication, teamwork and leadership skills. *Let's Talk About Race* is a specific application of this software that provides students with learning scenarios through which they can understand different types of race-based privilege, reflect on how privilege affects their own life and the lives of others, explore the relationship between intersectionality and privilege, and unwrap the myth of meritocracy. The application is available on VR, PC and mobile in English and French.

Source: Visionary Analytics, 2022, based on https://bodyswaps.co/soft-skills-training-in-vr/lets-talk-about-race/

Art and design

The use of XR also opens up many opportunities for art, architecture and fashion students. It can help to stimulate creativity, to explore and create works of art in a virtual environment. In this section, we will introduce how XR technologies are applied in the field of art, and how they affect students' learning processes.

The application of XR technologies significantly expands opportunities for **art students** (Back et al., 2019; Du, 2021; Guo, 2021; Hui et al. 2021; Li, 2021; Syczewska, 2021). For example, students can virtually visit museums and explore the world's most famous works of art while physically remaining in the classroom. This opportunity broadens students'

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[54] Ibid.
[55] https://www.telekom.com/en/company/details/using-virtual-reality-to-combat-everyday-racism-636502
[56] Ibid.
[57] Based on interviews.

horizons and encourages their creativity (Hui et al., 2021; Nisha, 2019; Syczewska, 2021). In addition, this such virtual experiences save time and financial resources, and create opportunities for students with financial difficulties to access museums. VR-based tools also allow students to explore and create new art forms such as 3D artworks, which would be impossible in reality (Du, 2021).

VR application for virtual museums

Opuscope (France) offers interaction with 3D images in mixed reality.[58]

EUseum (Netherlands) immerses users in a virtual world of museums, galleries and archives. Users experience the feeling of being in an actual museum, viewing the exhibition in a realistic way using the Meta Rift DK1 headset.[59]

VR-All-Art (Switzerland) is a platform that gives users the freedom to easily create exhibitions in VR and sell artworks without the limitations of time, space and geography.[60]

Source: Visionary Analytics, 2022, based on various sources. Image source: www.vrallart.com

Architecture students can analyse architectural projects by wearing VR headsets, which allow them to walk virtually around virtual 3D buildings to gain a realistic impression of their structure and floorplan, furniture, decorations and even changing shadows depending on the time of day (Cabero-Almenara, 2021; Delgado et al., 2017; Kharvari & Hohl, 2019; Sanchez-Sepulveda, 2019; Williams, 2019). For example, *VRVis*[61] enables digital stage design and virtual construction processes at the Vienna State Opera. The main advantage of such virtual exploration is that users can gain a faster, more natural and accurate understanding of the building space by seeing structures at their true scale, rather than using a two-dimensional view (Sanchez-Sepulveda et al., 2019; Williams, 2019).

Application of XR in architecture

PaintingVR (Belgium) is a virtual painter's studio of more than 900 sq. m. with inspiring tools, an unlimited supply of paint, and canvases of all sizes.[62]

VR Sketch (Estonia) allows users to preview their designs directly in VR in a permanent studio setup. The app can be used multiple times a day to validate sizes and design features and even go through technical details and installation processes in VR with engineers.[63]

Source: Visionary Analytics, 2022, based on various sources. Image source: https://www.paintingvr.xyz/

In recent years, students of **fashion design** have actively used VR-based computer software that allows them to design clothes out of various materials and styles in a 3D virtual design environment (Eurokreator, 2022; Westra, 2018). This makes it possible to create clothes in 3D and view a high-quality image that reflects the texture of the material used, providing a realistic design experience. The main added value of such training (e.g. based on *eTryOn*[64]) is that students can change the design of clothes at any point, eliminating the fear of failure that comes with committing to a design in real life, as virtual designs do not have any real-life consequences such as wasting fabric (Hu, 2021; Syczewska, 2021). This is particularly useful for newcomers who are still experimenting with their own design styles.

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58 https://arvrjourney.com/made-in-europe-5-european-xr-startups-at-the-service-of-art-that-you-should-know-about-e4b9f545f8ea
59 https://thevirtualdutchmen.com/en/2018/02/02/euseum-europes-first-vr-museum/
60 https://vrallart.com/
61 https://www.vrvis.at/en/research/research-projects/virtual-reality-stage-designs-for-the-vienna-state-opera
62 https://www.paintingvr.xyz/
63 https://vrsketch.eu/blog-jarl.html
64 https://etryon-h2020.eu/

Application of XR in fashion education

SUSTAIN:AR[65] (Denmark) is an app that allows users to see designs made in 3D by VIA University College students using their phones. Sustain:AR also offers a virtual fashion show for Copenhagen fashion week (Ferguson, 2021).

Gravity Sketch (UK, EU H2020-funded) is an intuitive 3D design platform for cross-disciplinary teams to create, collaborate and review in an entirely new way. The Gravity Sketch allows users to express their ideas in real time, at any scale, from concept sketches to detailed 3D models.[66]

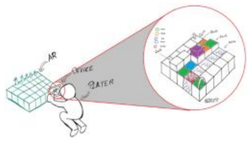
Source: Visionary Analytics, 2022, based on Ferguson, 2021. Image source: https://www.scandinavianmind.com/news/mannd-creates-ar-fashion-show-for-design-students

Development of computational thinking

Educational institutions are beginning to pay increased attention to the development of students' **computational thinking skills** –integrating computing techniques and methods into other disciplines to solve problems (Agbo, 2021; Lai, 2021, Gardeli & Vosinakis, 2019; Lin, 2021; Saraiva et al., 2021; Sims et al., 2021; Tsarava et al., 2017; Román-González, Pérez-González, & Jiménez-Fernández, 2017). XR tools are being adopted for this purpose due to the inadequacy of traditional teaching methods such as class learning in developing these skills (Lai, 2021), mostly due to their inability to ensure a sufficient variety of suitable situations to train problem-solving skills.

Students' computational thinking skills can be developed with the help of **XR-based video games**. Students can play these video games using specific applications on their smart devices (e.g. tablets or smartphones), which allow them to tackle tasks oriented around problem solving in an AR or VR-based environment. These tasks are usually interactive, which allows for the tracking of users' actions to evaluate progress made and suggest possible further actions. Research has shown that the use of such XR tools has a significant positive impact on students' performance (Saraiva et al., 2021; Tsarava et al., 2017).

Examples of XR-based video games for developing computational thinking skills



SHREWS is a video game that integrates AR features for the development of computational thinking. The objective of the game is to move a group of shrews (small rodents) across a map from entrance to exit. To do this, the player needs to find a flat surface and use a smartphone or tablet to generate a map, analyse the terrain, and figure out the best paths to guide the shrews across the map. This game helps to develop four key concepts of computational thinking: decomposition, abstraction, algorithms, and pattern recognition (Saraiva et al., 2021).

CodeCubes, developed in Portugal, is a hybrid interface that combines physical paper cubes with AR to develop computational thinking. CodeCubes creates a labyrinth with various paths, along which cubes and pyramids are scattered. Learners manipulate physical paper cubes, which have an AR marker on each face associated with a programming instruction, to overcome the challenges that have been set. The goal of the game is for students to collaboratively generate their own labyrinths and constuct different buildings in order to learn basic programming concepts (Cleto et al., 2019).

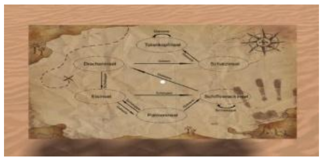
Source: Visionary Analytics, 2022, based on Saraiva et al., 2021 and Cleto et al., 2018.

Educational institutions also use XR tools to **model and visualise problem situations** in a virtual environment. Students wearing head-mounted displays (HMDs) participate and interact in a virtual problem-solving environment in which their actions are recorded

[65] https://www.mannd.dk/portfolio/sustainar
[66] https://www.gravitysketch.com/

(Dangel, 2018; Araiza-Alba, 2021). The main added value of this training is that students have an opportunity to observe and analyse the problem situation in greater detail, rather than rely on simple descriptions of the problem. Moreover, VR tools offer a wide variety of virtual scenarios that can be applied in various educational fields, thus solving the limitations of the traditional learning approach, in which the list of such scenarios is limited (Dangel, 2018; Lai, 2021).

Example of the use of a virtual environment to visualise problem-solving tasks (Germany)



Treasure Hunt VR is a VR-based game developed in Germany that immerses students in the world of a treasure island. Students wearing HMDs navigate through the virtual world to reach the Treasure Island and find the treasure chest (the easy way), or by completing the map – identifying all possible routes to the treasure island (the hard way). According to the game's developers, understanding the representations of islands (as states) and shipping routes (as transition functions) is crucial to the development of computational thinking.

Source: Visionary Analytics, 2022, based on Dangel, 2018

Collaboration

XR tools enable students to collaborate virtually with their peers in order to foster learning and develop communication and teamwork skills (Greenwald et al., 2017; Martin-Gutiérrez, 2017; Ke, 2016). In this section, we provide examples of how XR technologies are being used for this purpose.

VR is used to create **collaborative learning experiences** that enable students to work together to complete assignments in a virtual environment (using computer software and/or VR tools such as HMDs). For example, ECIU University XR Campus provides new interactive spaces for communication and shared understanding, such as virtual meetings in parks or classrooms.[67] Students who participate in these virtual activities can communicate with each other, use virtual sticky notes, draw 3D paintings, and even make video presentations, thus increasing their interactivity.[68] This virtual experience can promote learners' identification with the learning topic and ensure higher engagement, which in turn leads to increased motivation, improved learning performance and better teamwork skills (Greenwald et al., 2017).

Example of the use of XR for collaborative learning

Laerdal[69] (Norway) is a health care company that employs Varjo's MR headsets[70] to create a shared simulation in which students work simultaneously in the same immersive patient treatment scenario.

Osgenic[71] (Finland) uses Varjo headsets[72] to create a fail-safe collaborative immersive VR training environment for open surgeries.

TeamViewer Classroom[73] (Germany) is a virtual learning platform that enables interactive cooperation at all levels of education. It provides not only simple online meetings but also enables teachers and learners to jointly edit uploaded documents and use digital whiteboards.

Source: Visionary Analytics, 2022. Image source: https://varjo.com/blog/case-laerdal-mixed-reality-for-healthcare-and-medical-simulation/

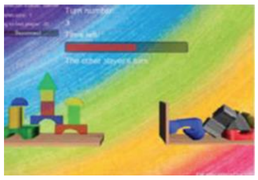
[67] https://www.eciu.org/news/xr-campus-virtual-reality-for-instant-collaboration-shared-understanding-and-focus

[69] https://laerdal.com/
[70] https://varjo.com/blog/case-laerdal-mixed-reality-for-healthcare-and-medical-simulation/
[71] https://www.osgenic.com/
[72] https://varjo.com/blog/vr-is-the-future-of-surgical-training-and-vr-1-is-the-piece-of-the-puzzle-thats-been-missing-arne-schlenzka/
[73] https://www.teamviewer.com/en/classroom/

Teachers can also apply a virtual collaborative learning environment to the **learning and communication of children with autism**. These students are invited to collaborate with peers in a virtual environment to complete set tasks and develop necessary communication and problem-solving skills (Greenwald et al., 2017). For example, students may be required to work in partnership in an *OpenSimulator*-based virtual world to rebuild a virtual Japanese neighbourhood that was devastated during the earthquake (Ke, 2016). This specific design task involves the design/creation of multiple constructions from scratch, and requires cooperation in decision making (e.g. deciding on a building's design, considering both their own and end users perspective (i.e. those of the Japanese residents'). Research in this field has shown that children with autism who participate in such activities are able to socially interact with their peers in VR-based design tasks, were actively engaged in the collaborative design task, and achieved the targeted design goal (Ke, 2016).

A virtual collaborative learning environment for children with autism

The Puzzle Game was designed to enhance the collaboration skills of users with autism. The game evaluates three important collaborative behaviours: sequential work, information sharing, and simultaneous work. For this purpose, the application suggests three types of games: turn-taking games, information-sharing games, and collaboration games. Together, these games require sequential interactions, simultaneous interactions, and the sharing of information (Zhang et al., 2018).



Source: Visionary Analytics, 2022, based on Zhang et al., 2018

The application of XR also allows learners to study interactively and collaboratively in a **virtual laboratory**, complete with virtual assistants and 3D models that virtually illustrate chemical or physical reactions (Martin-Gutiérrez, 2015). Open-access virtual laboratory *Labster* provides students with an opportunity to use advanced lab equipment to solve real-world challenges (e.g. DNA and gene sequencing, chemical reactions, etc.). The virtual environment of the laboratory can also be changed depending on the experiment's scenario (e.g. by switching to a view of a forest or desert plains), thus increasing the sense of reality[74]. These features address the limitations of traditional laboratories. These include: i) difficulties in tracking the progress of students due to teachers' high workload, given the number of students per class (Martin-Gutiérrez, 2015; Sypsas & Kalles, 2018); and ii) the risk of an unsafe learning environment (Potkonjak et al., 2016). On the other hand, training in virtual laboratories also has some negative impacts, such as a potential lack of seriousness and responsibility on the part of students (due to the lack of real-world consequences), excessive simplification and gamification of the learning process, and the necessity to repeat training using actual hands-on experience (Potkonjak et al., 2016).

Other examples of virtual laboratories include Smartgridmaster (Erasmus+ funded)[75], Aqua Excel 2020 (Horizon2020 funded)[76], EURlab (Erasmus+ funded)[77], Evonik Cyberclassroom[78], VRLabAcademy (Netherlands)[79], and the CHARMING project[80].

Physical training

XR can be applied in all areas of physical education and training (PET), including teaching, learning and strengthening athletes' sports knowledge and skills (Loia & Orciuoli, 2019;

[74] https://www.labster.com/
[75] https://smartgridsmaster.eu/laboratories/virtual-labs/
[76] https://aquaexcel2020.eu/virtual-laboratory
[77] http://www.eurlab.org/index.php/en/virtual-labs
[78] https://corporate.evonik.be/nl/attachment/134393?rev=1
[79] https://www.vrlabacademy.com/
[80] https://charming-etn.eu/2019/04/03/training-in-virtual-reality-for-the-chemical-industry/

Zhang & Liu, 2016). This section aims to provide detailed examples of XR applications across these areas.

VR fitness apps have become increasingly popular since the launch of VR systems. For example, the popular game on Meta Quest 2 *Racket Fury: Table Tennis VR,*[81] developed by Polish company Pixel Edge Games, challenges players to exercise and compete at table tennis against an AI opponent[82] (Hemminki-Reijonen, 2022). The Japanese game *HADO* combines AR technology with motion sensors to create a digital experience that resembles a dodgeball video game.[83] Similarly, *Quell* – an immersive gaming platform developed by UK-based innovation studio Morrama – uses wearable technology, life-like haptics and resistance to create an inclusive all-body workout.[84]

The use of XR tools such as those mentioned previously can **ensure a better quality of instruction and a greater variety of sports in physical education and training (PET) programmes** (Akbas et al., 2019; Farič et al., 2021). By using VR tools (e.g. HDMs, motion sensors, 3D display devices), PET teachers can guide students in real time through the process and challenges of VR-based exercise rather than instructing them beforehand (Tang, 2021; Zhang, Shi & Bai, 2021). In addition, VR tools reduce the constraints imposed by the external environment on specific training (e.g. skiing, diving, snowboarding, etc.). VR also enables students to participate in certain sports (e.g. shooting, climbing or trampolining) that otherwise cannot be offered due to insufficient equipment, lack of space, funding, etc. A PET curriculum that implements XR practices can therefore encourage more students to become physically active, as well as diversifying sporting activities and improving the quality of PET (Calabuig-Moreno et al., 2020; Li, Yi & Gu, 2021; Zhang & Liu, 2016).

ICAROS, an example of the application of XR in PET

ICAROS (Germany) combines fitness and VR to create entertaining and effective training experiences. The product is designed to give participants a full-body workout while providing a fun and active way to enjoy VR training. Using a gyroscopic mechanical device, players lie in a horizontal position and navigate through virtual 3D worlds using balance, coordination and muscle strength. ICAROS systems can be used in athletic, strength and rehabilitation training as well as in group classes or for home fitness. Various studies conducted by recognised sports universities prove the effectiveness of ICAROS training in the areas of strength and balance.[85]

Source: ICAROS (n.d), available at: https://www.icaros.com/experiences/. Image source: https://searasports.com/product/icaros-home/

VR technology also **allows the improvement of students' athletic skills and the prevention of possible injuries** (Akbas et al., 2019). Specifically, educators using VR tools can flexibly adapt the digital training environment according to students' needs, providing accurate instructions in real time (Liu, 2019; Zhang & Liu, 2016; Jensen & Konradsen, 2018). In turn, simulation systems in the digital environment can analyse athletes' training, evaluate movement techniques or identify areas for improvement to prevent accidents later on in the training sessions (Faure et al., 2020; Zhang & Liu, 2016; Loia, & Orciuoli, 2019). For example, Prague's Charles University adopted *Sense Arena*[86], a VR-based training software package, to improve the skills of the university's hockey players and goalkeepers.[87] XR technologies can also be applied to enhance students' skills in competitive sports – for example, by analysing videos and other data about opponents, a virtual opponent can be

[81] https://www.Meta.com/experiences/quest/1952355814856769
[82] https://steamunlocked.one/racket-fury-table-tennis-vr-free-download/
[83] https://hado-official.com/en/.
[84] https://playquell.com
[85] https://www.icaros.com/fileadmin/user_upload/ICAROS_-_Studies_2020.pdf
[86] https://www.sensearena.com
[87] More information available at: https://www.vrfitnessinsider.com/hockey-players-train-using-virtual-reality-hone-skills/.

created with the same characteristics as a real athlete (Ali et al., 2017; Loia & Orciuoli, 2019).

PuttView, an example of the application of XR in PET

PuttView (Germany) provides golf coaches and golfers with visual aids for training. Golfers looking to improve their putting can animate targets that appear anywhere on the putting surface, challenging players to learn both break and pace in a series of putts as the clock counts down. *PuttView* helps players to analyse their mistakes, become more accurate, and understand various aspects of the sport such as how different speeds lead to different ball paths.

Source: Visionary Analytics, 2022, based on Golf Monthly (2019), https://www.golfmonthly.com/tech50/putt-view-162871

Despite the positive effects of XR in PET mentioned above, its **application in formal education remains fairly limited.** A number of reasons may explain this: i) the practical application of XR in PET requires further research (Ali et al., 2017); ii) better hardware equipment is needed (Jensen & Konradsen, 2018; Tang, 2021; Soltani & Andrade, 2021); iii) the digital environment cannot completely replace physical training (Tang, 2021); and iv) proper and safe implementation of high-quality VR PET equipment in formal education is relatively expensive (Tang, 2021).

Learning languages

Growing research on this topic has identified key areas for the possible application of XR in foreign language learning: i) formal educational settings, (e.g. schools and university programmes); and ii) informal education in foreign languages through the individual use of various XR tools (Pegrum, 2019). This section discusses in detail several examples of the application of XR in foreign language learning.

Systematic reviews of research articles on the subject reveal that **XR is already being used in formal educational settings to enhance the effectiveness of foreign language learning,** due to its flexibility, efficiency and accessibility (Berns, & Reyes Sánchez, 2021; Casañ-Pitarch, & Gong, 2021; Papanastasiou et al., 2019; Repetto et al., 2021; Tegoan, Wibowo & Grandhi, 2021). For example, Gold Lotus, an Italian company, offers a programme for schools to learn and teach English as a foreign language through VR, implemented at a secondary school in Bari, Italy.[88] Another application called *CityCompass VR*,[89] developed by Finnish researchers at the University of Tampere for the purpose of language learning, also promotes situational and collaborative conversation skills through interactive VR 360 videos (Kallioniemi et al., 2019). This approach enables students to practise both conversational and vocabulary skills in their target language, as well as raising cultural awareness of other cities or countries.

Gold Lotus, an example of the application of VR in English language learning

Gold Lotus (Italy) offers several VR-based language teaching and learning solutions in addition to the programme for schools mentioned above. These include:

- VR language teachers – human educators offering live English and Spanish lessons.
- Self-study or live VR English lessons are available 24/7, and learners can study at their own pace.
- A handy English VR app allows users to interact, create vocabulary lists and practise pronunciation in an immersive environment using hand-tracking technology.

[88] https://www.goldlotus.co/vr-english-schools
[89] https://dl.acm.org/doi/abs/10.1007/978-3-030-29390-1_33

Source: Visionary Analytics, 2022, based on Gold Lotus (n.d.), https://www.goldlotus.co/vrenglishlessons

Immersive environments also create a holistic, student-centred approach to learning (Meyran-Martinez & Spanghero-Gaillard, 2021; Yang et al., 2020). For example, VR-based apps such as *Play2Speak*[90] combine different aspects of reading comprehension, vocabulary retention and speaking skills through gamification, making language learning more engaging and less dependent on face-to-face teaching (Casañ-Pitarch, & Gong, 2021; Parmaxi & Demetriou, 2020; Panagiotidis, 2021). Such learner-centred educational environments can also provide more practical experiences of interaction with native speakers, bringing learners closer to a genuine community of speakers of the target language (Hemminki-Reijonen, 2022; Nicolaidou, Pissas, & Boglou, 2021). Moreover, an AR-based approach can facilitate teaching English for students with reading and spelling difficulties.

Example of the application of XR in English language learning

Play2Speak (Spain) is an EdTech start-up founded to offer language learners an alternative to traditional language learning methods. The app mixes VR, AI and digital storytelling to help improve students' English skills. For example, one of the games takes users on an ocean adventure in which they can converse with virtual characters and practise the language in real-life conversations.

Source: Visionary Analytics, 2022, based on Play2Speak (n.d.), https://www.seedrs.com/play2speak.

Furthermore, teachers can use QR codes to augment their lesson materials and incorporate XR aspects into teaching (e.g. to access various reading and listening activities or dictionaries, to receive instructions for complicated language exercises, or to access additional learning resources without the need for constant intervention by the teacher) (Cruse & Brereton, 2018; Koutsopoulos, Doukas, & Kotsanis, 2017). These activities encourage students to be autonomous and self-directed, as well as motivating them to take responsibility for language learning and actively participate in learning activities (Klimova, 2021; Meyran-Martinez, & Spanghero-Gaillard, 2021; Yang et al., 2020).

Various EU-funded projects also facilitate and promote the use of XR tools in language learning. For example, *EVEIL-3D* created a game that lets language learners explore the history of Strasbourg Cathedral through immersive communication, interaction and speech recognition.[91] Similarly, *VR4ALL* is developing an innovative platform to carry out collaborative group language exercises in the classroom.[92] *VirtuLApp* (the Virtual Language App) has created the multilingual, multiplayer augmented reality game *BabelAR* for pupils aged 7-12 years, which enables teachers to foster multilingualism in class through an innovative multi-didactic approach[93].

Using AR to facilitate the teaching of English literacy skills

Pilot 1 of the project *ARETE*, funded under Horizon 2020, aims to make the teaching and learning of English more accessible and successful by integrating more aspects of AR into the WordsWorthLearning (WWL) literacy programme. The programme embraces clinical, educational, social and political solutions to illiteracy. The project will redevelop an existing WWL digital programme into an app that incorporates AR. Teachers participating in Pilot 1 will use the WWL AR app to facilitate the teaching of English to students with reading and spelling difficulties.

Source: Visionary Analytics, 2022, based on ARETE (n.d.), https://www.areteproject.eu/pilots/.

[90] https://www.seedrs.com/play2speak.
[91] https://ec.europa.eu/regional_policy/en/projects/france/eveil-3d-learning-foreign-languages-through-immersive-virtual-reality-games
[92] https://vr4ll.com/
[93] https://virtulapp.eu/

XR is also applied in **informal educational settings, mainly through a combination of mobile-based apps, AR and/or VR** (Berns, & Reyes Sánchez, 2021; Pegrum, 2019). For example, the London-based start-up *VirtualSpeech*[94] offers a Business English course which the learner can take in a VR setting. Research shows that such applications of XR create a safer, more comfortable and less apprehensive environment for learners to practise their target language (Divekar et al., 2021; Panagiotidis, 2021; Sadiku, 2018). This, in turn, improves the effectiveness of learning and increases students' interest and motivation to learn a new language (Hemminki-Reijonen, 2022; Kaplan-Rakowski, & Wojdynski, 2018; Yang et al., 2020).

The application of XR in language learning

Mondly (Romania) is an app that takes an innovative approach to foreign language teaching and learning. It is the first app to combine AR, chatbot technology and speech recognition to create an immersive and lifelike language learning environment. The app offers four features to different client groups: Mondly VR, which allows learners to have realistic conversations with virtual characters; Mondly AR, an AR app with chatbot and speech recognition; Mondly Works, a language learning software for businesses; and Mondly Kids, a free educational game. The VR version of the app requires a head-mounted VR display), while the mobile app only requires a mobile device (Nicolaidou, Pissas & Boglou, 2021).

Source: Mondly (n.d.), https://www.mondly.com; Nicolaidou, Pissas & Boglou, 2021.

Despite the successes mentioned above, many challenges may still arise in the application of XR technologies to language learning in formal education. These include: i) the effectiveness of using XR in language learning and teaching is highly dependent on users' digital abilities (Pinto et al., 2021); and ii) insufficient digital abilities in using XR tools may prevent users from participating in the educational process altogether (Lin & Wang, 2021). Therefore, before XR is used for language learning in academic settings, training programmes must be prepared for teachers and students to make full use of XR technologies (Meyran-Martinez & Spanghero-Gaillard, 2021; Tegoan, Wibowo & Grandhi, 2021).

Moreover, due to a lack of long-term studies on the effects of XR usage in language learning (Pinto et al., 2021), further research is needed regarding various aspects of XR applications, such as the content of applications or XR for learners with special educational needs (Pegrum & Lan, 2021; Parmaxi, 2020).

Affordances of XR by instructional approach

The use of XR in education can also be categorised in terms of the instructional approaches used and the learning activities that are required by the learner. Selecting the most appropriate instructional approach depends on the aims of the instruction and the nature of the learners who will use the XR technologies. This study adopts the conceptual framework for the use of immersive technology outlined by Suh and Prophet (2018). The authors find that system features (sensory and perceptual stimuli) and content topics (learning and training, psycho- and physiotherapy, virtual journeys and tours, interactive simulation, and gaming) influence users' cognitive and affective reactions.

With this in mind, three main instructional approaches or approaches to delivering educational content have been identified that represent the features of the immersive system (i.e. stimuli), outlined in the framework above:

1. Visualisation (sensory stimuli),
2. Virtual field trips (content stimuli),

[94] https://virtualspeech.com/

3. Storytelling/annotation (perceptual stimuli).

Visualisation

XR offers 3D learning materials that can be especially beneficial in teaching subjects where it is important for learners to visualise the subject matter (e.g. **engineering, anatomy, and STEM**). This feature ensures interactivity in learning, thus addressing the common issue with traditional videos, which are usually passive learning objects (Allcoat and von Mühlenen, 2018; Kamińska et al., 2017; Fombona-Pascual, Fombona, & Vázquez-Cano, 2022).

Engineering students tend to have difficulties in reading and understanding 2D and even 3D representations, as well as a lack of knowledge regarding the functions of components and in the analysis of the chain of power transmission and transformation of movement (Bohné, et al., 2021; Carbonell-Carrera, Saorin, & Jaeger, 2021; Lukačević, et al., 2020; Marino, et al., 2021; Scaravetti & François, 2021; Tarradas, et al., 2021; Wolf, et al., 2021; Wolfartsberger, 2019). In this case, an AR application can foster their learning process. To illustrate this, Scaravetti and François (2021) conducted an experiment on first- and second-year Bachelor students in engineering using different AR scenarios, and found that i) 93.3% of them were satisfied with the AR application; and ii) the AR ensured easier understanding of complex systems as, on average, the students who had access to AR achieved scores 22.6% higher than the students who worked with traditional documentation.

Another example of the application of XR for engineering is the Educational Laboratory – Big Machine (ELBigMAC)[95] project in Portugal, co-funded by the Erasmus+ program. This entails the assessment of VR game-based platforms designed to introduce the field of civil engineering to pre-university students (Dinis et al., 2017). The results obtained show that VR is a relevant asset in civil engineering education, as it allows participants with no prior training to interact properly with the platform.

ViMeLa (Poland), an example of a VR tool for teaching mechatronics

Virtual Mechatronics Laboratory (ViMeLa)[96] is based on a blended learning method involving theory classes and using VR as an experimentation tool for teaching mechatronics. This is a joint European project by the University of Technology in Łódź, with the participation of the Universities of Skopje, Pavia and Tartu. The method involves three scenarios, namely:

1. The design, construction and operating principles of electric motors. This scenario includes tasks such as the observation of different types of electric motors and their construction (based on 3D visualisation), assembling a certain type of electric motor, placing the motor on the testing bench, and making appropriate connections with the power supply, control and adequate instrumentation.
2. An industrial automation solution to control the process of sorting packages in a warehouse. This scenario allows users to familiarise themselves with the functional principles of industrial automation and the details of the most important components necessary to control the process of sorting packages in a high-capacity storage warehouse.
3. A sorting line for industrial and domestic waste using a conveyor belt. Proposed Scenario A aims to build and use a waste sorting line, which should be able to segregate materials such as plastic, glass and organic waste. Meanwhile, in Scenario B, the user can sort other kinds of materials, e.g. ferromagnetic and conductive.

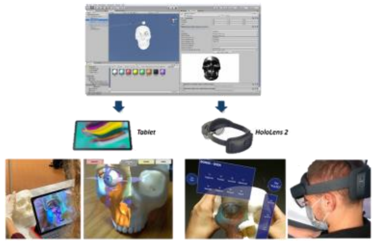
Source: Visionary Analytics, 2022, based on Cvetkovski et al., 2019

Another example of visualisation using XR technologies as an instructional approach in education is in **anatomy** where, due to recent advances in VR, researchers are now better

[95] https://paginas.fe.up.pt/~elbigmac/project/project
[96] https://internazionale.unipv.eu/en/vimela/

equipped to teach and study pulmonary anatomy and airflow patterns, and complex morphology (Bogomolova, et al, 2021; Cieri, et al., 2021; Triepels, et al., 2020). Examples of these include an Italian-made tool called *Anatomical Education with Augmented Reality (AEducaAR*), developed by Cercenelli et al. (2022), and a Finnish tool called *Touch of Life Technologie (Toltech)* by *Varjo*, shown in the box below:

The application AEducaAR (Italy), for use on a tablet or HoloLens 2 smart glasses



AEducaAR is based on a combination of AR technology and a tangible 3D printed model that can be explored and manipulated by trainees, thus favouring a three-dimensional and topographical learning approach. AEducaAR was tested and evaluated by 62 second-year degree medical students attending the human anatomy course at the International School of Medicine and Surgery of the University of Bologna. The pilot AEducaAR tool for studying orbital anatomy was successfully implemented both as a tablet-based solution[97] and a HoloLens-based solution. [98]

Touch of Life Technologies by Varjo (Finland) for anatomy education and training

The Toltech team, which provides virtual anatomy education and creates training environments, developed a comprehensive learning tool called *VH Dissector*. The tool allows medical students to interact with correlated 3D and cross-sectional views of over 2,000 anatomical structures. Using Varjo's virtual and mixed reality headsets, learners can observe even the smallest structures of the human body at human-eye resolution (over 60 pixels per degree).

Other examples in this field include Anatomage (Italy),[99] and Virtual Medicine (Slovakia)[100] as well as the Oslo University Hospital (Norway)[101] and the Faculty of Medicine at the University of Luxembourg.[102]

Source: Visionary Analytics, 2022, based on Cercenelli, L., De Stefano, A., Billi, A. M., Ruggeri, A., Marcelli, E., Marchetti, C., ... & Badiali, G. (2022). AEducaAR, Anatomical Education in Augmented Reality: A Pilot Experience of an Innovative Educational Tool Combining AR; Varjo (n.d.), https://varjo.com/case-studies/transforming-anatomy-education-with-virtual-and-mixed-reality-case-touch-of-life-technologies/.

The current high demand for **STEM**[103] competences and a lack of motivation on the part of students in attaining these (Altmeyer, et al., 2020; Pellas, Dengel, & Christopoulos, 2021; Truchly et al., 2018) requires the introduction of more attractive learning tools. In this case, XR not only helps to enhance student engagement (El Mawas et al., 2018; Pellas & Christopoulos, 2020; Thisgaard & Makransky, 2017; Truchly et al., 2018), but it also provides an opportunity to teach complex and abstract concepts, learn theory and apply practical aspects simultaneously, by conduct safe science experiments and enabling the visualisation of learning materials.

VR Eduthon[104], for example, provides biology students with a word list of human digestive organs, along with realistic visualisations and in-depth explanations of how they function as people eat (Samsung Newsroom, 2016; Trodsen, 2019). Another example is CleverBooks[105], an AR-based app that enables geometry students to examine 2D and 3D

[97] See Supplementary Material Video S1: https://www.mdpi.com/1660-4601/19/3/1024/htm#app1-ijerph-19-01024
[98] See Supplementary Material Video S2: https://www.mdpi.com/1660-4601/19/3/1024/htm#app1-ijerph-19-01024
[99] https://www.anatomage.com/vr/
[100] https://www.medicinevirtual.com/
[101] https://healthcare-in-europe.com/en/news/xr-is-fusing-surgical-reality-with-medical-images.html
[102] https://wwwfr.uni.lu/fstm/actualites/university_invests_in_virtual_reality_tool_for_new_medical_students
[103] Science, technology, engineering and mathematics (STEM)
[104] https://news.samsung.com/global/samsungs-vr-eduthon-makes-immersive-education-a-virtual-reality
[105] https://www.cleverbooks.eu/

geometric shapes from all angles, watch visualisations of how 3D figures unfold into 2D shapes, identify their main properties and variations, and learn about fractions.[106] Such XR applications contribute to the development of imagination, visualisation and cognitive skills, learning the basics of math and geometry, understanding abstract objects, and critical thinking.

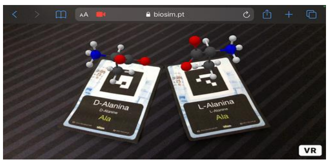
Another growing case for the XR-based visualisation is in chemistry. A comprehensive understanding of atomic and molecular elements requires spatial and visual thinking that is sometimes lacking in traditional methodologies, which employ only limited teaching aids and thus fall short of providing a detailed understanding of the scientific theories and concepts relating to molecular symmetry, for example (Achuthan et al., 2018; Chan et al., 2021). For this reason, in recent years, specific technologies have emerged to enable viable 3D-graphical digital representations of atomic and/or molecular interactions (Fombona-Pascual, Fombona, & Vázquez-Cano, 2022). Chemistry WebVR and/or EduChemVR (Sweden) are examples of such technologies. The former is a web-based platform (currently under development) for learning about organic chemistry and experiencing in VR concepts such as stereochemistry, molecular geometries, atom orbitals and reaction mechanisms; the latter involves a smartphone app placed in the Cardboard/GearVR viewer (EduChem, n.d. (Badiali, G., 2022). Many different studies have shown the potential benefits of using interactive visualisations as a resource to help all students during enquiry-based instruction (Ryoo et al., 2018; Macariu, Iftene & Gifu, 2020).

Examples of XR technologies in STEM education

After seeing students struggle to pass organic chemistry tests, teachers at *Umeå University in Sweden* decided to implement VR technology in chemistry lessons. With their VR glasses on, students can study molecular structures, twisting and turning around their models to better understand the connections and see how various chemical reactions occur. This new learning approach has improved a challenging organic chemistry course and helped students to gain deeper knowledge.

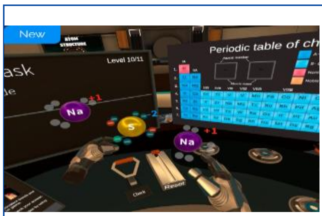
NEWTON is a large European innovation project that examines ways to promote cutting-edge technology to assist students in STEM learning. More than 30 different applications are involved, one of which is Final Frontier, a virtual 3D educational game about space for primary school learners. In the game, students undertake a mission to collect hidden stars and meteorites from various planets.

CHARMING[107] develops learning strategies, content and prototypes for the application of games and VR/AR to motivate, teach and train children, students and employees in chemistry, chemical engineering and chemical operations. These crucial building blocks together define the way in which working memory capacity is enhanced and learning outcomes can be effectively improved.



BioSIM Augmented Reality (BioSIMAR)[108] is an open-source application developed with the aim of providing an interactive platform to explore a molecular model using a versatile, powerful, and easy-to-set-up technology. BioSIMAR offers a free and interactive alternative to explain a panoply of different chemical concepts. For example, it can be useful to provide a spatial comparison between the L and D isomers of alanine.

[106] https://www.areteproject.eu/pilots/
[107] The European Training Network for Chemical Engineering Immersive Learning
[108] https://ar.biosim.pt



Futuclass is an educational platform with gamified lessons for chemistry and physics topics in the 7th to 9th grades. Co-created with natural science teachers and schools, Futuclass VR lessons are highly effective, yielding an improvement of 70% in learning outcomes. Hands-on VR learning puzzles significantly increase student engagement by involving more senses. Examples in the 3D world and real-life help students see behind complex formulas and enable deep thinking.

Other examples of the use of XR in science education include software such as Avogadro[109] and Molden.[110]

Source: Visionary Analytics, 2022, based on https://www.umu.se/en/feature/vr-glasses-help-students-visualize-molecules-/; El Mawas et al., 2019; https://charming-etn.eu/charming-project/; Fernandes, Cerqueria, & Sousa, 2022; Futuclass (https://futuclass.com/lessons/)

Virtual field trips

Virtual field experiences help to broaden access to field learning in various subjects, which may be limited due to geographical constraints in real-life settings. The effectiveness of virtual field trips has been shown in studies by Recupero et al. (2019), Han (2021), and Mead et al. (2019). While the first of these demonstrated that for elementary students, such immersive trips are engaging and expand their learning opportunities, Mead et al. (2019) validated the advantages of interactive virtual field trips in high school and higher education settings. Subjects covered by virtual field trip applications include **art and culture**, **history**, **geography,** and **astronomy**, among others.

In recent years, the use of XR in the context of museums and exhibitions has changed from the display of information to offering emotive, immersive, and rich experiences. The emergence of AR glasses offers the possibility for more accessible connections to social and cultural audiences, personalising the visitor experience and enhancing communication (Martí-Testón et al., 2021; Torres-Ruiz et al., 2020). Technology has proven an essential tool in reinventing the role and relevance of museums and heritage institutions, facilitating access by new and wider audiences (Liu & Lan, 2021; Margetis et al., 2020; Vistisen, Selvadurai, & Krishnasamy, 2020; Panagiotis, Despina, & Chrysanthou, 2013; Recupero et al., 2019). Relevant examples include:

- Leiden's Rijksmuseum, which collaborated with the University of Delft to exhibit the *Egyptian Temple of Teffeh* (Reuters, 2016);
- The *Hellenic Cosmos*, the Cultural Centre of the Foundation of the Hellenic World, which has an infrastructural space called Tholos ('Dome' in English), where visitors can create immersive experiences for themselves;
- *eHeritage*,[111] an EU-funded project which supports and expands the capacity of the Virtual Reality and Robotics Department (VRRD) of the Transilvania University of Brasov (UTBv) in Romania to interact through twinning with research centres at Slovenia's Jožef Stefan Institute in Ljubljana and Italy's Scuola Superiore Sant'Anna in Pisa;
- *Time Machine*[112], another EU-funded project, which aims to develop the Big Data of the Past, a huge distributed digital information system mapping European social, cultural and geographical evolution over time;
- *VirtualArch*[113] is an Interreg-funded project which ended in 2020, which unveils regional archaeological heritage – located underground or submerged – to local and regional stakeholders that are responsible for economic development.

[109] https://avogadro.cc
[110] https://www.theochem.ru.nl/molden/
[111] https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/history-springs-back-life-virtual-reality
[112] https://www.timemachine.eu
[113] https://www.interreg-central.eu/Content.Node/VirtualArch.html

From a **history** perspective, another notable way to apply this technology has been demonstrated by the Muséum national d'Histoire naturelle in Paris, which launched an augmented reality experience in 2021 using Microsoft's HoloLens. The project, called 'REVIVRE' ('To Live Again')[114], allowed visitors to come face to face with digital animals that are extinct in the real world (Muséum national d'Histoire naturelle, 2021). From beetles to the giant tortoise, the REVIVRE experience shows species that are fully modelled in 3D and animated at their actual size.

Similarly, Historium Virtual Reality[115] in Belgium offers a field trip experience whereby userscan take a virtual flight past 15th-century architecture, including the Water Halls, a large storage area that stood on the Market Square in Bruges for five centuries. Another example is Noesis (Thessaloniki Science Center and Technology Museum)[116] – an EU-funded project that offers 2D and 3D shows in a virtualrReality simulator.

Example of a virtual field trip application using museography

Martí-Testón et al. (2021) recently developed an experimental prototype designed for the archaeological museum of the Almoina in Spain.[117] As a result of applying the principles of *Museography 4.0*[118], which they conceived themselves for the Almoina experience, they found that: i) the storytelling methodology, designed and adapted to the wishes and profiles of visitors, allowed them to be placed at the centre of the experience and provided personalised content for users; ii) the intuitive manner in which the AR-based media is operated eliminates the barriers usually faced with digital media; and iii) the use of audio, video and animated 3D recreations makes the experiences of visitors much more immersive.

Source: Visionary Analytics, 2022, based on Martí-Testón et al., 2021

In the field of **geography**, VR/AR can be used to motivate and engage students in key fieldwork practices and techniques and improve employability prospects as said technologies grow in commercial usage and applications (Bos, Miller, & Bull, 2021). Young et al. (2020) visualised the attitudes and behaviours of 50 students from the Department of Geography at Trinity College Dublin when applying a virtual field experience platform inventory to the classroom. The authors found an overall positive response to the attractiveness, hedonistic, and pragmatic effects of VR applied in this context. Relevant examples of virtual field trips include the following:

- *Google Expeditions*[119] is a VR teaching tool that allows users to lead or join immersive virtual trips all over the world. Google Expeditions allows a teacher, acting as a guide, to lead classroom-sized groups of explorers through collections of 360-degree and 3D images while pointing out interesting sights along the way.
- *Collaborative immersive virtual environments (CIVE*) was developed by Masaryk University (Czechia) as a software solution for learning about hypsography. It allows switching between a 2D contour map and a 3D model, increasing intelligibility and clarity. Gamification principles were also applied (Šašinka et al., 2019).
- The Balaton[120] VR environment was designed by a research group of the Hungarian Academy of Sciences for use by teachers. With this VR environment, students are

[114] https://www.mnhn.fr/en/experience/revivre-extinct-animals-in-augmented-reality
[115] https://www.historium.be/nl/ontdek-historium/v
[116] https://www.noesis.edu.gr/en/
[117] https://cultural.valencia.es/es/museu/la-almoina-centro-arqueologico/
[118] According to the authors, Museography 4.0 is a set of techniques and practices relating to the functioning of the museum, which have evolved from analogical museography towards the natural, immersive and intuitive integration of digital data into the expositional context. It can be immersive, experiential, naturalised, narrative, interactive, intelligent, gamified, transmedia and social.
[119] https://sites.google.com/tcsnc.org/tcs-g-expeditions/home
[120] Referring to Lake Balaton, one of Hungary's most visited tourist regions.

encouraged to create their own projects based on information raised in the teaching material (Bujdosó et al, 2019).

The final example of the application of virtual field trips is in **astronomy**. In a typical virtual field trip, software and hardware are used to replicate what a real field trip would be like. The virtual trip is capable of going beyond realistic possibilities and can provide field trips to places that are impossible to undertake in reality using today's technology, such as a space exploration field trip. Examples include:

- *Overview Experience*[121], a French platform powered by Space Engine, relies on data gathered from various sources, such as ESA's star machine, Hipparcos, or NASA's Solar System Dynamics group, for a 32-minute documentary experience (the Earth, the solar system, the planets, Saturn, the Milky Way) and an infinite number of activities within the VR setting (scale of the universe, the solar system, galaxy exploration (under development);
- The *Herschel Space Observatory VR application* (part of the CESAR project, funded by the European Space Agency) was created to commemorate the mission and bring the Herschel's observations to the public. The application allows users to move around a map of the universe created by the Herschel's instruments, zoom in to view details, and switch wavelengths;
- *GaiaVR*[122] is a VR application developed by the European Space Agency that provides an immersive experience of the entire sky, based on data from Gaia's second release. It contains the positions and brightness of 1.7 billion stars in the Milky Way and nearby galaxies.

Storytelling and/or annotation[123]

In interactive storytelling, the story generated depends on pre-prepared content and the choices of the interactor (e.g. the player or user) in the story world (Skult & Smed, 2020). Handler Miller defines digital storytelling as digital media platforms and interactivity for narrative purposes, either for fictional or non-fiction stories (Miller, 2019, as cited in Okanovic, 2022). Two examples of such an approach are identified below in the domains of **speech and language therapy** for children and **cultural heritage**.

When it comes to creating an educational environment for children to pursue **language learning and speech development**, a good example is the project 'Sanalanka Adventures – Speech and Language Therapy Tool'.[124] This tool presents an interactive environment for 3–6-year-old children who have difficulties in language learning and speech development. It helps the children to overcome communication challenges by engaging them in a gaming experience that utilises AR content, speech recognition and neural networks (Skult & Smed, 2020).

Virtual depictions of crafts and traditions offer users the possibility of **time travel**, taking them into the past through the use of 3D reconstructions of cultural monuments and sites. However, digital resources alone are not enough to adequately present **cultural heritage** (Okanovic, 2022). Additional information on the historical context is needed, in the form of stories, virtual reconstructions and digitised objects. All of this can be implemented using a digital multimedia presentation technique called digital storytelling. One example is Unlocking Porto, a location-based game with a central, yet adaptable, story that engages the player with the main sights along an augmented reality path, while playing small games (Nóbrega et al., 2017).

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[121] https://www.overviewexperience.com/
[122] https://sci.esa.int/web/gaia/-/60036-gaia-data-release-2-virtual-reality-resources
[123] While storytelling may be embedded in virtual field trips, it can be considered a different way of delivering information and content.
[124] https://sanalanka.game.blog/games/

Example of a storytelling approach

Keys to Rome was an international museum exhibition developed through the VMust.net project, which took place in four cities in 2014 (Rome, Amsterdam, Alexandria and Sarajevo) (Rizvic, 2018). Its goal was to depict the uniqueness of the Roman Empire. The museums' collections were available as part of a virtual journey through computer animations, natural interaction installations, as well as multimedia and mobile applications (Virtual Museum Transnational Network, n.d.). The story connected the four cities, and gave visitors the ability to explore Roman culture through the characters of the old merchant Gaius and his nephew Marcus. Users were able to walk through virtual environments, collect objects and hear stories.

Source: Visionary Analytics, 2022, based on Okanovic, 2022.

A further subject area in which storytelling can be applied is **history**. One developer, BetaRoom[125] from Germany, creates immersive experiences to make the user feel like they are inside a historical event. Two of its applications are MauAR[126] and Augmented Berlin[127], which are actively used in schools across Germany. The apps have been officially endorsed for digital education by the Berlin-Brandenburg State Institute of Pedagogy for Schools and the Media (LISUM)n. MauAR shows users the course and structure of the Berlin Wall and its construction phases. Users can also follow two leading actors through the decades of division (Andreas from East Berlin, Johanna from West Berlin), and take part in important moments from the building to the fall of the Wall. Similarly, Augmented Berlin takes users on a virtual trip through Berlin's history – from the Weimar Republic to the Second World War, the fall of the Wall, and the years following German reunification.

ArkaeVision VR Game: user experience research between real and virtual Paestum (Italy)

ArkaeVision is an integrated digital experiential platform that provides different ways of enjoying cultural heritage. It comprises: i) an online portal, accessible from any mobile device (smartphone or tablet) or desktop-based system; ii) an immersive VR application (ArkaeVision Archeo, the subject of this contribution); and iii) an AR application (ArkaeVision Art) – available soon at the Archaeological Museum of Paestum. Users can take advantage of two explorative modalities: an emotional and semi-guided visit, where events and facts evolve in the storyline to catch their attention and push them to follow up; during this phase, they can carry out some actions, such as walking and looking around in VR.

Source: Visionary Analytics, 2022 based on Pagano et al., 2020

Though not yet available online, further examples of XR applications include the work of Rizvic et al. (2021), who have designed a number of storytelling experiences relating to Bosnia and Herzegovina, as well as the findings of Hammady, Ma and Strathearn (2020) in relation to the Ambient Information Visualisation Concept (AIVC).[128] The latter specifically places the spectator at the centre of a multilevel globe populated with physical and virtual objects, used to communicate ideas and guide visitors around the museum – in doing so, the AIVC positively influences the enjoyment, ease of use and usefulness of the guided tour.

[125] https://www.betaroom.vision/
[126] https://apps.apple.com/us/app/mauar-berlin-wall/id1439084007?ign-itscg=30200&ign-itsct=apps_box
[127] https://apps.apple.com/us/app/augmented-berlin/id1510589561?ign-itscg=30200&ign-itsct=apps_box
[128] The Ambient Information Visualisation System provides a continuous cycle of interactive data through a sphere of visuals around the operator. The design places the spectator at the centre of a multilevel globe populated with physical and virtual objects, which are used to communicate ideas and guide visitors around the museum. The AIVC is a potential application for Microsoft HoloLens, Meta Glasses and Magic Leap, and is designed to effectively communicate information to users through three layers, which are separated spatially.

1.1.3. Other sectors

Beyond the healthcare and education sectors, XR technologies are also actively applied in sectors such as logistics, manufacturing, engineering and architecture. In all of these cases, XR allows the automation and digitalisation of work processes, which in turn minimises manual work and fosters work efficiency. In the bullet points below, we present the areas of XR application identified during our analysis of success stories. More details about these applications are provided in Annex 3.

- **Logistics/warehousing:** XR technologies include digital solutions that automate manual processes in the fields of logistics and warehousing. For example, workers in these sectors can use smart glasses (with AR functionality) to view order information as well as item location and quantities in their field of vision. This feature leaves workers' hands free for other tasks, thus speeding up their working processes and minimising human errors (TeamViewer, 2022).
- **Manufacturing:** XR also supports the manufacturing sector by providing companies with virtual assistance. In particular, workers can use smart glasses with AR functionality to have all the relevant information about a production process available in their field of vision, while both hands remain free for the other work activities. Moreover, workers also have the opportunity to virtually consult with experts about work processes and/or technical problems that have occurred. Using this feature, workers can directly stream their field of vision (recorded using smart glasses) to experts and receive feedback and/or instructions. These features help companies to overcome challenges such as seasonal work and employee fluctuations, which require constant training for new employees. In addition, this application results in a smaller number of errors and higher quality of work (TeamViewer, 2022).
- **Engineering/architecture:** the application of XR enables engineers and industrial designers to use MR-based tools/software (e.g. *AR3S*[129]) to visualise, edit and share computer-aided design (CAD) data as 3D holograms in a natural environment. Moreover, XR solutions in this sector also enable more active collaboration. For example, when using XR-based software (e.g. *ISAR*[130]), engineers can stream entire AR or VR applications, visualise high-polygon content and interact with it via local servers or the cloud. This XR-based software is ideally suited to prototyping, factory planning and quality control (e.g. in mechanical engineering, the automotive and process industry, aerospace, aviation and architecture). These solutions allow engineers to optimise the development and efficiency of workflows to reduce time and costs (Holo-light, 2022).

[129] https://holo-light.com/products/ar3s/
[130] https://holo-light.com/products/isar-sdk/

TeamViewer™ and Holo-light™ as cases supporting other sectors through the use of XR technologies

Leading global technology company *TeamViewer*, founded in Germany in 2005, has developed and presented a number of AR-based solutions for companies and individual customers, such as Assist AR[131] and lifeAR[132]. The company's latest product, *TeamViewer Frontline*, offers a consolidated AR-based platform that integrates different AR solutions, which can be applied by companies operating in different sectors and for different purposes[133]:

- **xPick[134]** – provides a digital solution to automate manual processes in the field of **logistics** and **warehousing;**
- **xMake[135]** – an innovative make-by-vision solution that can be configured specifically for respective **manufacturing** processes;
- **xInspect[136]**– an AR solution for **inspections** and **maintenance** processes;
- **xAssist[137]** – an AR-based **remote assistance** solution that allows on-site workers to access remote technical support.

These solutions (separately or in combination) are applied by world-leading companies including BMW, Coca-Cola HBC, DHL, Siemens, Schenker Deutschland AG, WS System, Airbus Helicopters, Liebherr, Novajo and many others.

Holo-light, a company based in Germany and Austria, focuses on creating and integrating a server-based system that could equalise the opportunities for end users by eliminating performance issues and incompatibility between different XR devices and data security. Holo-Light offers three main software solutions:

- ISAR SDK[138] – a server-based streaming system for XR apps;
- AR3S[139] – an augmented reality engineering app;
- XRnow[140] – an all-encompassing streaming metaverse.

These solutions (either separately or in combination) are applied by such world-leading companies as Hololab, ShipReality, BMW group, Omlox, BASF, ThyssenKrupp Marine Systems and many others.

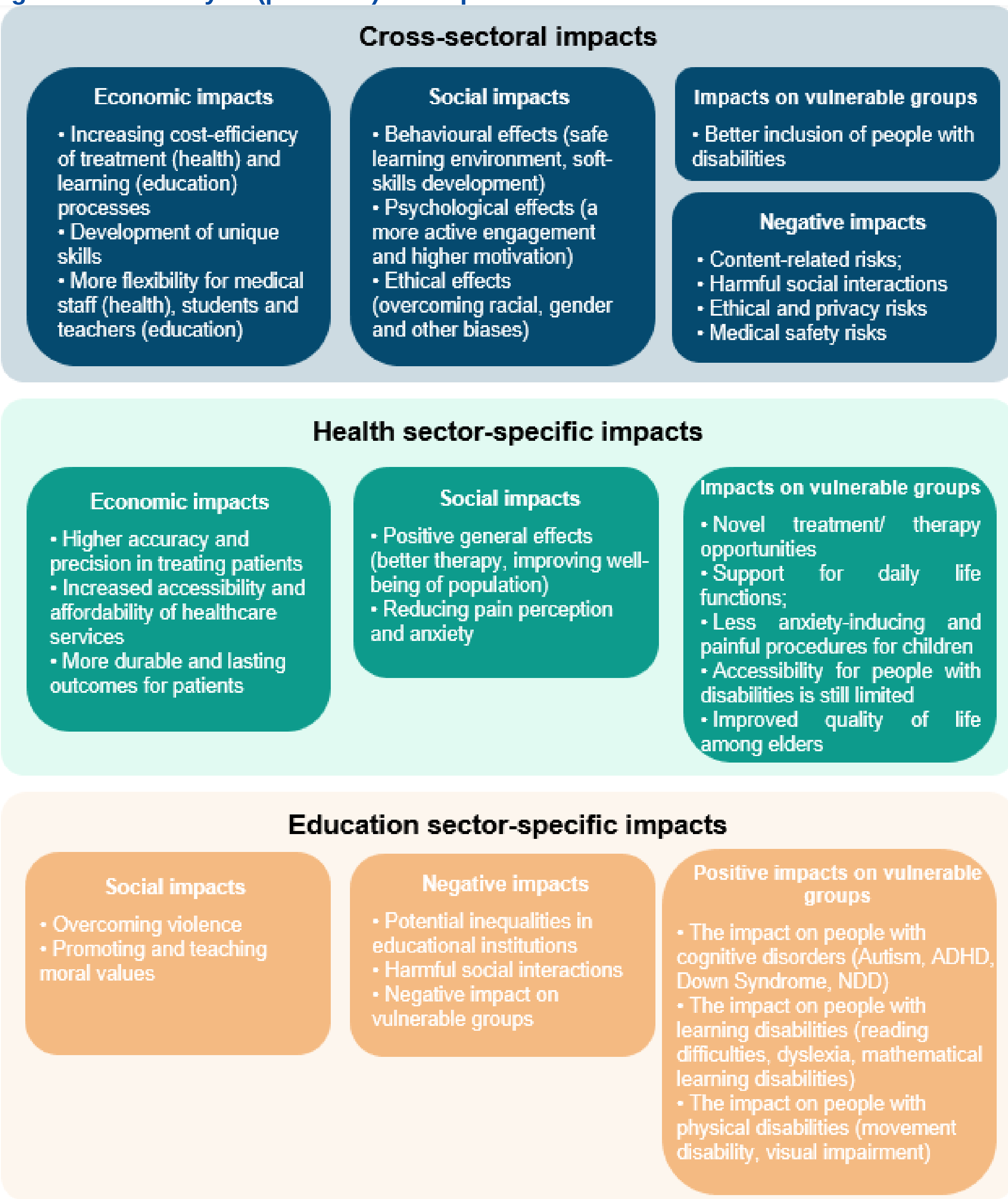
Source: Visionary Analytics, 2022, based on TeamViewer and Holo-light.
Note: more-detailed information about the companies, solutions and use cases presented in the box is provided in Annex 3.

[131] https://www.teamviewer.com/en/augmented-reality/
[132] https://www.lifear.app/en/
[133] TeamViewer Frontline. Available at: https://www.teamviewer.com/en/solutions/frontline/
[134] https://www.teamviewer.com/en/frontline/xpick/
[135] https://www.teamviewer.com/en/frontline/xpick/
[136] https://www.teamviewer.com/en/frontline/xinspect/
[137] https://www.teamviewer.com/en/frontline/xassist/
[138] https://holo-light.com/products/isar-sdk/
[139] https://holo-light.com/products/ar3s/
[140] https://holo-light.com/products/xrnow/

1.2. (Potential) impact on the economy and society

This chapter presents the impacts of XR identified in the healthcare and education sectors, focusing on economic and social impacts, impact on vulnerable groups, as well potential negative impacts. In addition, we present the available evidence on the quantitative impact of XR across other sectors based on a literature review, success stories and a survey of researchers and representatives of the XR industry.

Figure 3. Summary of (potential) XR impacts in health and education



Source: Visionary Analytics, 2022

1.2.1. Cross-sectoral impact

This section discusses the impacts of applying XR (economic impacts, social impacts, negative impacts, and impacts on vulnerable groups) in both the health and education sectors.

Economic impacts

Increased cost-efficiency

The application of XR in both the health and education sectors allows an increase in the efficiency of treatment and learning processes. In other words, XR ensures better results can be achieved in less time and with lower financial costs. Particular cases in the health and education sectors are discussed below.

In the **healthcare sector**, XR allows an increase in the cost-efficiency of treatments. Although actual analysis of cost-efficiency of XR in the academic literature is rare, a limited number of studies (Delshad et al., 2018; Islam & Brunner, 2019; R. Pot-Kolder et al., 2020b) show that cost reductions relate to shortening the length of hospital stays, less doctor time being needed for aftercare, reductions in the use of opioids and an increase in patient satisfaction. In addition, respondents to the healthcare sector survey rated XR's impact in terms of time and resource savings among its greatest impacts. Time savings were observed as positive by 67% of respondents, while resource savings were seen as positive by 47% of respondents. Other illustrative examples include:

- A study of US hypothetical hospitals (Delshad et al., 2018) which implemented an economic analysis of VR therapy for pain, and found an average cost saving of $5.39 per patient[141] compared with usual care.
- A study in the Netherlands of VR cognitive behavioural therapy (CBT) for psychosis in patients with paranoid delusions (R. Pot-Kolder et al., 2020b) found that in the short-term, VR CBT, on top of treatment as usual, is an economically viable approach to improving patients' health in a cost-effective manner. Long-term effects require further research.
- A cost analysis study conducted on stroke patients in Denmark, Norway and Belgium (Islam & Brunner, 2019) estimated that VR therapy could save approximately $8.2 to $75 per patient, depending on the time saved by therapists[142].

In the **education sector,** XR allows training to be organised at lower cost.[143] This is especially useful for training involving a large number of participants (e.g. training for military servants), which usually leads to increased transportation and living costs for the training organisers. Transferring training to a VR environment avoids these costs while ensuring the broad involvement of participants (Liu et al., 2018). In addition, XR also allows savings when simulators are used instead of specific expensive technologies being required for training (e.g. for the training of aircraft pilots, seafarers and manufacturing equipment installers). In such cases, VR-based simulators can ensure a full training experience for trainees without the need to use costly tools for training (e.g. parts of ships, planes, manufacturing equipment), and with no risk of damage. Thus, VR-based simulators offer an opportunity to deliver a full training experience with fewer costs (Bahadoran, 2021; Fussell & Truong, 2020; Labedan, Dehais & Peysakhovich, 2018; Mallam et al., 2019).

On top of this, research in this area reveals that the use of XR allows students to achieve better learning outcomes in less time (Checa and Bustillo, 2020, García et al., 2016, Rajgopalan et al., 2018). Several reasons for this are suggested. First, that XR-based immersive learning is more effective than traditional approaches (Villena-Taranilla et al., 2022; Wu et al., 2020). Second, that the application of XR makes students more engaged in the learning process, and thus they remain more focused on learning and ignore external distractions that usually make the learning process less effective (Barteit, 2021; Garzón, Pavón, & Baldiris, 2019; Fernández-Batanero, Montenegro-Rueda, & Fernández-Cerero, 2022; Fracaro, 2022; Ibáñez, & Delgado-Kloos, 2018; Mystakidis, Christopoulos, & Pellas,

[141] 95% confidence interval for the cost saved was between $11 loss and $156.17 gain. VR therapy remained cost-saving in 89.2% of hypothetical hospitals of varying size and staffing.
[142] The time saved by therapists is assumed for three different scenarios and not tested in a real-world environment.
[143] Based on interviews.

2021; Mystakidis, Fragkaki & Filippousis, 2021; Pedaste, Mitt & Jürivete, 2020;Ređep & Hajdin, 2022). In addition, students interacting with a virtual environment have the opportunity to identify with the learning topic, which allows for faster acquisition of theoretical knowledge (Greenwald et al., 2017). Lastly, the application of XR offers a more interactive learning process, implementing the principle of learning by doing, which increases students' satisfaction as well as their learning performance.[144]

Indeed, Scaravetti & François (2021) conducted an experiment on first- and second-year Bachelor students in engineering using different AR scenarios and found that: i) in terms of user experience, 93.3% of learners were satisfied; and ii) the AR experiences generated a better understanding of complex systems since on average, those learners who benefitted from AR obtained results that were 22.6% higher than others.

Impact of AR measures on environmental education (Greece)

The Research Center of Environmental Communication and Education has conducted a study on the effects of AR-based tools on student performance. The study covered 241 school students in grades 4 to 6 at two primary schools located in Athens. These students used AR-based smartphone apps (including QR codes and 3D models) during classes on environmental issues. The results of the survey and the comparison of students' grades (before and after the application of AR technologies) show that AR measures had a positive effect on student satisfaction and achievement. The research results indicate that the change in knowledge among 4th-graders was 29.5%, 25.6% for 5th-graders, and 21.7% for the 6th-grade students. Meanwhile, satisfaction with the learning experience increased by 38% among 4th-grade students, 32.3% among 5th-grade students and 26.9% and 6th-grade students.

Source: Visionary Analytics, 2022, based on Theodorou et al., 2018

In addition to an analysis of the healthcare and education sectors, during the literature review (complemented with information from success stories and the survey of XR industry representatives and researchers) additional evidence was identified on the quantitative impacts of XR across other sectors:

- Improved working conditions for employees
- Cost and time savings

Economic effects are usually observed with respect to the application of XR in industry. Even though industrial production has been heavily automated, certain aspects still remain inefficient, risky and financially demanding. The process of procuring goods from design to trials to implementation and maintenance is lengthy and requires a long chain of workers to fulfil. The most useful aspect of XR is the ability to incorporate it in various forms in order to solve several problems at once. For instance, VR can reduce the chances of employees having to endure risky conditions while training or improving certain skillsets (e.g. electricians, structural iron and steel workers). AR can allow employees to consult manuals and experts on a case-by-case basis, improving efficiency in daily tasks, as well as allowing the quicker resolution of less common situations. Successful cases of XR implementation include at companies such as Ford and Boeing. Since Ford implemented VR into its assembly line, the company has seen a 70% drop in employee injuries and a 90% reduction in ergonomic issues. Similarly, when Boeing implemented AR in the form of a hands-free manual for airplane wiring, it saw a 25% reduction in wiring production time, as well as a 40% increase in productivity[145].

Furthermore, XR can reduce the costs and amount of time spent in processes such as product design. Time and resource savings were also rated as present or very much present by the majority of survey respondents (65% and 60%, respectively). Usually, product design

[144] Based on the interviews.
[145] Capgemini Research Institute (2018). *Augmented and Virtual Reality in Operations*.

from model to realisation can take weeks; with XR, design teams are able to create and test designs with the aid of virtual simulations. Using XR technologies, design teams can identify and avoid flaws that might otherwise have been overlooked up until the final product is put into testing, in turn resulting in company loses[146]. The use of AR can also increase the accuracy and efficiency of work. For example, Coca-Cola HBC and DHL managed to increase the rates of accuracy and productivity by 6-15% through the use of AR solutions. Meanwhile, the use of AR solutions at Airbus Helicopters ensured 40% faster inspections for helicopters.

Development of unique skills

In general, the application of XR allows students to develop the skills required in the labour market. These include both **technical ('hard') and non-technical ('soft') skills**. With regard to technical skills, the application of XR provides an opportunity for procedural training through the use of simulators (Bahadoran, 2021; EC Cordis, 2018; Liu et al., 2018). VR-based tools also offer various training scenarios that would be barely possible or too dangerous in real life (Bahadoran, 2021). Moreover, XR tools also provide an opportunity for students to develop non-technical skills that are highly valued by employers (Federica et al., 2021; Kic-Drgas, 2018; Saraiva et al., 2021). On top of these benefits, 60% of XR company representatives and XR researchers/academics survey respondents state that XR technologies can increase psychomotor and cognitive skills (N=15). Using XR tools, students can play various collaboration-based video games, use virtual platforms or participate in virtual creative workshops (García et al., 2016; Hu, 2020; Saraiva et al., 2021).

For **medical** students, XR enables **more and better opportunities for practice**, which may result in a faster learning curve to achieve higher precision and speed during a real procedure. From an economic standpoint, virtual simulators reduce the costs and need for cadavers for educational purposes, and give students the freedom to practice medical scenarios that in a traditional setting would be limited both financially and in terms of resources (Kordali, 2021; XR4ALL, 2020). Moreover, using virtual simulators or even MR apps on mobile devices increases the engagement, flow, presence and skill of students in the course of medical training (Mäkinen et al., 2020; Stretton et al., 2018). Lastly, highly realistic training in VR allows medical students and trainees to **become more quickly prepared for real-life situations.** These findings are confirmed by the survey results, in which the (potential) impact of XR in educating the workforce was experienced/observed as positive by 47% of respondents in the healthcare sector.

Greater flexibility and availability

The application of XR in the health and education sectors provides greater flexibility to professionals (medical staff and teachers), as well as to practitioners (newly qualified medical staff and students in general).

In the **healthcare sector**, **remote surgery/telesurgery** addresses the issue of the **availability of professional medical services**. This includes greater professional guidance for medical staff in extreme conditions, such as those carrying out emergency surgeries without the presence of an experienced doctor. It can also reduce differences in the quality of health care between developed and undeveloped countries. The technology will not only allow surgeons to perform surgery remotely, but also teach health staff from other regions who are not equipped with the same advanced training/equipment/opportunities as surgeons in developed countries (Iqbal et al., 2019). Through AR support, medical institutions can **entrust more complex tasks to novice medical staff**. For instance, during minimally invasive spinal surgery, AR has been able to reduce the risk of drilling mistakes among novice surgeons (Dennler et al., 2020).

[146] PwC (2019). *Seeing Is Believing How Virtual Reality and Augmented Reality Are Transforming Business and the Economy*.

The same applies to the **education sector**. Here, the application of XR has had a positive impact on **teachers' work effectiveness**. The traditional learning approach based on contact learning (i.e. learning in a classroom) places a heavy burden on teachers, with students usually receiving insufficient attention. XR-based tools address this issue by offering virtual assistance services. For example, students learning in virtual laboratories (such as Labster[147]) can be advised by virtual assistants at various stages of learning (Martin-Gutiérrez, 2015). This allows teachers to access students' learning data, track their progress, and provide more personalised feedback, thus creating a better learning process and providing more objective evaluations while reducing their own working burden.[148]

Indeed, the benefits of XR tools have been particularly evident during the **global COVID-19 pandemic**, which restricted the normal learning process. During quarantine, the learning process shifted to the virtual environment, including XR-based tools. The application of such tools enabled the learning process and kept students' learning progress on track (Jamah *et al.*, 2020). In a systematic umbrella review by Nesenberg et al. (2020), the authors concluded that properly adopted AR/VR-based courses could potentially raise the number of good, qualified specialists around the globe, not just in local regions, thus democratising education in hands-on skills. Rivu et al. (2020) even created a framework for running VR studies remotely via participant-owned HMDs, depending on what kind of balance of needs must be met. With the transition to remote learning being considered successful in most countries, some educational institutions (especially in higher education) have continued to use a hybrid learning approach that includes both contact and distance learning.

Social impacts

Behavioural effects

XR, and VR in particular, provide a testbed for tasks that are unsafe, life-threatening or too expensive to recreate in real life but nonetheless represent realistic situations. This ability provides several benefits for both the healthcare and education sectors:

- A **safe learning environment** for students. Psychological safety, greater enjoyment and less pressure are assured for students, since mistakes can be made and learned from in a virtual environment. Once the scenarios are completed, learners receive automatically generated feedback, allowing them to assess their performance in greater detail, as well as discussing specific learning points with their colleagues (Pottle, 2019).
- The **possibility for patients to practice behavioural skills** in a safe environment with the support of a therapist. This was noted as a positive impact of XR by 29% of healthcare sector respondents to the survey. VR exposure therapy, for example, permits individualised, gradual, controlled and immersive exposure that is often more acceptable to patients than *in vivo* or imagined exposure (Boeldt et al., 2019, Ma, et al 2021). Moreover, patients with anxiety and/or neurological disorders can practice their social skills and prepare in advance for overwhelming situations (e.g. VR can be used to simulate a visit to a doctor or being in a crowded and noisy place, helping children with sensory issues cope with such situations in real life). The same is applicable to students, as research in this area has revealed that students developing behavioural skills in a virtual environment feel safer and less embarrassed than in real-life training settings (Carlton, 2018, García et al., 2016). Conversely, findings from the stakeholder survey indicate that the transfer of XR behavioural skills to the real world can be challenging, with 63% of respondents state this difficulty is moderately present in XR technologies in their respective fields (N=8).

[147] https://www.labster.com/
[148] Based on the interviews.

- The **possibility to develop soft skills** in a safe environment with support from teachers. For example, students are encouraged to develop communication, teamwork and problem-solving skills through collaborating with peers in a virtual learning environment. Teachers observe students' behaviour, and track and discuss their performance (García et al., 2016).

Psychological effects

People tend to find XR experiences more engaging and motivating than traditional treatment, therapy or learning methods (Thisgaard and Makransky, 2017; Makransky and Lilleholt, 2018; Makransky et al., 2019). Particular cases in the healthcare and education sectors are discussed below.

Survey respondents from the **healthcare sector** experienced/observed the impact of XR in terms of increasing patient engagement (observed by 50% of respondents), enhanced positive attitudes (observed by 32% of respondents) and satisfaction (observed by 36% of respondents). Treatment adherence to physical therapy among post-stroke patients is often limited, especially when the therapy is experienced as being boring or when patients feel fatigued and depressed (K. K. Miller et al., 2016). VR can offer more exciting alternatives and thus increase compliance. A clinical trial showed that VR-based balance exercises performed during vestibular rehabilitation were not superior to conventional balance exercises, but that the VR-based group reported significantly greater enjoyment, less difficulty and less tiredness after such exercises (Meldrum et al., 2015). The intensive and motivational character of VR training appears to have a significant influence on patients' moods and engagement, and appears to promote enthusiasm, making them feel that they can perform more repetitions (which is a key factor in, for example, regaining motor function after a stroke) (Pallesen et al., 2018)

Meanwhile, in the **education sector,** traditional learning approaches may be insufficiently interactive or appealing to younger students, who usually are less focused on learning and require more gamified activities. Teachers may also face difficulties in teaching complex learning content, as students may lose focus, lack motivation or be insufficiently involved in the learning process (Saraiva et al., 2021). Research in this field indicates that the application of XR can address these challenges by increasing student satisfaction with the learning process (Acosta et al., 2019; Allcoat et al., 2021; Ilić et al., 2021; Tegoan et al., 2021). Higher motivation, interest and engagement were also mentioned by 60% of stakeholders in the survey (N=15). Moreover, students argue that an XR-based learning approach is a more entertaining and informative way of learning, thus they are more motivated and engaged. A comparative analysis of students' performance shows higher learning progress following the use of XR technologies (Theodoror et al., 2018).

In addition, by learning in a virtual environment, students can rid themselves of the fear of the costly or dangerous consequences of their actions that can occur when training in real-life settings (Rajgopalan, 2018). For example, fashion design students practising in a virtual environment can experiment with design ideas without fear of wasting fabric (Hu, 2021; Syczewska, 2021). Another example is chemistry students who can safely perform various chemical experiments in a virtual environment without fear of dangerous chemical reactions. The sense of danger decreases among students in dangerous occupational fields, such as aviation, the maritime industry and firefighting (Bellemans et al., 2020; Fussell & Truong, 2020). These opportunities give students more freedom, and have a positive effect on their creativity in problem solving (Martin-Gutiérrez, 2015*).*

Ethical effects

VR can ensure higher ethical norms, thus narrowing the gap between people of different genders, race, age, sexual orientations and health conditions (Maister et al., 2015, Seinfeld et al., 2018). To this end, VR tools, by mirroring aspects of other peoples' experiences, provide an opportunity to experience the world from the perspective of someone other than oneself (rated in the survey as a positive impact of XR by 28% of respondents from the healthcare sector). By having an opportunity to embody someone else's experiences, people can face the challenges that such individuals encounter on a daily basis. Such learning experiences can lead to emotional, cognitive and behavioural changes, which **may help to overcome common ethical issues such discrimination, harassment and violence, thus fostering tolerance and moral values** (Madary & Metzinger, 2016). The following examples describe the ethical effects of XR on both the health and education sectors:

- XR tools can be customised to **address challenges relating to racial bias** inside and outside educational institutions. For this purpose XR offers, for example, the opportunity for students to embody the experiences of a dark-skinned student through a simulated virtual environment and thus experience racism. Such experiences can raise students' awareness of racism and increase tolerance toward students from ethnic minorities (Bertrand et al., 2018; Roswell, 2020; Ziker, 2021).
- XR tools can also be helpful in **overcoming homophobia**. One VR tool incorporating a 360-degree view, makes it possible for users to participate in an experiment as a young lesbian woman, wearing a shirt that reads 'I am a homosexual' and inviting passers-by to hug her. The video could be watched from her perspective, with people either hugging her or walking away, or from the perspective of the passers-by. By offering the opportunity to virtually participate in this social experiment, its authors aimed to change people's attitudes toward LGBTQ people (Khosravi, 2018).
- XR-based learning allows **students' awareness about cognitive and physical disabilities to be raised** via embodiment or simulations in virtual space, thus **reducing stigma**. Using VR tools, learners can experience real barriers and perceptions faced by people with mental or mobility impairments. For example, medical students are able to participate in experiments using VR-based visuotactile disabled embodiment with social barriers within a wheelchair (Meijer & Batalas, 2020). Another example is training, which provides an opportunity for neurotypical individuals to experience the sensory processing difficulties of people with autism spectrum disorders[149]. Such simulations increase trainees' knowledge about disabilities, enhance empathy, help to tackle biases, overcome stereotypes, and raise awareness in a world where social attitudes towards disability can be more limiting than real dysfunctions. One industry representative who was interviewed also mentioned that XR could reduce the social stigma of talking about mental health problems.

Impacts on vulnerable groups

XR tools allow the **better inclusion of persons with disabilities**. Particular cases in the healthcare and education sectors are discussed below.

In the **healthcare sector**, XR can serve as a therapeutic modality, since persons with mobility limitations can enjoy 360-degree relaxation videos in VR. More complex XR experiences (such as gaming) can become accessible to most people if developers follow the principles of universal design. This could be fostered by integrating accessibility features and the guiding principles for universal design into the design and programming tools used by developers (Emil Gejrot et al., 2021). In fact, many off-the-shelf hardware tools are already available to make game design more inclusive (e.g. the *Quadstick* remaps all of the buttons on a standard controller to a device that can be controlled using facial muscles and breath) (Dombrowski et al., 2019a).

In the **education sector**, XR tools provide an opportunity to **participate remotely in the education process** for students who cannot attend contact lessons due to physical limitations. This ensures equal educational opportunities for such students, helps them to develop a relationship with their peers, and improves their learning performance (Atchison

[149] https://www.training2care.com/autism-reality-experience.htm

et al., 2019). Similarly, XR tools, particularly VR-based applications, create opportunities for students with a physical disability to participate in various virtual educational and entertainment experiences such as virtual trips and fieldwork, thus increasing their social inclusion (Martín-Gutiérrez et al., 2017, Mallam, 2019).

Negative impacts

Content-related risks

The content of XR interventions may not be suitable for all users. Since XR can be used as **persuasive technology**, our understanding of deeply embedded notions, such as conscious experience, selfhood, authenticity or realness may be altered. Illusions of embodiment or certain stressful experiences in VR may have a lasting emotional, and psychological impact on a person (Madary & Metzinger, 2016). The related risks are further discussed below.

There is a risk that people seeking treatment may try out a VR exposure therapy programme without first consulting a clinician, and thus end up with no positive results or even **aggravated trauma symptoms** (Blum, 2021; Ma et al., 2021). Moreover, it is important that content is appropriate to the intended age group (J. S. Spiegel, 2018). The same risk applies to the education sector, where content is tailored only to students in specific fields of education or should only be shown after special psychological preparation. For example, students at elementary schools could be exposed to realistic simulated images of natural disasters (e.g. fires, tsunamis, earthquakes, falling celestial objects) during emergency evacuation training or as part of climate-education programmes. These images can not only cause a physical response such as increased heartbeat or blood pressure, but they may also provoke anxiety, fear and even post-traumatic stress disorder (LaMotte, 2017; Stavroulia, Christofi, Baka, Michael-Grigoriou, Magnenat-Thalmann & Lanitis, 2019).

XR embodiments may also **alter personal identities** (Ramirez, 2021). The ability to take on different avatars in VR worlds or superimpose AR filters on their real-life appearance empowers people to modify their bodies in the way in which they would like to be seen. VR and AR embodiments raise new questions about who should have control over users' appearance, how to reinforce identification through XR devices, or how social interactions and virtual romantic relationships might be affected by a mismatch between virtual and real representations (Ramirez, 2021).

Another concern is physical safety. AR applications can distract attention from aspects of the physical world and lead to accidents, even lethal ones (Christopoulos et al., 2021).

Similarly, engaging with VR-based content may cause **difficulties in distinguishing what is real** from what is produced by virtual reality tools (ANSES, 2021; Kenwright, 2018; Madary & Metzinger, 2016). Consequently, there is a risk that people will be eager to spend more time in a potentially better or more interesting reality, which could result in **addiction**. Long hours spent in an immersive environment could lead to depression, reduced attentiveness, autistic features, obesity, insomnia and increased aggression (Rajan et al., 2018). On top of this, it could result in an alteration of the individual's relationship with reality and unnoticed psychological changes (ANSES, 2021; Tromp et al., 2018; interview with a researcher).

Lastly, the use of XR technologies in education itself could also have a negative impact on students' mental well-being. While traditional learning is based on real-life communication and human connection, immersive learning approaches could **induce personal isolation** from the learner's peers, since most of the time XR tools are used individually (Fernandez, 2017). For example, watching a film with others using VR tools leads to less overall interaction between individuals, the loss of a feeling of being together, and a sense of social isolation compared with watching a film in a shared physical space (Wagener et al., 2020).

Harmful social interactions

Certain risks also stem from novel forms of social interaction. In multiplayer/social environments such as virtual worlds, there is the possibility of **fraud, harassment and bullying** (Cortese & Outlaw, 2021). While similar things are possible in conventional Internet communities, the sense of realness in VR environments may aggravate the effects of such harmful interactions. The physical embodiment of social XR platforms, together with the moral disengagement of some users, can create toxic environments with derogatory comments, threats and discrimination (Robertson, 2022). For example, functionalities to create personal boundaries in virtual worlds have begun to roll out in social XR to combat harassment.

Children are especially vulnerable to these risks, since they may be exposed to inappropriate content and contact in virtual environments. Research has shown how prone children are to creating false memories when presented with events in VR, thinking that they have occurred in real life (Segovia & Bailenson, 2009). As yet, it is unknown if and how immersive devices affect the development of young children's physical, psychological and social abilities. To alleviate the possibility of these risks, one interviewee suggests imposing social rules in XR, although there is no clear framework as to how this could be achieved.

Ethical and privacy risks

Although XR tools have been deemed safe research methods for exploring sensitive mental health topics (Huang et al., 2021), certain types of XR experiences can also **threaten the intimacy and personal space of specific populations**. Particular cases are discussed further below.

First, documentaries can employ XR to **portray sensitive stories** from a first-person perspective about refugees, the homeless, disabled people, victims of violence, or can even recreate deceased relatives using interactive holograms. Although these recreations intend to elicit empathy, some researchers have pointed out the unethical aspects of such experiences. For instance, they may promote biased representations of the actual situation, generate a false sense of complete understanding, or may lack fidelity because some contextual parts cannot be communicated visually (Ramirez et al., 2021; Raz, 2022).

Dual use of information (Mason, 1986) also applies to XR. The persuasive capabilities of XR technologies may produce positive and negative effects in health care applications. For example, it may facilitate the resocialisation of convicted offenders (Ligthart et al., 2021), but it may also elicit violence through specific cues in video content. XR, as a digital behavioural technology, must account for the legal and moral consequences implied in changing someone's actions.

In addition, **manipulation of agency** may occur in virtual environments. For instance, marketing agencies operating in virtual worlds could use unethical marketing strategies that may be more convincing in immersive environments (e.g. hidden advertising, distorting facts, hiding information about a product) to "nudge" the person to follow the desired direction.

Identity hacking could occur in immersive environments. XR could allow virtual copies of people to be made that look, act and talk like a real person, even demonstrating aspects of personality (applying behaviour-based machine learning on recordings of the real person) (Slater et al., 2020). This could lead to fake news (portraying people as having carried out actions that they did not do), identity theft (using other people's identities to gain sensitive information about them by communicating with significant others), or moral disengagement (where people may normalise inhuman actions towards others because the interactions happen virtually and are not 'real').

Data exploitation is also possible (risks to the security and privacy of personal data were observed as a negative effect by 18% of survey respondents). Users' physical and psychological responses can be analysed automatically and used for "neuromarketing" (Tromp et al., 2018). Privacy risks also stem from the convergence of XR with social networks, e.g. the *Metaverse* developed by *Meta (formerly Facebook)*, and the fact that the software can potentially track users' faces, eyes, voice and movements and recognise the identity of a user or predict their behaviour on the basis of that (O'Brolcháin et al., 2016). In addition, AR devices need to scan user's environments, which may also be considered sensitive information. This may be done without consent and the data sold to third parties, no legislation yet exists to regulate the selling of such novel types of data. The acquisition of identifiable personal information may be justified more easily in health-related XR applications than in fields such as gaming or education, justifying the possible therapeutic outcomes of accessing such data. This could be especially dangerous for groups that are susceptible to attacks, such as underaged people and people with certain cognitive impairments. Further details about privacy-related risks are presented in Section 1.3.1.

Due to the collection of sensitive information, several interviewees, including academics and industry representatives, expressed concerns about potential additional privacy issues for people with disabilities due to the higher likelihood of misuse of their data. In addition, every XR application intended for use within sensitive areas of society, such as in health care or education, needs to be **ethically scrutinised**. Such scrutiny is proposed by early-stage code of conduct documents that envisage the foreseeable consequences of VR and AR applications across multiple healthcare sectors (Evans, 2022; Ramirez, 2021).

Medical safety risks

Hygiene risks may occur due to the lack of sanitation of XR devices, especially in hospitals, educational institutions and other public settings where devices may be used by multiple people. The risk of infection is particularly relevant during the COVID-19 pandemic, given the lack of regulation and protocols on how to adequately sanitise such tools (Suh & Prophet, 2018). As interest grows in the adoption of XR applications into practice in the fields of healthcare and education, the necessity to build regulatory frameworks that ensure the safety and effectiveness of innovative XR solutions becomes clearer (Evans, 2022)**.** To achieve this, members of institutional review boards and research ethics committees should become acquainted with the benefits and potential hazards of XR.

In addition, **motion sickness** (or cybersickness), as well as symptoms of eye strain, disorientation, simulator sickness, dizziness, headache and nausea are commonly known risks in XR research (ANSES, 2021; Chang et al., 2020; Chang, Kim, & Yoo, 2020; Liagkou, Salmas & Stylios 2019). These effects usually quickly subside after the use of VR/AR technologies (Knack et al., 2019). It should be noted that much of this research carried out previously no longer applies, as hardware has been catching up and cancelling out some of the most common triggers for motion sickness (i.e. lag or refresh rates). Currently, cybersickness is usually the result of software design and not the hardware itself[150]. Nevertheless, even among the current generation of VR head-mounted displays, some people (e.g. those who already have some health problems and are often more susceptible to negative motion sickness effects) still experience these symptoms. The nature of movement and, in particular, sensory mismatch as well as perceived motion have been the leading cause of cybersickness (Caserman et al., 2021). VR sickness (rated as a present by 30% of respondents) and physical discomfort (rated as a present by 25% of respondents) were the most highly ranked negative effects XR in the survey of industry representative and researchers. In addition, a cross-sectoral survey of XR professionals (i.e. senior-level decision makers, covering content creators, hardware and software manufacturers, industry end users, consultants and analysts)[151] conducted in Q2-Q3 2019 for an industry report, showed that out of 761 respondents, 56% listed comfort and usability as issues in relation to current-generation XR technologies[152].

[150] Based on insights from health sector workshop.
[151] The geographical scope was unidentified.
[152] Hadwick, Alex (2019). *XR Industry Insight Report 2019-2020*.

Nevertheless, since the majority of research on XR technologies has focused on Caucasian males aged 20-30, the implications of these side effects on other segments of the population such as older men and women, as well as people from non-Caucasian backgrounds, are yet to be understood (Munafo et al, 2017). Two of the researchers and experts interviewed noted that, in their experience, VR sickness can affect older people much more than younger users, especially given the fact that they are less likely to be used to virtual environments and digital media in general.

On top of this, exposure to VR or AR can result in a **temporary modification of sensorimotor and perceptual capacities** (ANSES, 2021). These effects can last for several hours. In addition, while luminance levels of light emitted by the screens of XR devices are comparatively low, the devices potentially emit light that is rich in blue light. This is proven to disturb circadian rhythms and sleep, with children, adolescents and young adults being more sensitive to it, as their lenses filter blue light poorly (ANSES, 2021). Long-term exposure to blue light at a short distance from the eyes has still not been sufficiently researched. As the negative impacts of XR use in children are not yet known, it is considered advisable to proceed cautiously in the use of and experimentation with XR among this group until its real impacts have been assessed (Ramirez, 2021).

1.2.2. Health sector-specific impact

This section discusses the impacts of XR (economic, social, and impacts on vulnerable groups) specific to the health sector.

Economic impacts

Higher accuracy and precision in treating patients

XR has the potential to allow **better diagnosis**, which may lead to better and more accurate treatment and rehabilitation methods, impacting both society and the economy. In societal terms, patients whose diagnosis is more accurate will not need to try different types of rehabilitation/treatment (for instance, neurodevelopment disorders in children can be difficult to detect using traditional methods). Economically, this also saves medical institutions and insurance providers the time and resources they would otherwise spend finding the right diagnosis and selecting treatment methods. In addition, XR saves time by allowing doctors to detect diseases more quickly by analysing CT and/or MRI scans in 3D. For example, the use of AR has already been demonstrated (Pelanis et al., 2019) to reduce the time needed for a spatial understanding of liver segments associated with lesions to a quarter of that required under conventional approaches (Pelanis et al., 2019).

XR may also benefit preoperative planning and intraoperative navigation, which leads to **higher precision during surgery and a reduced risk of surgery complications**. This results in reduced time/financial costs for the hospital and fewer hospital days for the patient (Heinrich et al., 2019). Such savings are not only achieved in complex surgical procedures, but also in more straightforward procedures such as injections, which can nonetheless have negative side effects if performed inaccurately (Madison, 2018).

Increased accessibility and affordability of healthcare services

Even though XR is unlikely to completely replace traditional therapy and rehabilitation practices, it offers the opportunity to improve certain conditions either without or with less involvement of medical staff.

Currently, many **mental health issues** remain untreated or are inadequately addressed. Simulating real-life situations in VR can help to treat certain disorders (such as PTSD, phobias or eating disorders) more effectively compared with traditional methods. For instance, *in vivo* exposure therapy (therapy that takes place in the real world) can be difficult or impossible to arrange in a therapist’s office, while VR-based exposure therapy requires only a headset and software to be installed. Due to the difficulty of reaching a therapist during COVID-19, many companies in Europe and the U.S. began to offer VR therapy via telemedicine, and others have supplied relaxation apps for mild anxiety and stress directly to consumers (Blum, 2021). These self-help or relaxation apps using VR may prevent more serious mental health issues from occurring, and may empower patients with tools to engage in self-care (Riva, Bernardelli, et al., 2021).

In terms of **rehabilitation**, VR and AR offer cost-effective, accessible and flexible interventions for patients who have difficulty in attending outpatient appointments due to distance, lack of transport or disability, which is often the case with older patients suffering from dementia or post-stroke symptoms (Kim et al., 2019). Due to limited resources, the rehabilitation needs of post-stroke patients are often not fully met (Ullberg et al., 2016). Moreover, since the COVID-19 pandemic disrupted the availability of health services in medical establishments, the need for remote delivery of health services (which may include VR and AR therapy) has become more evident (Mantovani et al., 2020). Telerehabilitation therapy, in combination with low-cost VR equipment, can reduce the number of hospital days for stroke patients and can promote self-motivation in the home for chronic patients (Ku & Kang, 2018; Piron et al., 2009).

More durable and lasting outcomes for patients

After an XR experience, patients often demonstrate more durable and lasting outcomes, especially when it is used as an adjunct to traditional treatment. A review of 72 clinical trials that used VR for **stroke rehabilitation** demonstrates that VR therapy does not appear to be as effective (e.g. in restoring upper limb function) as the same amount of conventional rehabilitation, but may be effective when applied in addition to conventional treatment (Laver et al., 2017)[153].

In addition, since XR environments are more engaging, they **may be especially beneficial for children and adolescents**. For instance, a VR-based soccer scenario had a positive influence on the walking performance of children with cerebral palsy[154] and other different neurological gait disorders (Brütsch et al., 2010). In addition, according to one interviewee (an XR practitioner), skills used in VR environments can be transferred into real-life situations. For instance, while painting in VR, one of their paediatric patients was able to lift their arm higher than they normally would. Afterwards, the patient became more confident in using the arm in daily tasks such as bathing, and the overall range of motion increased.

Practical use cases for VR analgesia in North American and Italian hospitals have proven that **VR can significantly lower pain perception** and make time appear to pass more quickly during painful episodes such as childbirth, changing the bandages on burn wounds, endoscopy and even dental procedures, as well as in cases of chronic visceral pain (Spiegel, 2020; Mosso-Vázquez et al., 2017; Riva et al., 2018). VR analgesia can **contribute to reducing reliance on painkillers**, which could bring positive economic and societal effects globally. Currently, pharmacological intervention is the main type of therapy administered to patients experiencing both chronic and acute pain. Painkillers can reduce inflammation and the levels of pain perceived, but they may also bring considerable side effects (e.g. dizziness, nausea, depression). Furthermore, when tolerance occurs, it is necessary to increase the amount of drug administered to maintain the desired level of analgesia (Guarino et al., 2017). Opioids eventually lose their effect and, at the same time, **make patients physically and emotionally dependent** on a failing medical regimen (B. Spiegel, 2020). While opioids are prescribed fairly rarely in Europe, mostly as part of cancer therapy or palliative care (Häuser et al., 2021), VR can nonetheless become a viable alternative or supplement to traditional pharmacological treatments.

[153] However, it was not analysed if conventional therapy with the addition of XR treatment is more effective than conventional therapy plus additional conventional therapy.
[154] Cerebral palsy is a group of disorders that affect the ability to move and maintain balance or posture.

Moreover, VR analgesia is highly effective in **reducing pain perception and anxiety**. Studies on paediatric patients have shown that immersive VR experiences may reduce pain-related brain activity by more than 50%, since they act on both direct and indirect pain perception and signalling through attention, emotion, concentration, memory and other senses (Arane et al., 2017).

On the other hand, there is a general **lack of longitudinal studies concerning the long-term effects of XR treatments and therapies**. One study showed that individuals undergoing combined VR and biofeedback treatment for a specific phobia suffered no relapse after three years (Wiederhold & Wiederhold, 2003). Long-term follow-ups need to be conducted on larger groups of participants and those with other mental health disorders. For instance, it is not clear whether patients with psychosis who have undergone VR-based exposure therapy will have a better quality of life after five years than those who received treatment-as-usual (Pot-Kolder et al., 2020).

Social impacts

Positive general effects

XR may help in tackling medical conditions that have a considerable impact on the health of the population. Evidence shows that patients who undergo XR treatment in conjunction with treatment-as-usual experience better therapy and rehabilitation outcomes and faster recovery (Guarino et al., 2017; Pot-Kolder et al., 2018). If XR is to be used on a wider scale in areas such as pain treatment, mental health care and occupational therapy, it may have a noticeable societal impact, since millions of people across Europe need these types of treatments. For instance, in 2019, stroke was the second leading cause of death, while Alzheimer's disease and other forms of dementia rank as the seventh leading cause of death globally[155]. Both of these conditions are also among the top causes of disability worldwide (World Health Organization, 2019). Neurodevelopmental disorders such as autism and ADHD have a high prevalence in childhood and constitute a large proportion of global disability (Márquez-Caraveo et al., 2021). Therefore, the utilisation of novel technologies to reduce the burden of these conditions is critical from both an economic and a societal perspective.

The **wellbeing of the general population may also improve** once the use of XR becomes more widespread. Currently, relaxation apps or exergaming[156] can help people to deal with stress and anxiety and motivate them to increase physical activity. Such solutions became especially relevant during the COVID-19 pandemic, when lockdown measures isolated people, leaving them in charge of their own mental health. Furthermore, in the future, virtual environments will be used increasingly for socialising, which may counter loneliness and social isolation (e.g. see the presentation on the *Metaverse* by *Meta*[157]). However, studies on the use of social media show that high social media use does not appear to be linked with feeling less socially isolated (Primack et al., 2017).

Self-help virtual therapeutic experience helps users to cope with the psychological burden of coronavirus

An international team of researchers created COVID Feel Good – a free, easy-to-use self-help solution that aims to relieve anxiety, improve well-being and reinforce social connectedness. A 360-degree VR video of the "Secret Garden" is combined with daily exercises designed to be experienced with another person (not necessarily physically together) to facilitate a process of critical examination and the eventual revision of core assumptions and beliefs related to personal identity, relationships and goals. The first study of the effectiveness of the COVID Feel Good

[155] Statistics for the EU27 were not available.
[156] Exercising while gaming.
[157] https://about.facebook.com/meta/

solution demonstrated significant clinical outcomes, low-to-no risks for the treatment, and no adverse effects or risks.

Source: Visionary Analytics, 2022, based on (Riva et al., 2021), https://www.covidfeelgood.com/

Patient/caregiver education could improve the doctor-patient relationships, as well as **benefitting the principle of informed consent**. For instance, visualising a risky surgical procedure that is to be performed on a child's head may provide a clearer picture of the process, reassure parents and help them decide whether to give consent for the surgery (Dombrowski et al., 2019b).

Impacts on vulnerable groups

Novel treatments

XR offers **novel treatment/therapy opportunities for persons with different disabilities and disorders** (e.g. help to regain motor function or learn how to move around with a wheelchair). This includes patients with mental health problems or disorders, neurodegeneration, neurodevelopmental disorders and mobility challenges. Moreover, AR-based assistive technology **helps people with disabilities to function more independently in daily life** (e.g. by providing visual aids for visually impaired or blind people, aiding the hearing of hearing-impaired people). This is already witnessed by the growing popularity of wearable AR devices for visually impaired persons.

Less anxiety-inducing and painful procedures for children

In particular, XR can benefit children by making them less anxious about undergoing medical procedures and enduring painful episodes (McCahill et al., 2021), as well as by bringing playful and exciting elements into repetitive rehabilitation exercises. Moreover, children with ADHD or autism spectrum disorders are especially keen to process visual information and use digital devices, making XR technologies an enjoyable alternative to conventional therapy (I. T. Miller et al., 2019).

Accessibility for people with disabilities remains limited

Accessibility for people with disabilities and children remains limited. The issue of adapting XR devices and software for people with impaired hearing or vision as well as sensory or cognitive challenges should be addressed more horizontally. It may be difficult for people with such impairments to benefit from XR-based treatments and therapies, as well as to enjoy regular games and apps (e.g. visual contrasts and text size can be difficult to adjust, experiences in the virtual world may rely heavily on audible cues) (Emil Gejrot et al., 2021). Moreover, paediatric care units are reluctant to use VR due to the size and weight of the headsets. As the interpupillary distance[158] of most devices is designed for older children and adults, they may cause headaches and eye aches for younger patients (Alqudimat et al., 2021).

In the future, once XR uptake increases in the public sector (e.g. hospitals), regulation could be a potential driver to address limited accessibility. For instance, the European Accessibility Act and various other Directives currently make no specific mention of VR or XR.

[158] The distance between the centres of a person's two eyes.

Improved quality of life among elders

XR could also **improve the quality of life among elders**. Immersive VR journeys could bring exciting and meaningful experiences and improve connectedness with their environment and loved ones (e.g. by allowing them to socialise without leaving home).

1.2.3. Education sector-specific impacts

This section discusses the impacts (social, negative, and impact on vulnerable groups) of the application of XR, specifically in the education sector.

Social impacts

Overcoming violence

XR tools help to **overcome violence**. For this purpose, immersive VR tools put the perpetrators of violence into the body of a victim. An experiment revealed that, compared with a control group, perpetrators tend to misinterpret fearful faces as happy. After the virtual experiment, perpetrators showed an improved ability to recognise fearful faces. Thus, VR could be helpful in modifying socio-perceptual processes such as emotion recognition (Seinfeld et al., 2018).

Promoting and teaching moral values

The application of XR-based technologies in the learning process can be a more effective tool to **promote and teach moral values** than traditional approaches. Many aspects of real-life situations can be safely presented in VR, giving students the opportunity to solve ethical dilemmas and understand the consequences of their actions. For example, a study conducted to compare VR-based and traditional learning methods for ethical education revealed that the promotion of moral qualities such as humanity, respect, responsibility, peace, honesty, courage, cooperation, friendship, discipline, justice, humility, conscience, kindness, tolerance and modesty through VR was more effective than traditional approaches (Safdar et al., 2019). According to researchers in this study, the VR tool had a more powerful impact due to its ability to create different moral dilemmas, integrate theories and concepts, as well as provide an opportunity to apply this knowledge, demonstrate issue recognition and evaluate different moral perspectives (Safdar et al., 2019).

Impacts on vulnerable groups

The impact of XR applications in education on people with cognitive disorders

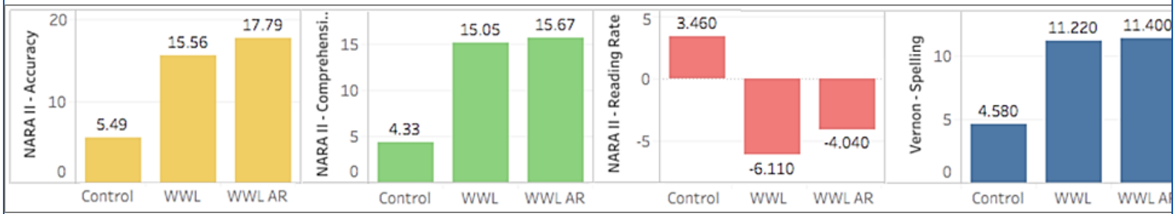
The application of XR tools creates opportunities to involve students with **autism** more actively in the education process. For this purpose, XR offers gamified educational tools for persons with autism to develop communication and teamwork skills. Research in this field Has shown that children with autism who used such tools were able to successfully perform VR-based designs and maintain social interactions with peers. Thus, they were actively engaged in a collaborative design task and achieved the targeted goals (Ke, 2016). Moreover, XR allows them to learn how to behave in real-life situations (e.g. crossing the street or shopping at the supermarket) in a safe manner that is specifically tailored to them.

In the same vein, according to insights from one of the interviews with XR experts, students with **ADHD** were able to better concentrate and achieve lesson objectives when using VR headsets (Zitter, 2020). Moreover, XR tools also allowed students with ADHD to develop their social skills and psychosomatic behaviour. Long-term XR training effects were maintained in students' memory and executive function (Shiratzky et al., 2018). For example, to assess how XR tools (e.g. AR-driven mobile apps, online literacy programmes) affect the ability of students with ADHD to remain focused, as well as their accuracy and capacity to finish tasks to the end, the EC funded the pilot project AHA. The results of the project show that AR increases these students' academic outcomes by stimulating their attention (Tosto et al., 2021).

AHA – AR-based project for students with ADHD in Ireland

AHA (ADHD Augmented) tests an AR-driven solution for an existing online literacy programme, which is expected to enable students with ADHD to achieve better learning results. The pilot study project is funded by the EC Directorate-General for Communications Networks, Content and Technology and is coordinated by Assoc. Prof. Eleni Mangina, from the School of Computer Science at University College Dublin.

The project involves 3rd, 4th and 5th-grade students (117 students in total) diagnosed with ADHD. The students were randomly appointed into three groups: a control group with no intervention, a group using the WordsWorthLearning (WWL) intervention, and a group using an AR-driven WWL intervention. All students were assessed for their literacy skills (reading, spelling, etc.) before the intervention, and then asked to use the designed tool for 16 weeks, with one session of 15 minutes each day.



After the course, the students were re-evaluated to see if there had been an impact of the AR-driven technology The results show that students' performance increased following the AR-driven WWL intervention. Student accuracy improved by 17.79%, comprehension by 15.67% and spelling by 11.4%. Meanwhile, the reading rate decreased after the intervention, in line with the desired outcome. This is because students normally read faster than they did during the intervention and thus usually make mistakes. To reduce the number of reading mistakes, their reading rate was reduced and thus their reading accuracy improved.

Source: Visionary Analytics, 2022, based on Tosto et al., 2021

XR technologies are also beneficial for students with **Down syndrome,** as it allows them to learn vocabulary and improve their reading skills in a more entertaining manner. To illustrate this, AR-based tools can overlay books with 2D and 3D animations. Moreover, visualisations can be displayed that integrate text, audio and video (Shaltout et al., 2020). The purpose of such tools is to provide students with deeper, meaningful and more joyful experiences by combining educational content with specific places and objects. Research in this field has revealed that students enjoyed the learning process, and were also more motivated to read and interact with the learning environment (Shaltout et al., 2020).

XR tools also have a positive effect on the behaviour of children with **NDD**. To achieve this, VR-driven software allows users to experience 3D virtual spaces using head-mounted displays that enable their virtual presence in a simulated environment. Research in this area showed that HMDs maximise the immersion effect by removing distractions in the outside world and increasing students' concentration. This in turn increases students' learning potential (Garzotto et al., 2017). For example, **Wildcard** – an educational tool for children with NDD – offers a distinctive collection of characteristics that have only been partially explored but have already demonstrated their potential for tackling the needs of patients with NDD (Gelsomini, 2016).

The impact of XR applications in education on people with learning disabilities

XR tools can increase the visual attention, motor balance, coordination and reading performance of students with **reading difficulties**. To achieve this, educational institutions use VR platforms that allow students' ocular, head and movements to be traced as they interact in a virtual environment (e.g. playing vocabulary-related problem-solving virtual games). The key advantage of such platforms is that they provide immediate feedback on students' movements in a virtual environment. Research in this area has revealed that such types of training results can accurately identify students' mistakes and increase their capacity to retain new words (Flores-Gallegos et al., 2021, Khoshnevisan, 2018; Roitsch et al., 2021).

In addition, XR tools ensure a safe and motivating learning environment for students with **dyslexia**. Using XR technologies, students have an opportunity to interact and learn in a playful virtual environment that fosters their engagement in the education process (Kurniawati et al., 2019) and eases their dyslexia symptoms (Rodríguez-Cano et al., 2021).

Examples of XR tools aimed at people with dyslexia

The European project **Erasmus+ FORDYSVAR** (Fostering inclusive learning for children with dyslexia in Europe by providing easy-to-use virtual and/or augmented reality tools and guidelines) is the first technological attempt to apply XR-based solutions. The project organisers have developed VR and AR software for students with dyslexia. The software is based on the Meta Question VR viewer, and integrates with VR glasses and controllers. Using VR glasses and controllers, students are invited to interact by participating in gamified VR and AR-based learning activities. The software integrates translations into various languages (including English, Spanish, Italian and Romanian) to ensure its wider application in different EU Member States.

The Smart Notebook software is proven to be effective in facilitating the learning of compound words, as it offers systematic and step-by-step instructions for children with dyslexia (Tsesmeli & Tsirozi, 2015).

Source: Visionary Analytics, 2022, based on Flores-Gallegos et al., 2021, official Fordysvar website: https://fordysvar.eu/

XR tools also have great potential to be used by students with **mathematical learning disabilities (MLD).** MLD students usually experience difficulties with both the visuo-spatial and reasoning aspects of mathematics. The AR function in dynamic geometry software **GeoGebra 3D**[159] facilitates a playful approach to mathematical modelling, thus increasing students' confidence and consequently, their academic performance (Haas, Kreis & Lavicza, 2021).

Indeed, combining the multimodal affordances of XR experiences in a learning setting that develops and implements inclusive education principles has the potential to offer all students accessible, interactive and transformative learning pathways, regardless of their type of learning disability. Gamified XR tools such as 'Helping Nemo' – an AR story developed for one primary school in Cyprus – enable the integration of fun and multidisciplinary approaches, enhancing overall engagement and interest (Stylianidou, Sofianidis, Manoli & Meletiou-Mavrotheris, 2020).

The impact of XR applications in education on people with a physical disability

People with movement disabilities have the opportunity to apply **WalkinVR**[160] tools, which allow them to simulate walking and thus interact with the virtual environment. In fact, XR tools can **boost physical education** among persons with physical disabilities. In particular, VR tools allow persons with disabilities to gain repetitive physical experience in a virtual environment in which there are no time or space restrictions. These activities are applied in a differentiated manner depending on the type and degree of disability, thus addressing the participant's individual needs. Students participating in these activities can also receive detailed feedback on their physical performance, which helps to identify a person's physical problems and solve them accordingly through the development of specific training

159 https://www.geogebra.org/3d?lang=ru
160 https://www.walkinvrdriver.com/

programmes. These features are expected to boost sports education among persons with disabilities, as well as enhancing sports technology for professional sports practitioners with disabilities (Kang, 2019).

Another tool, HeartRun, has been developed by Schmitz et al. (2015). This is a cardiopulmonary resuscitation (CPR) training approach for school kids that includes aids for blind and visually impaired people, as well as children with learning disabilities.

A summary by Ivascu, Moldoveanu A., Moldoveanu F., Morar & Balan (2019) offers solutions regarding how several XR games designed for sighted people can also be made available for the education of visually impaired people, e.g. by improving non-visual access to large touchscreens, through orientation games with 3D spatialised audio, different listening modes in audio games and other features.

Negative impacts

Potential inequalities among educational institutions

The application of XR technologies in the education process requires financial capacities and a sufficient level of digital skills on the part of teachers. However, not all educational institutions possess both of these. Research in this area reveals that XR tools are applied less often in Eastern European countries than in other regions of Europe, due to insufficient levels of digital skills (Kessel et al., 2022). Moreover, the attitudes of teachers in these countries are associated with a fear of change, which also leads to the less frequent use of XR technologies (Bucea et al., 2020). Such differences among institutions in terms of unequal financial capabilities and digital skills can lead to **unequal opportunities** in the application of XR tools in the education process.

Negative impacts on vulnerable groups

XR tools can be **harmful to children or adults with mental disabilities**. XR tools (VR in particular) are usually based on realistic virtual scenarios, which involve high-quality 360-degree environmental images (e.g. virtual trips). Such a feature can have an overwhelming effect on persons with mental disabilities, who are more sensitive to unpredictable and frequent changes in their environment (Mallam, 2019). Moreover, realistic images of emergencies (including blood, deaths, etc.) in this virtual experience can be especially detrimental to children/adults with mental disabilities (Mallam, 2019).

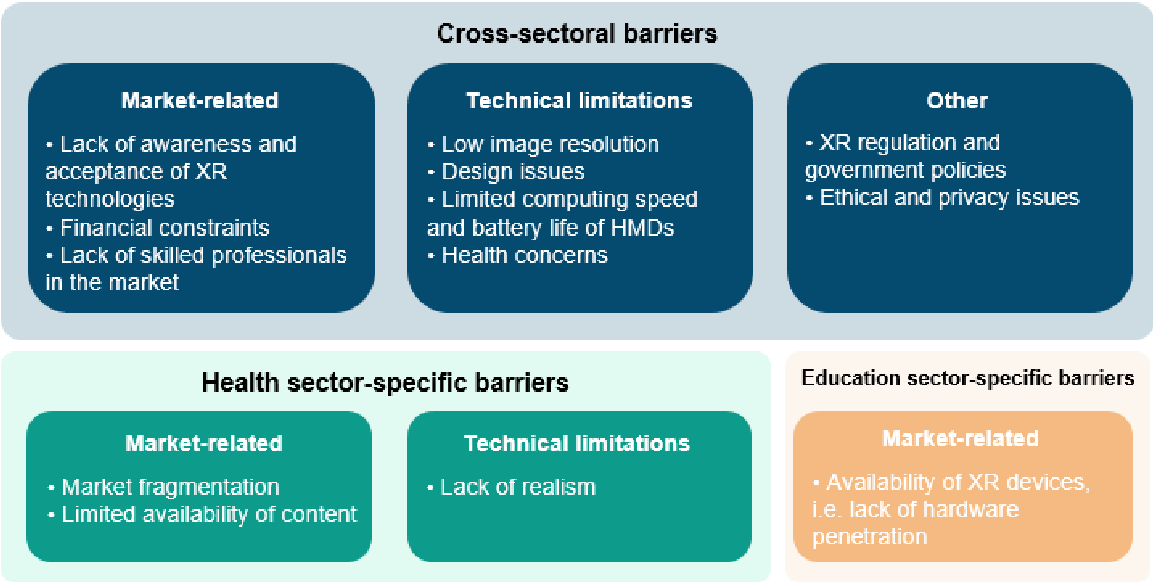
Furthermore, due to a lower level digital skills (McMorrine, 2017), people with mental disabilities may have **limited access** to XR-based training. Moreover, health impairments, such as restricted vision and hearing or epilepsy may also limit their access to certain XR equipment (such as HMD, XR glasses, etc.). HMDs are not the most convenient tool for people who wear glasses, or for those who experience motion sickness (Nisha, 2019). In such cases, traditional training approaches based on classroom learning would be more appropriate. Such challenges may create unequal opportunities for student with disabilities to participate in the learning process.

Another potential risk relates to the vulnerability of participants: cognitive, social, institutional, deferential or medical. People with vulnerable backgrounds may be unable to provide informed consent as a result of limited decision-making capacity or specific circumstances. This increases the risk of data privacy breaches, rights violations and of such individuals becoming the victims of manipulation or coercion (Diaz-Orueta, Hopper & Konstantinidis, 2020).

1.3. Barriers to be addressed

This section describes the main barriers to be addressed in order to maximise the positive impacts and counteract the potentially detrimental effects of XR in the healthcare and education sectors. The main categories of barriers are presented in the figure below. These are discussed in turn in the sections below.

Figure 4. Summary of barriers to the application of XR in the healthcare and education sectors



Source: Visionary Analytics, 2022

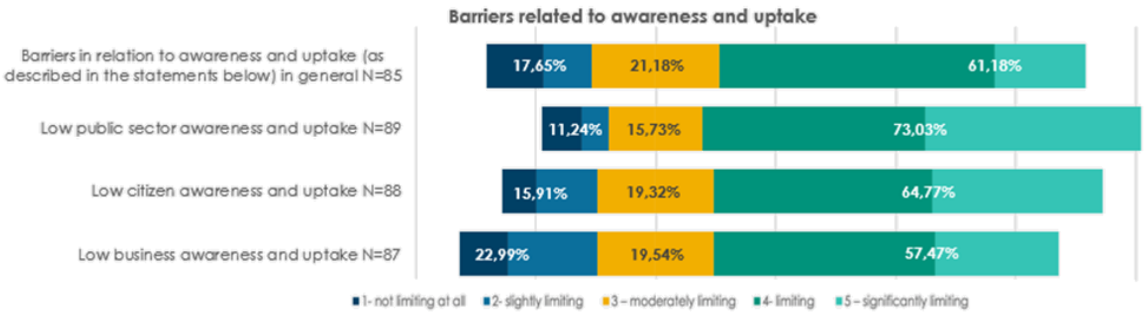
1.3.1. Cross-sectoral barriers

Market-related

Lack of awareness and acceptance of XR technologies

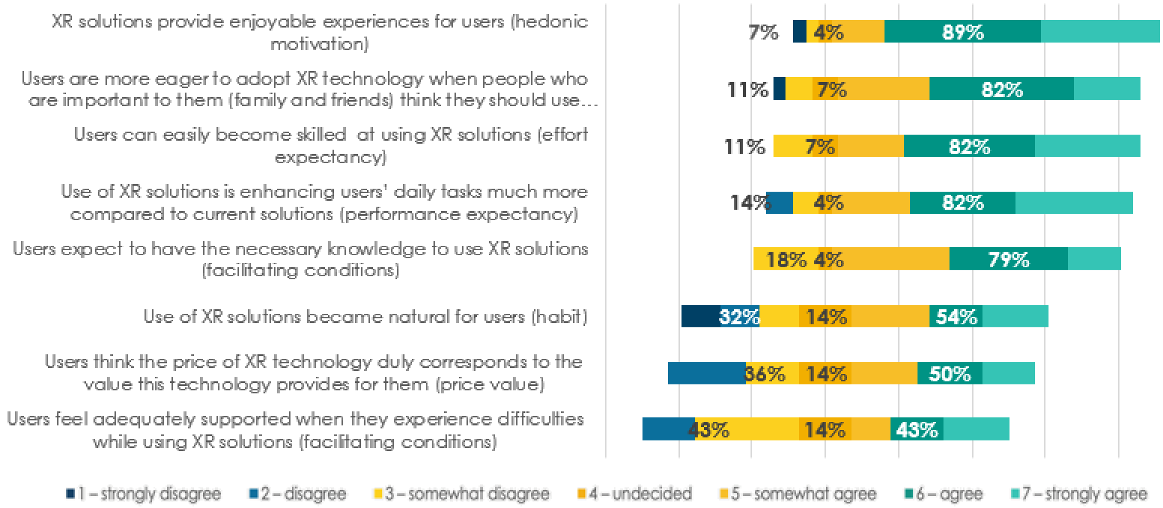
Barriers relating to awareness of potential XR users (i.e. low demand for XR solutions) were highlighted by multiple company representatives in interviews. In addition, barriers in relation to awareness and uptake of XR were among those rated highest by respondents to the survey of researchers and XR industry representatives (see figure below).

Figure 5. Importance of barriers related to awareness and uptake of XR solutions



Source: Visionary Analytics, 2022. XR company representatives and XR researchers/academics survey conducted between 16 11 2021 and 24 01 2022.

Figure 6. Extent to which respondents think users are ready to adopt their company's XR solutions (N=28)



Note: The question was shown only to company representatives who have clients.
Source: Visionary Analytics, 2022. XR company representatives and XR researchers/academics survey conducted between 16 11 2021 and 24 01 2022.

Since XR is still somewhat uncharted territory, further adjustments would have to be made to ease the consumer base into using this technology. While assessing the statements made in the survey in relation to the unified theory of acceptance and use of technology, company representatives were positive overall about users' acceptance of XR. The areas that still need improvement relate to the provision of support to users who experience difficulties, the price-value relationship of XR solutions, and to XR solutions beginning to feel more natural as individuals use them (see more details in the figure below). Hence, there is a need to target technology scepticism and facilitate education/training programmes, as well as adapt XR tools to become more user-friendly.

In the **healthcare** sector, some hospital managers and medical professionals may be sceptical about applying XR in their daily practice.[161] Research shows that VR may be especially suitable for distracting paediatric patients from their pain and anxiety; however, some hospitals have declined to participate in clinical research involving children due to concerns about GDPR and the related administrative burden[162]. Uncertainty about the validity of such tools due to a lack of large-scale clinical trials is also a common cause of mistrust among medical professionals (see Section 1.5 about research gaps).

As mentioned above, medical professionals are not yet familiar enough with the technology and its capabilities. Academic research is not sufficient when it comes to using XR in

[161] Based on interviews with industry representatives, XR experts.
[162] Based on interviews with industry representatives, XR experts.

everyday practice. Clinically relevant training and resources on how to practically adopt XR technologies should be made available for specialists. As stated by Spiegel (2020), one US-based doctor who uses VR on his patients on a daily basis, “VR doesn’t always work; sometimes it causes side effects; headsets need to be sanitised; clinicians need training on how to select and implement the right virtual treatments, and administering VR costs time and money”. Overall, the pace at which new technology is adopted by therapists is generally low and they often have concerns about adopting innovative treatment and therapy techniques (e.g. concerns about the reliability of new technology). Therefore, some authors advocate the development of accredited classes of continuing education as well as training in, for instance, VR exposure therapy for students who are about to become licensed mental health practitioners (Boeldt et al., 2019). One interview respondent (an end user) also suggested that an EU-level strategy or guidelines for the training of medical professionals in relation to XR at education institutions (e.g. defining the need for XR training, offering a framework for it, requiring to spend foreseen amount of hours in XR simulator, etc.) could help to raise awareness and preparedness for the use of new digital solutions. In addition, this could create further incentives for governments to invest in XR infrastructure at educational institutions. The Interactive Media Institute (a non-profit organisation) is accredited by the American Psychological Association to offer VR therapy training in Europe, Asia and North America. It has trained therapists in the use of VR for the past 15 years. Once these tools are offered during clinicians’ formal training, the problem of the low adoption of XR technologies among specialists will be resolved more quickly (Ma et al., 2021).

Interviews with end users (physicians) also highlight that the use of digital technologies raises questions in relation to liability. The system is vertical in the sense that the devices are provided by one organisation, software by others, etc. Hence, if something goes wrong, it may be unclear who is accountable for the mistake. This makes doctors reluctant to use XR.

According to interviews with industry representatives, there is a lack of continuous and regular usage of XR tools in organisations. Clients often only have enough budget to buy the product, but not for training to go with it. For instance, representatives of companies that sell VR tools for occupational therapy only come in once to provide basic training to the client’s staff. According to one industry representative, although most staff members are enthusiastic at first, they discontinue using the technology after encountering even the smallest technical issue. A potential solution for this is to sell XR platforms as a service, meaning that users pay a subscription fee each year and receive continuous updates and customer support, potentially increasing the organisation’s engagement. Some health-related XR service providers in Europe are already doing this (e.g. *Amelia (formerly Psious)*, *Lookback*).

As noted by some interviewees, the uptake of XR technologies in the **education** sector, has not been as fast, partly due to a lack of awareness of these technologies among stakeholders. Overall, both companies and members of society have only a rudimentary understanding of the technology.

According to an interview with an academic, another barrier that stems from low awareness is mistrust towards XR technologies generally, as well as mistrust with regard to specific pieces of technology such as Meta headsets and the Metaverse. Indeed, due to low levels of trust (especially with regard to ethical and privacy issues), people are less likely to invest in XR technologies, contributing to overall low user adoption rates across Europe.

Notably, however, users perceive AR systems for the most part as simple, fast, precise, work-relevant, worthwhile and reliable according to the Technology Acceptance Model, as noted by Jetter, Eimecke, and Rese (2018). This is supported by Cabero-Almenara et al. (2019), who found a high degree of acceptance and motivation for their experiments conducted using AR objects, independent of the educational courses the subjects were enrolled in. The same appears true for teachers, whose individual personalities and desire for cooperation appear to be positive factors in the uptake of AR applications in schools in northwestern Greece (Tzima, Styliaras & Bassounas, 2019).

On the other hand, when it comes to VR, the results in the literature are mixed. According to Tsivitanidou, Georgiou and Ioannou (2021), educators may encounter a diversity of student attitudes during the integration of immersive VR simulations into their classrooms. This is especially true for physics classes, as teaching needs to cater to the different needs of students – for this reason, introductory sessions are needed to familiarise both teachers and students with the technology and the corresponding pedagogical approach employed. In organisational settings too, the adoption of VR appears trickier. For example, trainers were sometimes rather sceptical about the technology because they questioned its usefulness or were initially afraid of using it, although younger trainers were generally more open to new technologies (Pletz, 2021). In another study, the main negative factor appeared to be the use of low-quality VR headsets, which resulted in a less positive user experience when watching 360-degree videos (Alamäk et al., 2021).

To overcome the barrier of low acceptance and adoption, the majority of the interviewees asserted that it is the responsibility of government bodies to ensure that XR-related training and awareness-raising events are held. Such official communication should improve the understanding and encourage the acceptance of XR technologies and lead to their higher uptake in education, according to multiple experts, industry representatives and researchers interviewed.

Another way to address this obstacle, according to one expert interview, is for government bodies to assess XR technologies, whereby they would ask companies to submit demos, assess them, and then disseminate them across the relevant sectors in the event of a positive assessment. According to the same interviewee, such bodies should function in close cooperation with the developers of the solutions rather than acting as yet another barrier to the development and spread of XR technologies.

Lastly, industry representatives also recommended that XR technologies should be included in official government policies/roadmaps. One industry representative noted that in Ireland, teachers and schools have been increasingly adopting XR solutions in the classrooms, and cited official government roadmaps in education. Partly due to this, XR technologies also become trendier in education, resulting in teachers learning from their peers and further disseminating the technologies within the education system. It is also important that teachers should try to educate using the technologies currently used in industry, since some industries do not yet use XR intensively.

Financial constraints

Adapting XR solutions remains costly for potential users. Although the price of XR hardware has become significantly lower, the availability of customisable software is limited. Developing personalised XR software requires a different set of skills (e.g. programming, 3D modelling, etc.) and thus significantly increases the costs to potential users of adopting an XR solution. In addition, the need for data to test and improve XR solutions is expected to increase. Collecting such data will increase the costs of developing XR solutions[163]. An open and standardised database containing data, models and tools already utilised by others could significantly reduce the cost of software development[164]. The development of the European Health Data Space[165] (see more details in Section 1.4.2) could be a step to towards such an open database. Among survey respondents, the limited availability of XR devices and the high cost of XR equipment to users were rated as limiting or significantly limiting barriers by 67% and 47% of XR industry representatives and researchers, respectively.

This study has identified the following examples of factors that increase the costs of XR solutions in the **healthcare sector**. A subscription to a professional VR exposure therapy

[163] Based on insights from the healthcare sector workshop and interview with a researcher.
[164] Based on insights from the healthcare sector workshop.
[165] https://ec.europa.eu/health/ehealth/dataspace_en

platform can cost between EUR 1,200 and EUR 10,000 per year, plus equipment – a cost that not every hospital or, especially, individual therapist can afford. Ensuring the availability of XR devices for all student courses, as well as software that enables students to learn using XR, is also considered costly by education institutions (particularly where software costs are based on a subscription per person)[166]. This is because there are only a few companies specialising in the field, which drives up costs[167]. In terms of rehabilitation, considerable cost, space requirements and programming expertise are required to develop and operate custom applications in specialised virtual environments using multiple data collection peripherals. The cost of equipment such as motion capture cameras, haptic gloves, inertial measurement units and external stimulus triggering can be a limiting factor for many organisations[168].

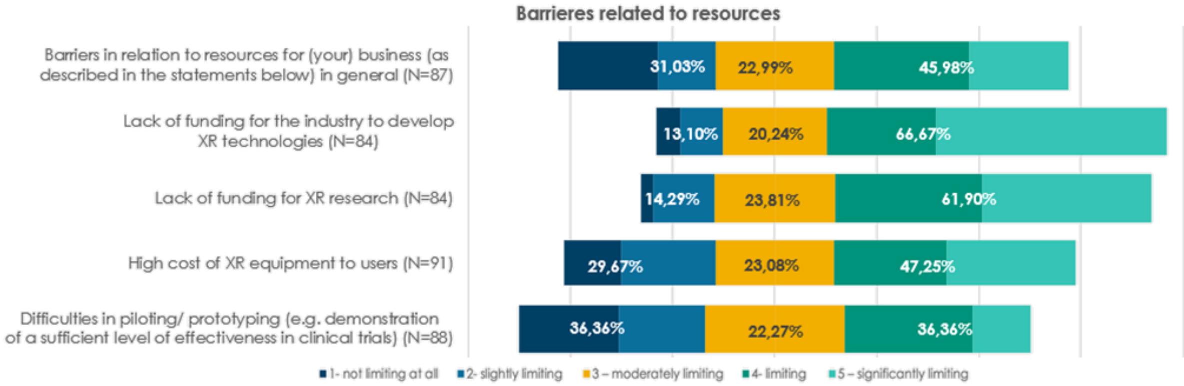
With regard to the **education** sector, the cost of setting up and maintaining the infrastructure for a VR/AR system (including devices, network connectivity and other physical infrastructure) can discourage the use such technologies (Ghobadi et al., 2020). The viability of VR/AR systems depends upon the organisation's data and technology infrastructure (Deloitte, 2018). However, delivering an impactful VR simulation requires the work of an interdisciplinary team including social psychologists, artists, modellers, filmmakers, developers, technologists and others. This requires a considerable financial investment (Knack, et al., 2019). There may also be questions regarding who ought to pay for the establishment of the infrastructure, particularly in relation to the use of VR/AR systems for public services and in cases where their benefits are insufficiently proven. Extensive technical support from specialists is typically required to set up and maintain such systems, which can significantly add to the cost of adopting VR/AR technologies (Ghobadi et al., 2020; Leovaridis and Bahna, 2017).

One of the solutions to overcome the low user adoption and societal uptake of XR in the education sector mentioned most frequently by survey participants in the study conducted by Knack et al. (2019) is to make it more affordable. Indeed, the high cost of devices may pose practical problems in its wider application (Tegoan, Wibowo & Grandhi, 2021). Specifically, industry experts suggest that governmental investment in VR headsets and equipment overall to reduce prices. The expense of XR equipment is a barrier in most areas of formal education, and thus the availability of more affordable headsets could accelerate the wider uptake of XR technologies in formal education. However, more than half of respondents to the education sector survey indicated that a lack of funding for developing and conducting research into XR technologies limits or significantly limits the expansion of the XR industry in Europe (57%, N=23; 54%, N=24, respectively), which could restrict the affordability of XR technologies.

Another issue arises from the difficulties that research teams and start-ups face in commercialising XR products, despite strong research results in Europe. Private investors in the EU are reluctant to fund XR solutions, particularly hardware. In addition, many XR applications are developed by research teams using only the resources of a single research grant, and do not therefore reach the commercialisation phase. Our survey of industry representatives and researchers shows that barriers in relation to a lack of funding were ranked among the top barriers to expanding XR businesses (see Figure 7 below).

[166] Based on interviews with industry representatives and end users.
[167] Based on an interview with an industry representative.
[168] Based on interviews with industry representatives.

Figure 7. Importance of barriers relating to resources



Source: Visionary Analytics, 2022. XR company representatives and XR researchers/academics survey conducted between 16 November 2021 and 24 January 2022.

Many VR apps discussed in academic papers do not become available to interested clinicians due to public health insurance in Europe only covering certified medical devices. Obtaining certification for a device is a complex, heavily regulated and expensive process that can take more than a year[169]. The difficult certification process also leads to the certification of XR devices for narrower applications, as this is relatively easier. However, this means that such devices can only be applied very narrowly, even though technically they may be able to be applied more broadly (e.g. if a device is certified to visualise the heart, it can be used only for that, despite its technical to visualise the kidneys or other organs)[170]. In addition, research groups attempting to start a university spin-off and commercialise their product, as well as companies interested in commercialising solutions developed by research groups, in many cases face bureaucracy at higher education institutions. Such institutions in Europe usually request a large equity share in the spin-off (from 25%, reaching up to 50%, whereas in the United States this share rarely surpasses 10%) and/or royalties (Benaich, 2021). Furthermore, the majority of respondents to the healthcare sector survey rated the lack of funding for the industry to develop XR solutions (70%) and for XR research (62%) as limiting or significantly limiting barriers to expanding their businesses. In addition, multiple interviewees (industry representatives) noted that it is not easy to attract funding from private investors, who are reluctant to fund XR solutions in general, and hardware in particular, due to a lack of knowledge about it. Investors in the US and UK are more willing to do so, but prefer to fund companies established within their own countries. Without the growth and improvement of commercially available VR clinical software, it will be impossible to encourage its widespread use in healthcare establishments (Riva, Malighetti et al., 2021).

In relation to the lack of funding in the **education sector**, the majority of the XR industry representatives, researchers and experts surveyed and interviewed acknowledge the importance of increasing public XR research funding, including support for industry start-ups and research institutions in the education sector. In addition, participants in the education workshop noted the lack of funding for XR hardware targeted at schools. Increased public funding would, in turn, strengthen the XR industry in Europe and support European software and hardware developers, thus reducing dependence on products from the USA or Asia.

One of the interviewed researchers even noted that, in their experience, funding tends to be given to larger companies because their size may create an image of greater trustworthiness in the eyes of the funding administrator. However, the interviewee maintained that start-ups are the companies that 'make this sector happen', and at the

[169] Based on interviews with industry representatives.
[170] Based on interviews with an XR practitioner and an industry representative.

moment, as a start-up, one needs a great deal of patience before some sort of funding can be obtained.

A further obstacle noted by the majority of interviewees – especially researchers – is the application process for funding. The abundance of red tape is regarded as the biggest issue, as the application process is not created for small companies, but is specifically adapted to the needs of companies with large in-house scientific laboratories for XR. In other words, such processes are not accessible to researchers at smaller universities or to representatives of start-ups; they require extensive administrative work and project planning at a level of detail that is much less familiar to start-ups with less experience and fewer resources than large organisations. Even then, when a start-up outlines a three-year project plan in its application, this plan either cannot be changed, or would otherwise be very difficult to change. In other words, the rigidity and lack of agility of the application process may lead to non-beneficial outcomes and/or discourage prospective start-ups from applying.

As a result of the lack of funding to create collaborative networks, the researchers interviewed also noted a lack of communication among academics in the field. While some networks exist, research is much too slow and tends to focus on niche areas. Part of the reason for this, one respondent elaborated, is the limited budget available for research. According to this respondent, most projects are industry-based, so the XR research community has to function on a demand basis, researching only those solutions that clients want.

Lack of skilled professionals in the market

Research on the European XR market[171] shows that it is difficult for companies to attract XR professionals. This relates both to difficulties in competing with global non-EU XR players that can offer more attractive salaries and working opportunities, as well as with other related sectors (mostly the gaming industry). The need for interdisciplinary skills (technical, creative, social and entrepreneurial) is also part of the difficulty. In addition, several interviewees among the industry representatives and researchers confirmed a severe lack of experts in the field of XR in education. This was also confirmed by the survey respondents. Both a lack of talented professionals for developing XR technologies (rated as a limiting factor by 56% of respondents) and a lack of intermediaries (e.g. trainers, teachers) for digital skills to enable XR experiences (rated as a limiting factor by 55% of respondents) were ranked among the top barriers to expanding XR businesses in the survey of XR industry representatives and researchers.

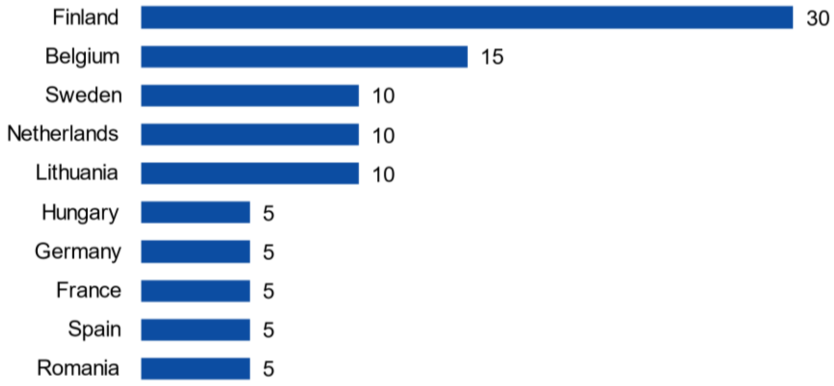
There is a lack of professionals in content creation and XR developers, as well as skilled XR instructional designers for the XR learning experience. This could be ascribed to the lack of dedicated formal education programmes in the field and the lack of overall funding available. This shortage of professionals makes it difficult to start, maintain, and expand a business, and may result in low-quality XR content.

Indeed, preliminary desk research reveals only a few university-level education opportunities in XR, as presented in the box below:

[171] Ecorys (2021). XR and its potential for Europe. Ecorys (2022). VR/AR Industrial Coalition: Final report (the findings from this report will be deblocked once the final version of the report is published)

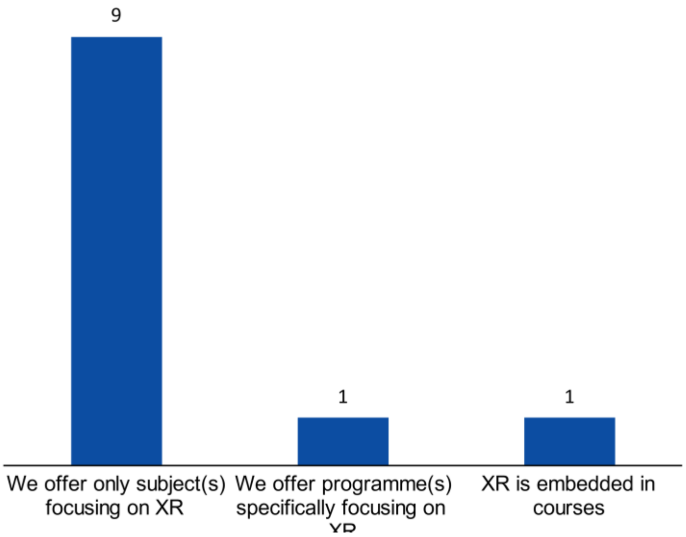
Overview of the XR university education landscape in Europe

A survey was distributed to over 150 universities across Europe, with the vast majority of those targeted coming from Finland, followed by Belgium, as seen below:



Having received 16 complete and 17 partial responses (N=33), most respondents said that they offer both programmes or subjects aimed at training professionals to work in the XR sector, as well as those aimed at helping users better exploit XR technologies (36.4%).

When asked about the forms of learning involved, nearly half of universities answered that they offer only formal learning, although 36.4% said they offer both. These programmes/subjects appear to be offered equally at Bachelor's as well as Master's level, though few universities offer a PhD (27.3%).



When it comes to the focus on XR in university programmes, most universities only appear to offer subjects containing XR content, forming a part of a different subject area/faculty, as seen below: Those who chose 'other' noted that they offer XR-related courses in the following:

- Product development: design in VR;
- VR-supported e-learning education;
- Chemo-informatics/computational drug design;
- Game-design for three humanities fields: history, theatre, and modern literature;
- VR for physical activity;
- XR in healthcare, social services, and rehabilitation;
- Media and arts;
- Other.

With regard to the content of the XR-related subjects/programmes, the majority focus on i) art and design (67%); ii) programming (67%); iii) app development (44%); and iv) end user training (44%).

However, only 22% of respondents perceive the end users of XR solutions (22%) or experts working in the field of XR (11%) as their target groups, mostly targeting the traditional student pool (100%).

Notably, over one-third of universities stated that they have agreements with the industry for traineeships for their students after they complete their XR-related programme/subject, while one-fifth stated that they do not have such an agreement, while 44% were uncertain as to whether they had such an agreement.

Source: Visionary Analytics, 2022

Other than the limited availability of formal education programmes offered in XR, such programmes may also be complex to construct, since the subject matter is highly multidisciplinary. Courses may cover the whole range from enabling technologies to the final user experience of XR applications, while also covering applications for industry.

Moreover, an important challenge remains limited XR skills among teachers, as identified by one industry representative during their interview. Teachers are not trained in how to use XR tech and integrate it within the curriculum. Because of this, they can be hesitant about introducing such innovative pedagogical methods into the classroom. Most of the time, the interviewee noted, the XR technology provider has to train the teacher not just in using the technology but also in constructing lesson plans that use XR technologies in class. Indeed, workshop participants concurred that teachers are not keeping up with the speed of students' digital skill development. Participants also stressed the importance of user-friendly educational courses for teachers and better access to XR technologies.

Technical limitations

XR devices are not ergonomic enough (e.g. due to weight and size), especially when they have to be worn for a longer period of time (e.g. during surgery) (Khor et al., 2016; Vávra et al., 2017). Low image resolution remains a challenge in relation to cameras and displays. In addition, a lack of precision in AR hardware can negatively affect its use (e.g. in surgical navigation, precision is crucial – a difference of even a millimetre could result in surgery being unsuccessful; if a device cannot detect objects under certain lighting conditions, it cannot sufficiently assist persons with disabilities) (Li et al., 2021; Pérez-Pachón et al., 2020). It must be noted that due to advances in hardware, image resolution is becoming more of a problem with software design rather than limited hardware capabilities.[172]

Moreover, an interview respondent noted that XR hardware at the moment is 'clumsy' – there is a need for wireless and standalone headsets that keep pace with the trend towards miniaturisation seen among devices. This ties in with the need for more frictionless technology – the more natural and non-disruptive the design, the higher the likelihood of its uptake. In addition, haptic feedback is often not available in XR devices.[173]

The processing speed and battery life of head-mounted devices are often limited due to the small size of such devices, and are thus insufficient for some more advanced operations. This also applies to smartphones, which can be used as an XR device. In addition, other factors such as poor internet connection can negatively affect the use of XR equipment. Smooth operation is crucial during educational and medical procedures. For example, after using mobile-based XR systems for learning, healthcare students described encountering issues such as slow response times, internet connection problems and phone incompatibility, all of which disrupted the flow of learning (Stretton et al., 2018).

Advances in 5G telecommunication could provide massive capacity for the transmission of information in real time, allowing real-time cloud computing[174]. Cloud computing could reduce the size and weight of devices and increase their computing power, as services such

[172] Based on the insights from the healthcare sector workshop.
[173] Based on insights from the healthcare sector workshop.
[174] Cloud computing is the delivery of various services (e.g. tools and applications such as data storage, servers, databases, networking and software) via the internet, removing the necessity to own them physically.

as storage and computing could be delivered via the cloud rather than on the physical device (Li et al., 2021). Nonetheless, the use of 5G networks for XR needs to take account of technical challenges in rendering 3D virtual environments. For example, in order to guarantee an appropriate user experience, mobile broadband should be able to handle stereoscopic images with a high dynamic range, at increased image resolutions and high refresh rates, while the device's power consumption low (ABI Research & Qualcomm, 2017).

Health concerns in relation to the technical limitations of XR hardware and software are presented in Section 1.2.1 on medical safety risks

Other

XR regulation and government policies

Policy frameworks usually lag behind fast-developing technologies (Ellysse Dick, 2021; Lemley & Volokh, 2018). This applies to XR in both the healthcare and education sectors.

In terms of the **healthcare sector**, one such example is compensation for XR treatments by public health insurance. Multiple industry representatives noted that treatments that use XR are either not compensated, or are compensated in an illogical way (e.g. compensating only for therapist time, and thus not compensating for sessions carried out by patients themselves[175]; or compensating mental healthcare institutions only for cheaper treatments instead of those that are more expensive but more effective (Lachmeijer, 2022)). This results in the lower uptake of XR in hospitals, as they do not have the resources to cover the costs of XR treatments on their own. In addition, becoming certified as medical device is a particularly complex, heavily regulated and expensive process which can take more than a year.[176]In relation to **education**, XR-specific regulation is lagging behind. For example, according to an interview with a researcher, the realm of harassment in the XR environment has yet to be addressed in terms of rules and mechanisms for punishment when violations occur. However, some procedural bureaucracy does exist, especially in relation to privacy requirements, thus slowing the emergence of XR. More specifically, some representatives of XR firms working in the education sector noted they were confused as to what exactly is allowed under the GDPR, suggesting that certain laws should be reviewed with feasibility and efficiency in mind.

Furthermore, no guidelines are provided to schools when it comes to the use of XR technologies by a teacher in class, as well as for feedback and assessment. The same is true of curricula that are adapted to include XR. Concerns about these issues were also expressed by in the participants education workshop, who stressed the importance of establishing standardised guidelines. In a similar vein, one industry representative said that public bodies do not provide training to teachers due to a lack of strategy for regarding use of XR technologies in education. The interviewee revealed that such training is, by and large, delivered to teachers by the companies that sell XR technologies. The interviewee noted that to help develop the XR industry for school education, as a minimum, public bodies could state their open support for the integration of XR into lesson plans and other aspects of education.

A lack of unified national policies is also apparent when it comes to understanding which schools in Europe have – or are interested in having – VR headsets and XR software. Having this information, preferably in the form of an open-access database, would enable companies and organisations to better create strategies for the wider deployment of XR in European schools, thus aligning European curricula with technologies.

[175] Based on interviews with industry representatives.
[176] Based on interview with industry representatives.

Ethical and privacy issues

The basic use of XR technologies requires the collection and use of significant amounts of data, thus making it impractical to impose constraints on its collection. Limitations on the use of such data must be carefully crafted to promote trust while ensuring the fundamental operation and safety of XR systems. In addition to account information being collected directly from a user, XR HMDs also collect an array of sensor information about the immediate environment (in the case of AR), physical movements, and the user themself. In fact, 20 minutes of VR use can generate approximately two million data points and unique recordings of body language – VR headsets track a dozen types of movements upwards of 90 times per second to convincingly render a scene (Jerome & Greenberg, 2021). The information provided by eye tracking can be augmented with other sensors, including movement sensors, electroencephalography and brain-computer interfaces, as well as other pressure and fitness sensors; bodily motions, and the relationship between different body movements and segments, can also serve as a tracking mechanism (ibid.). This also applies to the collection of information about the external world and bystanders, not just the users of XR technologies. In the long term, this data collection can generate surprising insights, both about the users and wearers of these technologies, and individuals that incidentally come into contact with XR users. Both of these categories have the potential to create risks for individuals, communities and society at large. Indeed, one expert interviewee noted that although XR devices from large corporations are affordable, they come at a cost in data collection.

On the one hand, compliance with legislation protecting personal data (e.g. GDPR) add an additional layer of complexity in the deployment of XR solutions. Indeed, 53% of survey respondents from the healthcare sector saw excessive government requirements as a barrier to developing XR business. One of the main issues with personal data protection is the need to transfer data outside of the EU since the main XR device providers are based outside of the EU[177].

On the other hand, because XR collects a lot of personal data, users of the technology want to trust that their data is safe before they begin to use it. Multiple interviewees (XR experts, practitioners and industry representatives) believe that a strict EU personal data policy is an advantage, as it allows users to trust that their data is safe, and thus makes them more willing to use XR. This trust also makes them behave more naturally while using XR, and thus gives developers more accurate data, which they can use to improve their products. In order to ensure data protection, XR companies are putting extra effort into ensuring data security (e.g. encrypting the information collected, implementing regular audits, and becoming certified under ISO27001 (the international standard for information security)[178]).

In addition, virtual worlds and the actions that happen within them raise a series of questions concerning legal certainty and how the existing legal framework should be applied and enforced in virtual words, as well as debates over liability (e.g. for accidents that occur while performing tasks assisted by XR) and all aspects surrounding the transposition of rights and freedoms to a virtual setting (Ellysse Dick, 2021; Lemley & Volokh, 2018).

With regard to instructional approaches in **education**, moral concerns include neutrality, grounded in science, regarding controversial topics, as well as the representation and comparison of multiple perspectives on debatable topics, and unauthorised content augmentation via location-based AR that could lead to the violation of cultural norms (Christopoulos et al., 2021). When it comes to privacy issues specific to the sector, GDPR is an important discussion point. Being fully GDPR-compliant can also become a barrier to achieving the intended goal of using the XR technologies in an educational setting to begin with. Germany is a case in point: for the German education system, the GDPR compliance of any XR application is extremely important. During the COVID-19 crisis, various German states even officially prohibited the use of international virtual meeting platforms. This

[177] Based on insights from the healthcare sector workshop.
[178] Based on interviews with industry representatives.

limited the ability of teachers to get in touch with students, and hence caused a huge gap in knowledge transfer during the lockdown period (XR World Academy, n.d.). While the overarching goals of privacy regulations can certainly be extended to AR/VR devices and applications, the mechanisms laid out in current laws such as the GDPR to achieve those objectives do not directly apply to immersive experiences, especially when it comes to the handling of biometric data under article 9 of the Regulation (European Parliament and Council of the European Union, 2016). Indeed, the ambiguous standard for obtaining users' informed consent, or the process by which a fully informed user participates in decisions about their personal data, may be a key criticism. This is important, because XR widens the gap between users' understanding of the implications of their consent and the actual consequences. More specifically, as stated above, the basic use of these technologies requires significant data collection and use. The providers of these services may thus have more information about their customers than the individuals do about themselves. Moreover, providing an immersive experience means customisations based on user data have to be unnoticeable to users, in order to avoid distractions. It is therefore imperative for users to more closely understand and consciously weigh the benefits and risks of using XR technologies.

Moreover, even though interest has grown in the use of AR and VR applications in education, difficulties remain in relation to governing the collection and interpretation of primary data such as frequency of use, interaction time, location tracking, noise levels, gesture tracking, eye movement, facial expressions, etc. (Christopoulos et al., 2021). This can create hesitation among potential users, especially the parents of underage children, but is equally true for any adult who is considering using XR technologies for education and training. The invasion of users' privacy and access to their personal data remains a challenge in this regard (Adams et al., 2018; O'Brolcháin et al., 2016).

1.3.2. Healthcare sector-specific barriers

Market-related

Market fragmentation

The European XR market is fragmented. On the one hand, a number of research groups and small companies are developing XR solutions[179.] These are too small to compete on a global level, and thus consolidation and further cooperation is needed. On the other hand, healthcare systems in Europe are also very fragmented[180]. Different countries and even different regions within countries have different healthcare models, different legal environments (e.g. for storing and collecting data), and different processes for the procurement, reimbursement and use of digital health services. This makes it difficult to scale up digital health solutions across the European market, and requires a lot of resources and a long-term strategy to do so. As a result, some the interviewed businesses that are based in the EU are focusing their resources on growth within the US market.

Moreover, XR devices are currently being adopted for medical education predominantly in high-income countries, despite the fact that XR devices may be particularly beneficial for supporting health care workers in low-resource contexts (Barteit et al., 2021). In addition, the digital divide between countries, regions and groups of people (e.g. the elderly) might hamper the consistent application of remote treatments for patients, such as VR-based post-stroke rehabilitation. The relatively high cost of hardware and software and slow internet speeds may impede the widespread application of these technology-based treatments. Nevertheless, cost-benefit analysis and strong policy support may help to overcome these issues (Mantovani et al., 2020).

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179 Based on interviews with industry representatives and XR experts.
180 Based on interviews with industry representatives and XR experts.

Limited availability of content

Another significant barrier is the limited availability of content. In the healthcare sector, survey, 48% of respondents rated low-quality content offerings as a limiting factor, while 43% also rated a lack of content as a barrier limiting the expansion of their businesses. Developing personalised VR software requires skills in programming, 3D modelling and so forth, which medical professionals (often) lack[181]. Most XR programmes on the market are games, while more serious applications that address specific medical conditions and can be easily personalised for each patient remain rare[182]. According to one of the XR practitioners interviewed, game developers often create games that are very rich in terms of design, but also have complex storylines, are fast-paced, and include sudden sounds, etc. which may not be suitable for children with autism, for example. The complexity of such off-the-shelf games does not allow clinicians to set clear targets linked to the child's individual occupational therapy programme. On the other hand, games developed by clinicians specifically for children with neurodevelopment disorders are often too simplistic and have poor-quality design features, making them less engaging for users[183]. Many groups have alleviated much of this problem by including end users in all aspects of the development process, from design and development to testing.

Commercially available software generally comes from the US, meaning that European patients (or students) usually cannot fully relate to the virtual environments (different scenery, buildings, clothes, etc.)[184]. However, there are examples of environments with cross-cultural designs. For example, a VR environment for treating panic disorder and agoraphobia which was developed in Italy worked equally well in a study performed with populations from Italy, California, Quebec and Seoul, South Korea (Molinari et al., 2002; Vincelli et al., 2001, 2003). Another issue can be that many patients do not understand English, which is often the only language available in such applications. This is an important barrier, given that the key benefit of XR is its immersion and resemblance to real-life situations. Solution providers are trying to reduce this barrier by offering their software in at least two languages.

Technical limitations

Lack of realism

With respect to diagnosis, VR tools are not always capable of simulating real-life situations (e.g. due to low image resolution, avatars that do not behave like real humans, unnatural conversations, and the absence of unexpected events in virtual environments). This can be confusing for users. For example, VR cognitive behavioural therapy cannot adequately address conversational issues. Technological limitations may restrict the possibilities for conversational interactions between participants and avatars (Pot-Kolder et al., 2018). In addition, the fact that avatars are not especially realistic may make patients and clinicians less able to immerse themselves in the scenario (speech recognition and more realistic facial expressions would be needed) (Fertleman et al., 2018). Due to this lack of realism, patients might not act the same way in the virtual world as they would in the real world, and may not perform accurately enough for a diagnosis (Aziz, 2018; Cogné et al., 2017). Combining VR with artificial intelligence (AI) may help to resolve this problem for users by allowing more realistic, life-like communication.

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[181] Based on interviews with an XR practitioner and expert.
[182] Based on an interview with an XR practitioner.
[183] Based on an interview with an XR practitioner.
[184] Based on interviews with an XR practitioner and expert.

1.3.3. Education sector-specific barriers

Market-related

Availability of XR devices, i.e., lack of hardware penetration

According to several interviewees – experts, academics, as well as representatives of XR organisations – Europe is currently completely dependent on Chinese and US-made hardware. This is a problem, because until recently, in order to use the most popular headset, Meta Quest 2, for example, one needed to have a Facebook account. This is especially problematic when it comes to schools using Meta: because the company has no option for business or organisational accounts, multiple fake accounts are created for the sole purpose of logging into the device. Although Meta is set to waive this policy, participants in the education workshop expressed that the crux of the problem is that the current market-leading devices are intricately linked, or locked, to specific ecosystems or software. This may create obstacles for the international and more streamlined application of such technologies for educational purposes.

1.4. National and European initiatives

1.4.1. Cross-sectoral initiatives

The European Commission (EC) highlights the importance of XR via its close connection to the development of other innovative technologies, including the application of artificial intelligence. XR is not considered a separate policy area, but rather as part of the broader area of innovative technology development.[185] However, this does not underestimate potential of XR technologies.

The previous European Framework programme for research, **Horizon 2020 (H2020)**, focused on XR through one of its challenges "to forge a competitive and sustainable ecosystem of European technology providers in interactive technologies". During the period 2018-2020, the EC launched a Coordination and Support Actions (CSA), including such networking initiatives as XR4ALL, as well as Research and Innovation Actions (RIA) and Innovation Actions (IA).[186] The H2020 call for interactive technologies (ICT-25-2018-2020) specifically focused on XR.[187] AR/VR was also funded in the call for interactive technologies (ICT-55-2020).[188] This call focused on "developing richer virtual environments, new user interfaces and improved immersion maximising the feeling of presence[189]." In total, the EC allocated more than EUR 42 million to the activities mentioned above. Next to Horizon 2020, the Eurostars SME programme also funded small to large innovative businesses, some of them in the XR industry[190].

XR is much more explicitly addressed in the new **Horizon Europe 2021-2027** programme, in comparison to under Horizon 2020. XR technology investments under the programme will be concentrated in the Digital, Industry and Space cluster of Pillar 2 (Global challenges and European industrial competitiveness), with a budget of EUR 15 billion.[191] Among other things, the cluster will focus on interactive technologies, including immersive technologies and language technologies. There are seven XR-related topics in the 2021-2022 work programme of the Digital, Industry and Space cluster (see Table 2 below).

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[185] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018IR3953
[186] https://xr4all.eu/wp-content/uploads/thomas-carlu-introduction.pdf
[187] The following projects have been funded under this call: ARETE, iv4XR, TACTILITY, PRESENT, ARtwin, PRIME-VR2.
[188] The following projects have been funded under this call: AdMiRe, PrismArch, ATLANTIS, HoviTron, INVICTUS, SOCRATES, BRIDGES, eTryOn, xR4DRAMA.
[189] https://digital-strategy.ec.europa.eu/en/news/fostering-european-interactive-technologies-ecosystem-new-h2020-projects-augmented-realityvirtual
[190] https://xr4all.medium.com/the-ultimate-guide-to-the-european-xr-healthcare-investing-scene-9c53e6f4f6c3
[191] https://xr4all.eu/wp-content/uploads/thomas-carlu-introduction.pdf

Table 2. Horizon Europe calls relating to XR (2021-2022)

The topic of the call	Action type	Code	Total indicative budget (€ m)
eXtended Reality Modelling	Research and Innovation Actions	HORIZON-CL4-2021-HUMAN-01-13	14.5
eXtended Reality for All – Haptics	Research and Innovation Actions	HORIZON-CL4-2021-HUMAN-01-14	6
eXtended Technologies	Research and Innovation Actions	HORIZON-CL4-2022-HUMAN-01-14	19
eXtended Collaborative Telepresence	Innovation Actions	HORIZON-CL4-2021-HUMAN-01-25	15
Innovation for Media, including eXtended Reality	Innovation Actions	HORIZON-CL4-2021-HUMAN-01-06	26
eXtended Learning – Engage and Interact	Innovation Actions	HORIZON-CL4-2022-HUMAN-01-19	21.5
eXtended Reality Ethics, Interoperability and Impact	Coordination and Support Actions	HORIZON-CL4-2021-HUMAN-01-28	2.5

Source: Visionary Analytics, 2022, based on European Commission, 2021, available at https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-7-digital-industry-and-space_horizon-2021-2022_en.pdf

In general, these seven topics have as their goal to promote more innovative, improved, accessible and competitive XR solutions in Europe. XR applications are intended for various professional groups in European industry and society. Different ambitions for European XR products are planned, including those relating to education and training, inclusive design, safety and ethics. Hardware for people with disabilities is to be designed, such as tactile solutions for the blind and visually impaired; XR training for young professionals and upskilling (including in healthcare) are to be supported; cross-cutting themes (such as the negative impact on health) are to be explored. In addition, other Horizon Europe pillars and other clusters of Pillar 2 may have XR-related projects, although neither of these will have calls specifically dedicated to XR.

Going beyond the Horizon Europe programme, there are other policy developments. XR is touched upon in the activities of the European Institute of Innovation and Technology (EIT) and its Knowledge and Innovation Communities (KICs), in particular **EIT Digital**. Within its focus area of digital well-being, EIT Digital aims to safeguard the health of the youth, working professionals and the elderly by analysing sensor data.[192]

Another European Commission initiative (Europe's Media in the Digital Decade: An Action Plan to Support Recovery and Transformation) is dedicated to **encouraging collaboration in the European XR sector.**[193] This will have interesting synergies with the XR sector. Two key steps include:

1. Creating a VR/AR industry coalition to stimulate cooperation across industry sectors and ensure European leadership. Such a goal is raised due to fragmentation in European VR/AR between sectors;
2. Launching a VR Media Lab for projects to develop new ways of storytelling and interacting. This will encourage joint work and mutual learning between people representing a range of professional groups.

Analysis at national level shows that XR is usually funded through initiatives and programmes supporting technological development, research and innovation in general. Initiatives directly supporting XR were rarely identified.

[192] https://www.eitdigital.eu/fileadmin/2021/publications/sia/EIT-Digital_SIA_2022-2024.pdf
[193] European Commission, COM(2020)784 – Communication: Europe's Media in the Digital Decade: An Action Plan to Support Recovery and Transformation, Brussels, 3.12.2020.

1.4.2. Healthcare sector-specific initiatives

Relevant initiatives, regulations and policy actions

The use of XR technologies in the healthcare sector is still at a fairly early stage in Europe. However, significant momentum is developing within the sector.

With regard to policy, the use of XR in health is at least partly coordinated by the Directorate-General for Communications Networks, Content and Technology, unit H.3 – eHealth, Well-Being and Ageing. Some initiatives have implicitly[194] relate to the use of XR in health. The first is the **eHealth Action Plan 2012-2020**[195]**,** which emphasised the importance of digital technologies (although without explicitly mentioning XR or wearables) for future healthcare. Also, the new **EU4Health 2021-2027 Programme** places an emphasis on strengthening digital tools and services as well as the digital transformation of healthcare, but does not explicitly mention XR either.[196] Another example is that after a public consultation in 2017, the European Commission confirmed that one of the three priorities of the Digital Transformation of Health and Care in the Digital Single Market is "citizen/patient empowerment with digital tools for user feedback and person-centred care"[197]. This ambition has been reconfirmed with the launch of a new instrument, the **Digital Europe Programme**. Between 2021 and 2027, the European Union will invest EUR 7.5 billion to address several key digital challenges, including (e)healthcare and citizen empowerment[198].

In addition, **EIT Health**[199] is dedicated to accelerating the modernisation of healthcare systems across Europe. This includes supporting European healthtech and medtech start-ups and entrepreneurs that incorporate XR. These funds also go towards helping develop new and innovative products and services, educating people about health and innovation, and coordinating a network of approximately 150 organisations.

The reason for this lack of explicit references to XR in health care may be because XR only started to develop at a faster pace in Europe around 2012. Until then, these technologies were usually restricted to research groups at universities. In particular, commercially available VR applications have only been part of large scientific trials in the last 6-7 years. However, recent literature shows that XR hardware is becoming more affordable in healthcare[200] and as discussed, the EU is starting to fund more initiatives and calls that incorporate XR and technology in healthcare. Thus, it is important to synthesise new knowledge to assist policymakers in understanding the huge potential of these technologies in relation to health.

At present, EU regulations currently do not explicitly cover XR. In a 2016 answer to the European Parliament, the European Commission noted that it did not plan to develop new legislation to address XR technologies separately [201]. Rather, the concept of XR is used in the broader context of digital technologies in the EU.

The most relevant regulation is the **Medical Devices Regulation** (Regulation (EU) 2017/745[202]), which governs market access to the EU. Manufacturers can place a **CE (Conformité Européenne) mark** on a medical device once it has passed a conformity

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[194] The initiatives cited and others often do not explicitly mention the use of XR technologies, although their use is implied by the concept of digital health and care itself (see: https://ec.europa.eu/health/ehealth/home_en).
[195] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012DC0736&from=EN
[196] https://ec.europa.eu/health/funding/eu4health_en
[197] https://digital-strategy.ec.europa.eu/en/policies/ehealth
[198] https://digital-strategy.ec.europa.eu/en/library/digital-europe-programme-proposed-eu75-billion-funding-2021-2027
[199] https://eithealth.eu/
[200] digitalhealth 2020, Augmented reality predicted to edge out VR in healthcare stakes, augmented reality (AR)/virtual reality (VR), News, viewed 15 September 2021.
[201] https://www.europarl.europa.eu/doceo/document/E-8-2016-003417-ASW_EN.html
[202] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R0745

assessment, which evaluates the efficacy and safety of the device. The revised regulation[203], which came into force in May 2021, establishes new definitions and obligations and imposes stricter requirements on market participants, including a stronger emphasis on clinical evidence. This may place significant costs on companies that produce XR devices and software intended for diagnosis and treatment.

On the other hand, the EU is seeking ways to strengthen EU cooperation on **health technology assessment[204].** This will influence national decisions regarding the reimbursement of medicines or medical devices by national health insurance schemes. Examples of such health technologies may include XR-based medical devices, diagnostic and treatment methods, as well as rehabilitation and prevention methods. The new rules foresee that the EU Member States may conduct joint clinical assessments and scientific consultations, as well as joining forces in the identification of emerging health technologies. The proposed measures should reduce the administrative burden, especially on smaller companies, and should make innovative health technologies available to patients more quickly.[205]

At national level, no government initiatives in the healthcare sector have been identified that specifically target XR. Stakeholders seek funding for XR projects in the healthcare sector through initiatives supporting business, technology development, research and innovation in general[206]. However, some initiatives by stakeholders were identified. An example of such an initiative in the healthcare sector is VR4Rehab. VR4Rehab is an open innovation network facilitating collaboration, linking ideas and exchanging knowledge between businesses, researchers, clinicians and patients[207]. In this way, the initiative aims to stimulate the creation of VR-based rehabilitation tools. The creation of VR4Rehab was funded by the Interreg North-West Europe Programme[208].

As mentioned in the section on barriers to XR, fragmented health care systems and different reimbursement procedures across Europe make it difficult for digital health service providers to sell their products to hospitals. To simplify this situation and increase the digitalisation of healthcare, **Germany introduced DiGa (legislation and a set of rules for healthcare)** in 2019[209]. DiGa offers digital healthcare providers (including those based outside of Germany) the opportunity to apply to be added to the country's digital healthcare applications directory. Once added to this directory, a digital healthcare application may be prescribed by doctors, and the costs incurred by patients to use the application are compensated by the German healthcare system. The application process is overseen by the German Federal Institute for Drugs and Medical Devices. is the process is designed to provide a fast track, with applications being reviewed in as little as three months.[210] One industry representative interviewed mentioned that DiGa was a very positive step in simplifying digital healthcare reimbursements. **Belgium** has followed Germany, launching its own digital healthcare application reimbursement system called mHealth Validation Pyramid to assess the quality and effectiveness of digital healthcare applications (Chawla, 2022). **France** has also developed a framework similar to Germany's DiGa, and is expected to launch it some time in 2022 (Chawla, 2022). In addition, representatives of **Italy, the Netherlands, Austria, Finland, Ireland, Luxembourg, Sweden, Denmark, Switzerland and Estonia** have expressed interest in implementing a standardised reimbursement process for digital healthcare applications (Chawla, 2022).

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[203] https://eur-lex.europa.eu/eli/reg/2020/561/oj
[204] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52018PC0051
[205] https://www.consilium.europa.eu/en/press/press-releases/2021/11/09/council-green-lights-new-rules-on-health-technology-assessment-improving-access-to-medicines-and-simplifying-procedures/
[206] Based on interviews with different stakeholders and desk research aiming to identify these initiatives at the national level.
[207] https://vr4rehab.org/
[208] https://www.nweurope.eu/projects/project-search/vr4rehab-virtual-reality-for-rehabilitation/
[209] https://www.bfarm.de/SharedDocs/Downloads/DE/Service/Beratungsverfahren/DiGA-Leitfaden.pdf?__blob=publicationFile&v=8; https://www.bfarm.de/DE/Medizinprodukte/Aufgaben/DiGA/_node.html
[210] https://vertrical.com/what-is-diga; https://www.healthxl.com/blog/the-role-of-diga-in-your-go-to-market-strategy-for-germany

Another concern is governance of health data. Although the EU introduced the General Data Protection Regulation (GDPR), the regulatory landscape with regard to processing data concerning individuals' health remains uncohesive (e.g. legal requirements differ between data types and purposes of use and data is collected in different ways, leading to conceptually different values being recorded under the same term) (Vayena, 2021). In 2020, the European Commission announced its commitment to establish the **European Health Data Space**[211], with the aim of facilitating access and use of European health data and generating value for European healthcare systems, policy, health research and innovation. Since XR devices (especially those involving body movement, eye tracking, biofeedback, etc.) can collect large amounts of personal data, it will be critical to promote the safety, interoperability and ethical use of data.

Public procurements in the healthcare sector

We have identified 15 public procurements of XR technology in the healthcare sector published from 2017 to 2022 March.[212] This is significantly lower number of procurements compared with the education sector (see Section 1.4.3). Procurements in the health sector were identified in five EU Member States and in the UK[213]. Seven of these procurements were solely concerned with XR, while in the other eight, XR formed only part of the procurement. Five of the procurements were not health-related, even though they were procured by organisations working in the healthcare sector. For example, these included XR equipment procured for the purpose of a healthy office campaign, and communication services using XR. The remaining 10 procurements were directly related to XR application in healthcare, and included the purchase of the following:

- Platform/software for XR training and simulations for medical students in universities and medical personnel (5 procurements)
- Virtual reality simulator for ophthalmology (1 procurement)
- Equipment for viewing and mapping 3D maps in virtual reality (1 procurement)
- VR and AR headsets for medical diagnosis (1 procurement)
- Procurement of microscopes that can be integrated with XR (2 procurements)

Nine different institutions in the EU[214] made the XR-related procurements mentioned above. These included three university hospitals, two public health insurance companies, two national/regional authorities, a non-profit association, and a public healthcare establishment.

1.4.3. Education sector-specific initiatives

Relevant initiatives, regulations and policy actions

Member States have adopted different views on XR-related education initiatives and policies. The majority of government officials interviewed note that XR is not on the priority list of regulations, but rather as part of the broader digitalisation strategy of the education sector, i.e. as part of EdTech transformation. For example, one policymaker from Austria highlighted that the country focuses on the development of e-learning platforms and open resource repositories for teaching and learning, but does not pay additional attention to the promotion of XR. The same interviewee also expressed doubts that the uptake of XR in K-12 would increase due to financial constraints and concerns over cost-effectiveness.

[211] https://ec.europa.eu/health/ehealth/dataspace_en
[212] Based on data extracted from Tenders Electronic Daily (TED).
[213] Germany (6), Hungary (1), Poland (1), Spain (2), Sweden (1) and United Kingdom (4)
[214] Three in the UK.

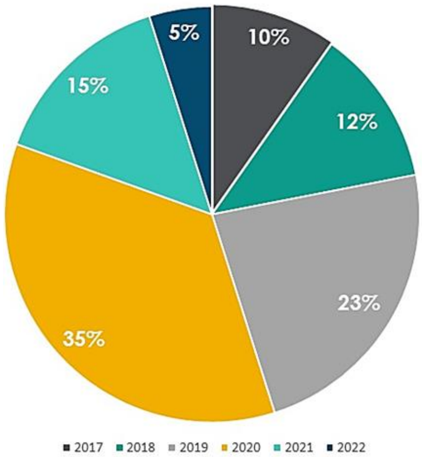
Representatives from Estonia and Finland, on the other hand, took a different approach. For example, an interviewee representing Finland mentioned that they see many opportunities to include XR in education and training. According to them, this approach is exemplified by policy debates to create a national strategy for the use of digital technologies in education, as well as Finnish public funding opportunities available for XR developers or schools that wish to implement XR tools. Similarly, a policymaker from Estonia highlighted that the country is expanding its cooperation with EdTech providers, including the use of XR, and preparing the market and education ecosystem for the future adoption of new technologies.

Nevertheless, while Finland and Estonia can be seen as good examples of governments paying more attention to the need to regulate and incorporate new technologies into education, desk research and interviews with policymakers show that, for now, most EU countries are focusing on general digitalisation strategies and initiatives.

Public procurements in the education sector

We have identified 82 relevant XR-related procurements published in the education sector between October 2017 and February 2022.[215] Relevant procurements were identified in 16 EU Member States, as well as Norway and the UK. Most of these were made in 2020, followed by 2019, while a slump was encountered during 2021-2022. The total value of procurements reflects this, coming in at more than EUR 2 billion.

Figure 8. A pie chart showing procurements by year (N=82)



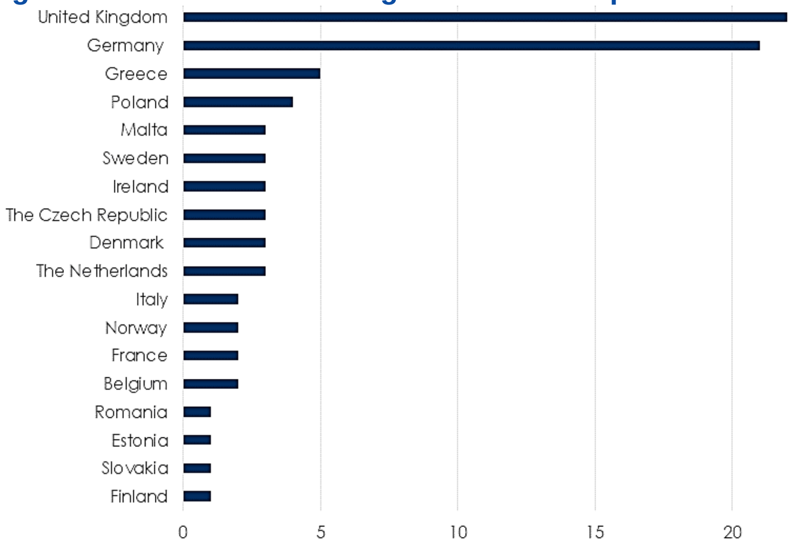
Source: Visionary Analytics, 2022

The majority of procurements (54) were solely concerned with XR, while in 28 XR represented only part of the procurement. In these cases, procurements aimed to modernise the educational environment and teachers' workplaces by through the purchasing and deployment of XR tools in combination with other software and equipment for the 'digital classroom', 3D printers, robotics, e-learning infrastructures, AI-based software, and others.

Within the EU, Germany was by far the largest procurer of XR-related devices and services, making five times as many procurements as Finland, Slovakia, Estonia, or Romania, and exceeded only by the United Kingdom, as seen in the figure below.

[215] Based on data extracted from Tenders Electronic Daily (TED).

Figure 9. A bar chart showing the number of procurements by country



Source: Visionary Analytics, 2022

Furthermore, almost all procurements were made by public organisations, i.e. public bodies governed by law such as ministries, municipalities and universities (51), national or local authorities and agencies (15), public universities (5), educational institutions (3), educational centres (2), public corporations (2), non-profit organisations (1). Meanwhile, only a few procurements were made by private organisations.[216]

Independent of the type of contracting authority, all procurements were intended for the purchase of XR-based devices and services for use in the field of education. More specifically, they consisted of:

- **Electronic equipment and supplies for XR-based training** for students and personnel (including audio-visual equipment, scanners, glasses, robots, optical instruments, scientific installations, machine tools) (approximately 56 procurements, or 68%);
- **Services required for the implementation of XR-based training** for students and personnel (including research services, education and training services, e-learning services, IT services, hardware installation services, soft-ware related services) (approximately 26 procurements, or 32%).

An example of a procurement for services and resources relating to an XR project by a university is provided in the box below, based on an interview with Dr Eleni Mangina, who was involved in the procurement:

A closer look at an XR procurement case in the education sector: the ARETE project

The Augmented Reality Interactive Educational System (ARETE) project aims to support pan-European efforts in the field of interactive technologies in industry and academia through multi-user interactions within AR technologies, evaluated in educational settings in both professional and private contexts. The main objective of ARETE is to establish a sustainable, competitive ecosystem of European technology and solution providers for AR interactive technologies through a targeted community engagement process in education, deployed, demonstrated, and evaluated across Europe via three pilot studies (English literacy skills, STEM and PBIS (Positive Behaviour Interventions and Supports)).

[216] Such as Tilburg University, CCC-BTP, and saz – the Schweriner Aus- und Weiterbildungszentrum e. V.

The project is funded under the Horizon 2020 programme. University College Dublin (UCD) coordinates the project, while the Open University leads the standardisation tasks.

As part of the project, the contracting authority, University College Dublin, issued a call for tenders entitled 'Provision of CEN Workshop and Secretariat Services for Augmented Reality Interactive Educational System Project (ARETE)' between 30 September 2019 and 19 October 2019. The call for tenders was aimed at national standardisation bodies (NSBs) for the provision of services and resources to lead a series of workshops and to provide secretariat services for their implementation. The activities expected to be undertaken by the selected NSB were categorised into the following four groups: i) pre-workshop establishment; ii) during the development of the CEN Workshop Agreement (CWA); iii) post-CWA; and iv) horizontal aspects for the duration of ARETE.

The total value of the procurement (excluding VAT) was EUR 85,000.00

The total value of the contract/lot (excluding VAT) was EUR 29,605.00

Two proposals were received, and the contractor that won the issued tender was the Spanish Association for Standardisation (Asociacion Espanola de Normalizacion, UNE). The project began in September 2021, and will run until April 2023. During this time, the CEN Workshop on 'eXtended Reality (XR) for Learning and Performance Augmentation' will take place.

The objective of the workshop is to elaborate the CWA ‘eXtended Reality (XR) for Learning and Performance Augmentation – Methodology, techniques, and data formats’. This aims to draw up a comprehensive set of specifications relevant to the creation, delivery and deployment of XR learning experiences, including proposals relating to the sharing of XR-enriched learning activities and 3D augmented reality learning objects.

The planned CWA is intended to be used by:

- Educational providers, to establish targets for the XR learning content services provided and to boost the resilience of XR learning and performance augmentation infrastructure, ensuring that there is a complete and systematic way to set up a service for teaching and learning any time, anywhere using 3D experiences.
- Educational managers, intermediaries and regulators (such as departments of education at Member State level, educational infrastructure providers, school systems), to systematically identify appropriate enhancing actions and ensure the effective allocation of digital learning resources for the provision of education any time, anywhere.
- Investors, to properly allocate resources to 3D content infrastructure.

Source: Visionary Analytics, 2022, based on stakeholder interview and project tender document, available at: https://ted.europa.eu/udl?uri=TED:NOTICE:85735-2020:TEXT:EN:HTML&src=0; the ARETE project (n.d.), https://www.areteproject.eu/project/

1.5. Research gaps

This section presents an outline of the current research gaps in the health and education sectors. These gaps will be presented in a general (i.e. cross-cutting) fashion, as well as (where possible) in specific areas of XR application.

First, although XR technologies are still in the early stages of development, XR is increasingly gaining traction in **health-related research**. Figure 10 below illustrates the rapid growth of XR-related academic publications over the past decade. Out of 19,841 publications found on *PubMed,* 1,839 were categorised as clinical trials.

Similarly, XR technologies are increasingly gaining traction in **education-related research**. Figure 11 below indicates the annual growth in publications and citations related to XR application in education (with the exception for 2021). While the leading countries in research investigating the application of XR in education are the US and the UK, since 2015 an increasing number of EU MSs have begun to pay attention to this topic, such as

Germany, Italy, Spain and France, and have thus become the EU leaders in XR research in this field (Guo et al., 2021).

However, despite the growing number of publications on the application of XR in the healthcare and education sectors, a number of research gaps remain (see Table 3 below for details).

Figure 10. Number of XR-related academic publications on PubMed (2000-2021)

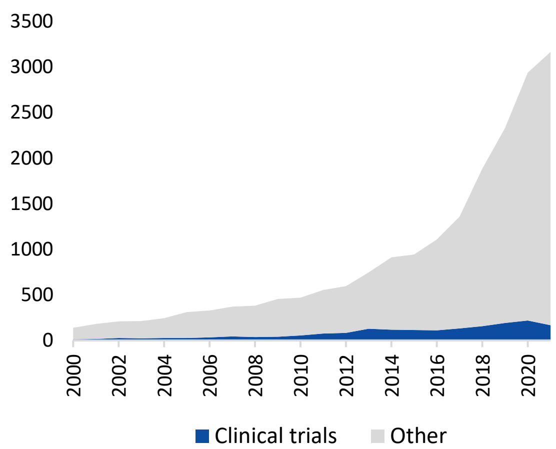
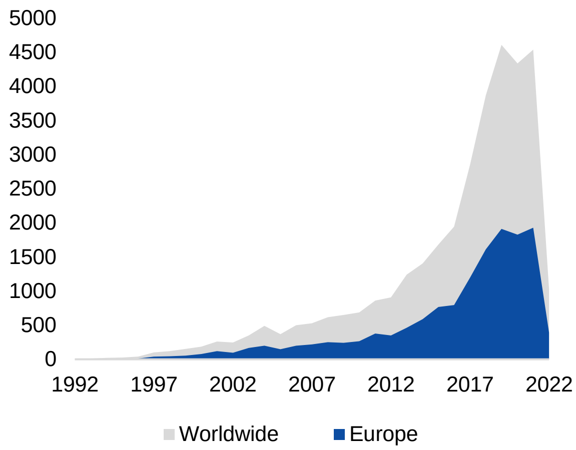


Figure 11. Number of publications in education-related XR research (1992-2022)



Note: Keywords searched: “(virtual reality) OR (augmented reality) OR (mixed reality)”.
Source: Visionary Analytics, 2022, based on EBSCO keyword search.

Table 3. Research gaps per sector and their examples

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
Absence of large-scale and longitudinal research *(cross-sectoral)*	Health	Learning in healthcare	More data are needed to demonstrate behavioural change in comparison to other training modes in "real life" settings (e.g. doctors may feel more able to say no to an avatar during training in a virtual environment than to a real person) (Fertleman et al., 2018).
		Rehabilitation and cognitive enhancement	More large-scale comparative studies need to be assessed that involve other types of rehabilitation therapies (such as robots and treadmills), as well as studies on the synergistic effects of simultaneous treatment with other therapies, the degree of improvement with different therapeutic doses, long-term effects after treatment, etc. (Ku & Kang, 2018). Diverse AR systems are being evaluated in limited small, one-site studies, some of which are pilot studies or involve healthy participants (Gorman & Gustafsson, 2020).
		Treatment and therapies for patients with mental health problems	Further research is needed to compare VR CBT with standard therapy in terms of treatment effects and cost-effectiveness in the long term (Pot-Kolder et al., 2018). Furthermore, current studies have a high risk of bias (due to small samples, poor selection procedures, etc.). Future studies should also consider the inclusion of follow-up assessments, since mental health issues (such as depression) have a high risk of recurrence (Fernández-Alvarez et al., 2021). Lastly, current studies use different types of VR equipment and different treatment protocols due to a lack of standardisation (Ma et al., 2021). This makes comparisons between different studies difficult.
		Pain management	Evidence for the impact of VR analgesia on chronic pain Is under-investigated, compared with its impacts on acute pain. More research is needed to support the long-term benefits of using VR to manage pain, particularly chronic pain (Ahmadpour et al., 2019).
		Surgery	Most accuracy tests include a low number of subjects and/or measurements, and do not normally explore how these systems affect surgery times and success rates (Pérez-Pachón et al., 2020).
	Education	Cross-cutting	Existing studies are based on a small number of participants, so the generalisation of findings regarding the impact of XR on the learning process is limited. Moreover, the brief time span of studies does not allow the investigation of the long-term impacts on students of XR use (Adam, 2019; Boel et al., 2021; Quintero et al., 2019).

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
			Main limitations are small sample sizes (often only a single subject is included) or the need for internet connectivity, given that such services may be deficient or do not exist for certain populations. Most studies have used small samples of 10 individuals or fewer, while a few have included 11 participants or more (Quintero et al., 2019). Most studies have not considered extending the time spent on testing and evaluating, nor extending research to scenarios other than those initially used (ibid.). Specifically with regard to VR in learning and training, research directions such as stepping away from lab-controlled research designs and diversifying research samples are important (Boel et al., 2021).
Insufficient research on sensory augmentation[217] and neurophysiologic changes *(cross-sectoral)*	Health	Treatment and therapies for patients with mental health problems	Though more broadly used for anxiety, stress, trauma and burnout, biofeedback[218] and neurofeedback[219] have not been used as often in the treatment of depression. These modalities may become relevant complementary strategies for the treatment of depression, but the effectiveness of such techniques has received mixed results so far (Fernández-Alvarez et al., 2021).
		Rehabilitation and cognitive enhancement	Providing force or tactile feedback and heat sensation could produce highly authentic VR experiences, and could promote functional and neurological recovery (Ku & Kang, 2018). Visual and auditory stimuli are not always sufficient to create a truly immersive experience; therefore HMDs could be combined with tactile stimuli (e.g. if the patient is not performing the exercise correctly, the device could induce specific vibrotactile stimuli on the body) (Cerritelli et al., 2021).

[217] **Sensory augmentation** – augmentation of the body's sensory apparatus with the aim of extending the body's ability to sense aspects of the environment or body that are not normally perceivable (e.g. skin temperature, muscle tension, sweat level).
[218] **Biofeedback** describes physiological signals from the human body (e.g. breathing, heart rate, sweat, muscle movement and tension, skin temperature) collected via special sensors.
[219] **Neurofeedback** is biofeedback received by measuring brain waves and providing a feedback signal.

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
		Pain management	Skill-building techniques using VR and biofeedback for those suffering from chronic pain could potentially improve patient self-efficacy in pain management (Ahmadpour et al., 2019).
		Cross-cutting	XR devices enable accurate patient monitoring (using data from the virtual environment, head or limb movement, bio-signal sensors, etc.). There are opportunities to analyse these data sources and use them to better understand patients and design more user-centred XR applications. However, data privacy should be fully ensured when using such data. Distributed web and/or blockchain could help to better ensure data privacy.
	Education	Cross-cutting	Insufficient research has been carried out to investigate the impact of XR use on students' health. For instance, it is known that the use of XR tools (e.g. glasses and headsets) can have negative side effects such as causing anxiety, nausea and eye strain (Kirsch, 2019). However, it is not clear what the likelihood is of encountering these negative impacts.
		Physical training	Research to investigate the impact on students' physical state of XR use in physical education is limited, due to the complexity of such activities (Ali et al., 2017), as well as the necessity for accurate equipment to track authentic students' movements, and to analyse huge amounts of data (Jensen & Konradsen, 2018; Tang, 2021).
Insufficient focus on potentially negative effects on vulnerable groups and on ethical considerations *(cross-sectoral)*	Health	Cross-cutting	Potential negative effects and ethical considerations of the use of XR should be better investigated (ANSES, 2021; Suh & Prophet, 2018). Furthermore, many ethical issues may arise as the adoption of immersive systems becomes more widespread (e.g. realistic VR avatars of children could be used to treat paedophilia, leading to questions over to what extent the same moral norms should be applied in virtual reality as in the real-world, etc.) (Slater, 2021).
	Education	Cross-cutting	No approved code of conduct exists for researchers, content creators and distributors of XR solutions in terms of ethical issues and potentially traumatic experiences. In addition, further ethical issues may arise as the adoption of immersive systems becomes more widespread (Slater, 2021). Due to the lack of longitudinal investigations, it is impossible to know if XR technologies may really help children with ASD to improve social interactions or emotion recognition over time and in different

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
			developmental contexts (Berenguer et al., 2020). Also, it is unclear how XR tools affect the health and psychological condition of vulnerable students in the long term. According to one interviewee, the lack of impact assessment studies analysing the effects of XR-driven tools on vulnerable groups, reduces opportunities to identify good practices and improve tools to achieve higher learning outcomes and stronger positive effects (meanwhile, reducing negative effects). According to Garzon, Pavon and Baldris (2019), it is important to recognise diversity in educational settings and address diversity through AR applications. Hence, it is important that stakeholders begin to take into account the criteria provided by the W3C Web Accessibility Initiative (WAI) accessibility standards/guidelines.
Human relations with avatars	Health	Cross-cutting	The therapist avatar or virtual coach could elicit feelings of aversion if it closely-but-not-exactly resembles a human. More research is required to confirm if a feeling of avoidance is likely to occur, especially in cases of chronic pain management, where sources of stress, anxiety or fear should be kept to a minimum (Cerritelli et al., 2021).
Limited research on integrating XR with AI and machine learning	Health	XR-assisted analysis and diagnosis	An augmented reality microscope could overlay AI-based information on to the current view of the sample in real time, potentially improving the accuracy and efficiency of cancer diagnosis (Chen et al., 2019).
		Assistance for persons with physical disabilities	For visually impaired persons, a combination of AI, the Internet of Things and XR could be used to improve navigation in public areas, transportation systems and home systems (Sobnath et al., 2020).
		Cross-cutting	AI can help to interpret the large amount of data collected via XR devices, for example by performing automatic skill evaluations on learners or patients. In addition, AI can confer intelligence on XR systems by creating interactions that are personalised for different types of users. Lastly, simulated XR

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
			environments can provide a large amount of data to train machine learning algorithms for specific tasks (Reiners et al., 2021).
Lack of case studies on new affordances; only limited research dedicated to domains other than STEM	Education	Engineering/manufacturing/construction	Engineering, manufacturing and construction training are the least researched application areas for XR technologies (Quintero et al., 2019).
		Physical training	There is a lack of studies relating to applications of XR in physical training at educational institutions and the opportunities for immersive technologies to change physical training in a modern way (Calabuig-Moreno et al., 2020).
Lack of research on the application of XR in primary education	Education	Collaboration	There is a lack of research investigating how XR-based collaboration platforms (e.g. virtual laboratories, virtual learning environments) are used in primary education (Greenwald et al., 2017, Ke, 2016) and VET.
		Soft-skills development	There is a lack of research investigating how XR technologies are applied in primary education and VET to develop students' soft skills (Carlton, 2018).
Lack of research on the application of XR in vocational education and training (VET)	Education	Cross-cutting	The effects of XR on VET training should be explored in the future (especially in practical training/apprenticeship) (Quintero et al., 2019).
Lack of research investigating the impact of XR use on students' psychological health,	Education	Procedural development	There is a lack of research on how students' emotional state and/or further behaviour is affected by XR-based simulators (e.g. aeroplanes, ships) and virtual emergency scenarios (e.g. plane or ship crashes, fire, terrorist attacks or wars, including emergency images of blood or dead people).
		Cross-cutting	There is a lack of research investigating the long-term side effects of XR on emotional, cognitive and behavioural changes among trainees (Martin-Gutiérrez et al., 2017).

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
including motivation and behavioural changes		Raising awareness	There is a lack of research on whether and how VR-based intergroup interactions with outgroup members, which are presented by avatars, increase trainees' empathy (Tassinari et al., 2022) towards different parts of society, e.g. minority groups, people with cognitive or physical disabilities.
Lack of research investigating the impact of XR application on students' learning performance	Education	Cross-cutting	There is a substantial lack of empirical evidence concerning the efficacy and implementation of XR in higher education (Jamah et al., 2020). Its results on secondary students' learning attitudes and effectiveness are positive, but research on university students is lacking (Tang et al., 2020, Kuleto et al., 2021). Prior literature has not emphasised the direct relationship between the features of immersive systems and user performance (e.g. learning effectiveness, learning engagement and intention to use (Prophet, 2018)).
		Collaboration	There is a lack of research on how online communication and feedback provided virtually affect students' progress and motivation (Carlton, 2018).
		Procedural training	There is a lack of studies assessing the effectiveness of the use of VR-based flight simulator technology as a training tool for pilots (Labedan et al., 2018).
		Visualisation	According to the literature, visualisation technologies have the potential to improve students' learning outcomes. However, insufficient investigations have been carried out on whether and how visualisation tools could be advantageous to learners (Ryoo et al., 2018).
Lack of research on XR integration in the natural setting of a classroom	Education	Cross-cutting	Research on XR application in actual classrooms, as well as its benefits and difficulties, is limited (Southgate, 2018). Such research is crucial not only to ascertain technical, safety and pedagogical issues, given the insufficient supply of XR devices and insufficient computer literacy in VR of teachers, but also to understand which are best frameworks in which to use XR tools for learning.
Lack of research on addressing data	Education	Cross-cutting	Existing research is insufficient to fully assess how often educational institutions face data protection issues when using XR tools in the education process, as well as what dangers exist and what the possible solutions could be (Southgate, 2019).

Gap in research	Sector covered	Application areas where it dominates	Concrete examples
protection issues in XR use		Collaboration	There has been a lack of investigations into potential security concerns regarding collaborative mixed reality applications (Happa et al., 2019). There is therefore not enough knowledge about cyber-security risks, vulnerabilities, potential social and economic effects and personal harm to users.
Lack of research investigating the negative impacts of XR use	Education	Cross-cutting	Existing research has mostly focused on the benefits of XR application; meanwhile, the negative impact and barriers are rarely discussed. Therefore, it is not entirely clear what are key challenges to the application of XR technologies in the education process, and what solutions could solve these. Also, it is unclear in what circumstances a traditional learning approach may be more advantageous than XR-based learning.
Absence of research on the economic impact of XR use in education	Education	Cross-cutting	Non-US-focused studies such as cost-benefit analyses or economic assessments of the adoption of XR technologies in the field of education and training are not yet available.

Source: Visionary Analytics, 2022.

2. Analysis of the European XR market

The objective of this chapter is to provide an overview of the landscape of the European XR market. This chapter looks at the market size, an analysis of different market segments by vertical market breakdowns, as well as providing a qualitative overview of the direct economic impacts in different EU XR market segments.

To complement existing analyses of the European XR market (Ecorys, 2021, 2022), this chapter will:

- Present the current situation and a forecast regarding the potential of the European XR market and expectations in the short and medium term.
- Focus on vertical market breakdown by roles in the value network for XR. The analysis presents the European players, their types and business models in each of these vertical market segments.
- Supplement the analysis with selected case studies of European XR companies across different vertical market segments, to illustrate the different types and business models of European players in XR.
- Provide an overview of technological standards directly related to the XR experience.

2.1. Current European market size, structure and future projections

The European market for XR can be analysed in both horizontal and vertical dimensions. The horizontal dimension observes how XR technologies are used in different industries, as described in existing analyses of the European XR market (Ecorys, 2021, 2022). This report deliberately takes a vertical look across all user industries, and focuses on the following two aspects of the XR market:

- The overall quantitative evolution of the XR market in Europe, as observed through revenue generated by the providers of hardware, software and services resulting from the XR technologies themselves.
- A vertical breakdown of how XR-related content is produced, and the contributions of various providers in the technology stack.

The forecast for the XR market in Europe is based mainly on the 2022 Market Report by Report Ocean, and is validated against other market forecasts. The Market Report by Report Ocean includes revenue generated by companies providing XR solutions and services in the European market, and provides forward-looking estimates for this revenue. Report Ocean (as all other market reports) includes companies regardless of whether they are headquartered in the EU or outside it. It must be noted that the major XR players generating revenues in Europe are either from the US or Asia (see the following section for more information). The Market Report uses figures on the revenue that is generated by XR in the European market, based on figures published in the companies' annual reports. The latest full-year reports of the companies included have been used[220].

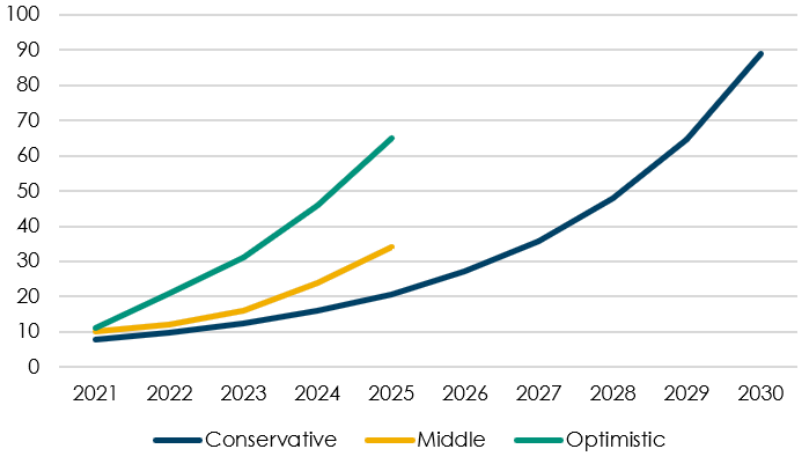
Report Ocean estimates the size of the European XR market in 2021 to be EUR 7.95 billion. This is very much in line with the estimates of other market research forecasts. In terms of growth projections, some differences in expectations exist between different forecasts (see Figure 12 below). The differences between the forecasts are mainly to be found in the compound annual growth rate (CAGR) assumed. When looking across forecasts on a global

[220] This report is based on the 2020 annual reports.

scale, there has been a lowering of expected CAGR in the most recent reports compared with the older reports, i.e. expected CAGR is lower today compared with two years ago.

XR grow could be further boosted by the emergence of the metaverse market. The global XRmarket is forecasted to reach €766 billion, creating employment for 440-860 thousand people by 2025, while the metaverse economy could grow up to around €12 trillion by 2030 (Ecorys, 2022; Deloitte, 2022). In addition, the impact of the metaverse market by 2030 is estimated between $180-270 billion on the academic virtual learning, $2-2.6 trillion on e-commerce, $144-206 billion on the advertising industry, and $108-125 billion on the gaming sector (McKinsey&Company, 2022).

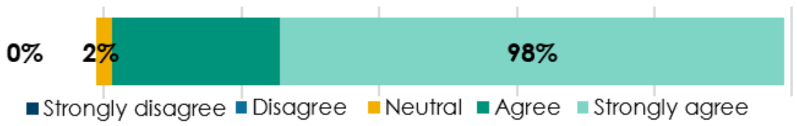
Figure 12. European XR market forecasts in €bn



Note: The forecast termed “Conservative” is based on Report Ocean (2022), whereas the “Middle” and “Optimistic” forecasts have been calculated by Ecorys (2021).
Source: Visionary Analytics, 2022

Stakeholder perceptions about the future of XR industry are in line with the market report forecasts. The survey of XR company representatives and XR researchers/academics shows that almost all respondents (98%) believe that XR technologies will contribute to the significant development of the sector in which the respective respondent works[221] over the next five years (see Figure 13). In addition, more than half of all respondents plan to increase their investments in XR businesses, allocating most of these resources to improving user experiences (see Figure 14).

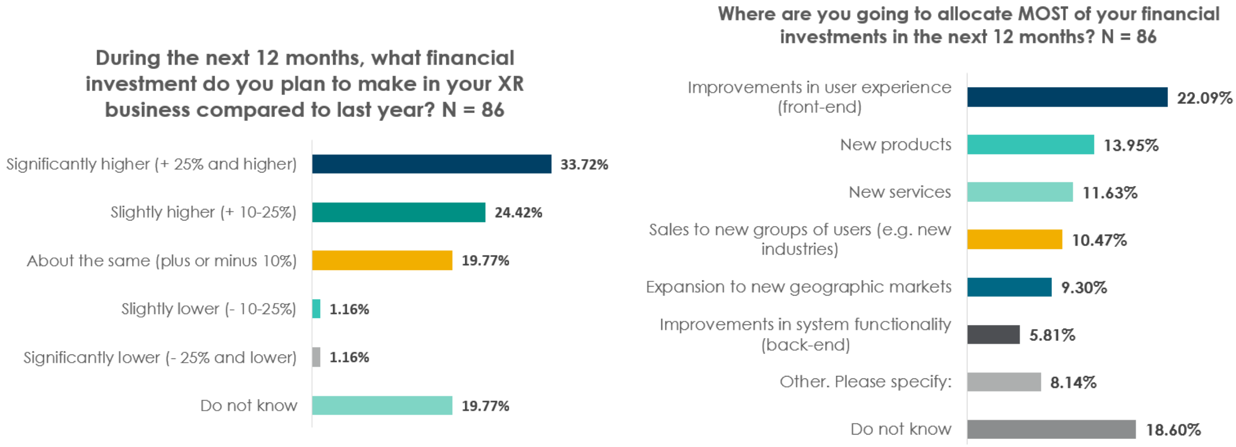
Figure 13. To what extent do you agree with the statement that XR technologies will contribute to the significant development of your sector over the next FIVE years? N=45



Note: The question was asked only to respondents whose work focuses on a specific economic sector.
Source: Visionary Analytics, 2022. XR company representatives and XR researchers/academics survey conducted between 16 11 2021 and 24 01 2022.

[221] 47.3% of all respondents (61) mentioned that their work is not sector-specific and is either horizontal/cross-sectoral in nature and involves several sectors. The sectors the remaining respondents work in are education (36), healthcare (27), manufacturing (12), tourism (11), marketing and advertising (9), gaming (9), movies and television (6), telecommunications (4), military and defence (4), logistics/transportation (4), live events (4), real estate (3), retail (3), and other (13). ‘Other’ includes: art/culture /museums; design and development; human-centred design; documentaries, impact storytelling; accessibility; information technology; architecture and planning; cultural heritage; aerospace; civil engineering and architecture; earth sciences; fashion. Multiple sectors could be selected by a single respondent.

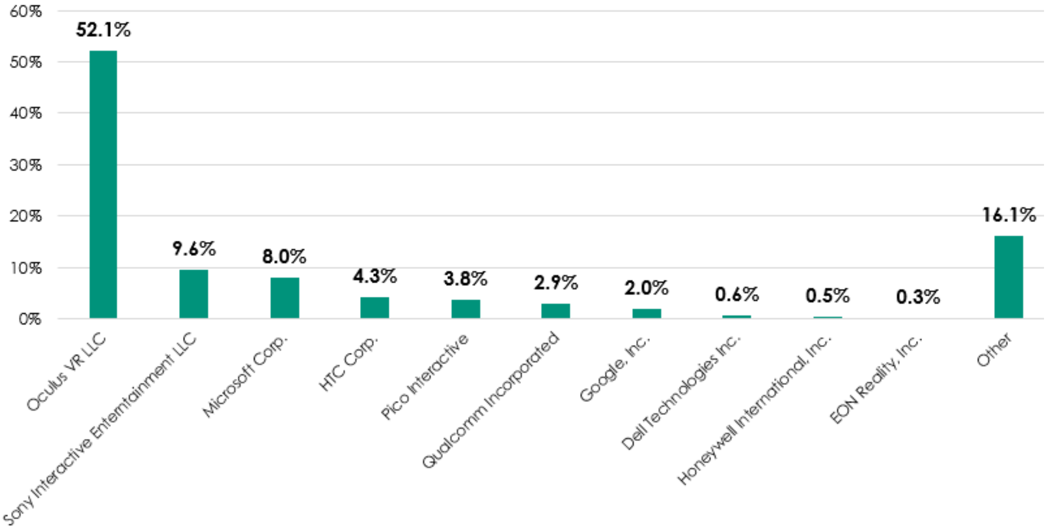
Figure 14. Financial investments that respondents plan to make in their XR business



Note: 'Other' includes events, consulting, educational products, equipment, investing in the community.
Source: Visionary Analytics, 2022. XR company representatives and XR researchers/academics survey conducted between 16 11 2021 and 24 01 2022.

The majority (84%) of the European XR market revenue is generated by the top 10 players, led by Oculus (Meta), Sony and Microsoft. Oculus is by far the market leader with a 52.1% market share, according to Report Ocean. It must be noted that none of the top 10 players are EU-based, as the market is dominated by US and Asian companies (see more details in Figure 15 below).

Figure 15. European XR market size by market player, based on revenue

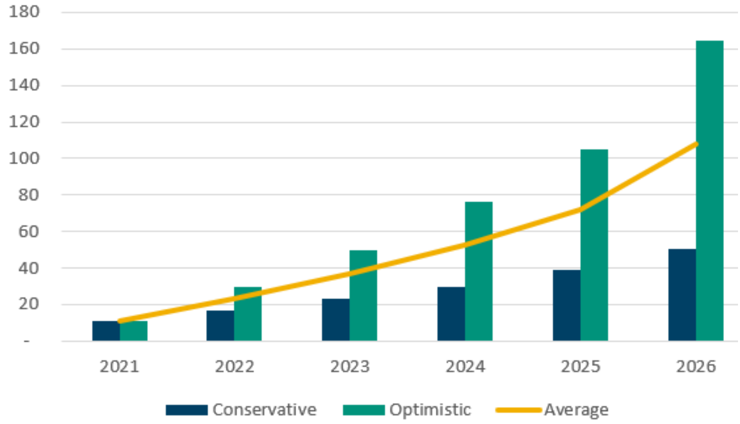


Source: Visionary Analytics, 2022, based on Report Ocean: Europe Extended Reality Market Europe - Industry Dynamics, Market Size and Opportunity Forecast to 2030 (March 2022)

Shipments of XR devices constitute a good indicator of growth expectations for the XR market. They provide a very tangible indicator of the adoption of XR, as users require a set of VR goggles, AR glasses or other XR device in order to experience XR. The projection for global shipments of XR devices provided in Figure 16 below is based on two forecasts[222], and reflects uncertainties with regard to projected growth.

[222] IDC and Counterpoint Research

Figure 16. Global device shipments, in millions of EUR



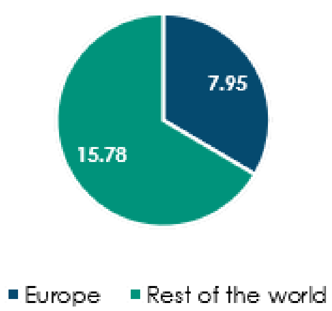
Notes: the 'Conservative' trend is provided by IDC; the optimistic trend by Counterpoint Research.
Source: Visionary Analytics, 2022, based on IDC and Counterpoint Research

The main distinguishing feature in the forecasts is the difference in expected uptake in the consumer segment. IDC, the source of one estimate, projects a compound annual growth rate (CAGR) of 22% in the consumer segment and 50% in the commercial (B2B) segment. This means that expectations of growth in the commercial segment will be more than double those of consumer segments. The forecast by the other source of data on device shipments, Counterpoint Research, is not broken down by consumer and commercial, but projects an overall CAGR of 57%. The consolidated CAGR across consumer and business in IDC is 22%. Thus, the forecast by Counterpoint Research is more optimistic.

2.2. European vs global market

Report Ocean reported the size of the European XR market in 2021 to be EUR 7.95 billion. The equivalent size for the global market shown in Figure 17 is approximately EUR 23.7 billion[223]. This means that Europe as accounts for around one-third of the global market. It must be noted that these estimates are based on revenues generated by companies providing XR solutions and services in the European market, regardless of whether they are headquartered within the EU or outside it. The impact on the European economy, including those proportions of the market that may be attributed as European value-added, is estimated below in Section 2.8.

Figure 17. Rest of world vs. European market size 2021



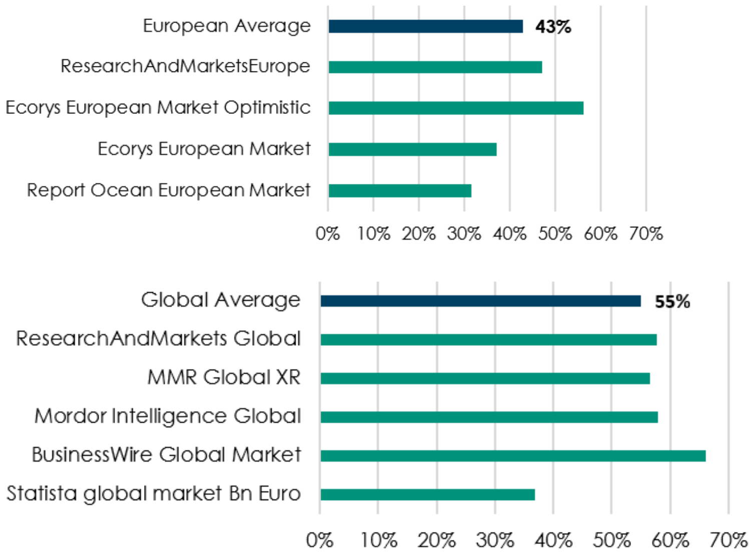
Source: Visionary Analytics, 2022

The usual metric for forecasts is CAGR (compound annual growth rate). A comparison of the European and global XR markets shows an average difference in estimated CAGR of 12% between the global and the European market forecasts (see more details in Figure 18 below). In other words, market research projects higher growth for XR outside Europe.

[223] Source: average, based on multiple market research companies.

However, this difference in growth rate could be related to differences in projections of GDP growth and not differences relating to XR uptake. The differences in CAGR between Europe and global markets correlate with long-term projections for GDP growth[224].

Figure 18. CAGR forecasts for the global and European XR markets



Source: Visionary Analytics, 2022

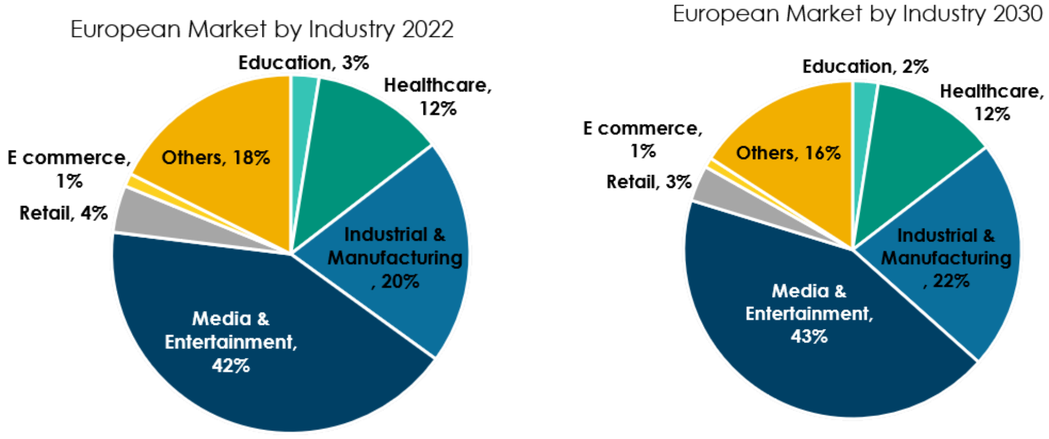
The current market structure observed around the core XR devices is clearly dominated by US and Asian tech companies. Europe hosts a relatively small number of niche manufacturers of XR devices. The largest market potential for EU companies is observed in “content-based services”. This is the area in which most European players operate, and where an understanding of the user context and user preferences through geographical, cultural and linguistic proximity is more important in delivering services than it is in other market segments. Section 2.7 below breaks down the content-based services market in more detail. Section 2.8 provides an assessment of European potential economic impact in different market segments. This assessment confirms that content-based services is the area in which the biggest direct economic impact of XR in Europe is projected.

2.3. European market by industry

Analysis of XR revenue by industry shows that media and entertainment, including gaming, is the largest industry, with a 42% share of the expected XR revenue for 2022. This is followed by industrial and manufacturing. Healthcare comes third with 12% (EUR 1.19 billion), while education offers a potential 3% (EUR 250 million) share of the XR market. The distribution of the XR market between industries is expected to remain relatively stable during the period to 2030 (see Figure 19 for more details).

[224] OECD long term GDP forecast.

Figure 19. European XR market by industry



Source: Visionary Analytics, 2022, based on Report Ocean: Europe Extended Reality Market Europe – Industry Dynamics, Market Size and Opportunity Forecast to 2030 (March 2022)

2.4. European market by geography

This section breaks down the potential size of the market in Europe by country. This breakdown has been produced using available XR market data projections on major EU economies (Germany, France, Spain and Italy), combined with projections on other European countries made using generic ICT indicators available from official statistics (Eurostat data on the size of the ICT sector in each country[225], as well as indicators on the rate of digitalisation in European companies by country (DESI indicator))[226].

Across the Member States, the size of the XR market forecast for 2022 represents an average of 0.7% of the size of the ICT sector. Projections for the XR market by country are presented in the table below. It is important to note that these projections are rough estimates and do not take into account the different pace of development of the ICT and XR industries in each country.

Table 4. Projections of the size of the XR market in each EU country for 2022, 2026 and 2030 (in EUR billions)

Country	2022	2026	2030	Country	2022	2026	2030
Belgium	0.38	1.05	3.48	**Lithuania**	0.03	0.08	0.28
Bulgaria	0.05	0.13	0.42	**Luxembourg**	0.03	0.09	0.31
Czechia	0.28	0.76	2.52	**Hungary**	0.20	0.55	1.81
Denmark	0.26	0.71	2.37	**Malta**	0.04	0.10	0.33
Germany	2.84	8.31	29.25	**Netherlands**	0.60	1.67	5.52
Estonia	0.04	0.10	0.33	**Austria**	0.23	0.63	2.07

[225] The following Eurostat tables were used for the per-EU country forecast breakdown: i) Digital Intensity [ISOC_E_DII__custom_2573677]; ii) Annual enterprise statistics for special aggregates of activities (NACE Rev. 2) [SBS_NA_SCA_R2__custom_2573821]; iii) GDP and main components (output, expenditure and income) [NAMA_10_GDP__custom_2573863].

[226] The per-country breakdown distributes the “other European countries” forecast from Report Ocean by using a weighted distribution of the ICT sector by country. The weight used is the digital intensity indicator. This means that the major assumption underlying this distribution is that it follows the size of the country’s ICT sector in general, and that countries in which companies are more digitalised in general will have a larger XR market potential. To illustrate this weighting, Belgium is responsible for 8.6% of the European ICT sector. Its weighted share is 8.73%, as Belgian companies are above average in terms of digital intensity.

Ireland	0.37	1.01	3.36	**Poland**	0.39	1.08	3.57
Greece	0.08	0.22	0.73	**Portugal**	0.16	0.45	1.50
Spain	0.81	2.17	6.93	**Romania**	0.14	0.39	1.30
France	2.22	6.11	20.15	**Slovenia**	0.03	0.09	0.30
Croatia	0.04	0.10	0.34	**Slovakia**	0.10	0.27	0.90
Italy	1.34	3.65	11.96	**Finland**	0.30	0.81	2.69
Cyprus	0.02	0.06	0.19	**Sweden**	0.57	1.58	5.23
Latvia	0.02	0.05	0.17	**Iceland**	0.01	0.04	0.12

Source: Visionary Analytics, 2022, based on Eurostat data and Report Ocean: Europe Extended Reality Market Europe – Industry Dynamics, Market Size and Opportunity Forecast to 2030 (March 2022)

2.5. Size of the broader XR market and its potential

As mentioned above, Report Ocean estimates the European XR 2021 market to be EUR 7.95 billion. However, it must be noted that the Report Ocean market report (as with all the other market reports) calculates market size on the basis of revenue from sales of XR solutions (i.e. products, software tools and services). Following this approach, estimates of the XR market size focus on those companies generating revenue directly from XR technologies. These XR market estimates exclude revenue from companies that utilise XR technology to improve and/or sell their existing products and services (e.g. a company providing building design services, which adds an option to produce a VR visualisation of a new building). It is challenging to quantitatively estimate the size of the XR market size including such companies (the broader XR market), as it is hard to identify all of those companies utilising XR technology.

This study provides a quantitative estimate of the broader XR market by looking at the example of the Apple ecosystem. The revenue generated by the Apple iPhone platform is split between the 64% of revenue for Apple and the 36% for the providers of apps that run on iPhones.[227] A parallel can be drawn with the XR ecosystem. Apple could be considered a company generating revenue directly from XR technologies. Providers of apps could be considered companies that utilise XR technology. Using the breakdown of the revenue percentages delivered by the Apple ecosystem along with the Report Ocean baseline for the XR market, the estimated size of the broader European XR market in 2021 was EUR 11.8 billion. The broader European market is expected to grow to EUR 140 billion by 2030, of which EUR 51 billion consists of revenue from companies that utilise XR technology. While such estimates based on the Apple ecosystem are highly uncertain; they can, however, provide a rough indication of the size of the broader XR market in Europe.

2.6. Key XR technological standards

A number of standards and standardisation initiatives are important in the XR industry. The major standardisation effort for XR technologies is driven by OpenXR, which provides a common application programming interface (API) for developers of XR content and manufacturers of XR devices. This effort is driven by the Khronos Group[228]. The ambition of OpenXR is to provide a common API that can bridge the universe of XR applications and

[227] For this calculation, we have ignored revenue associated with accessories and focused on the app economy.
[228] The Khronos Group is a not-for-profit, member-funded consortium creating open standards to enable applications to access the power of 3D graphics, virtual and augmented Reality, parallel computing, machine learning and vision processing.

different XR devices. It provides a standard for applications to interact with XR devices. The major device manufacturers now provide an OpenXR API, meaning that app developers can in theory create apps that work with multiple XR devices.

In addition an effort has been made to standardise XR using web standards driven by the “immersive working group[229]” hosted by the W3. A working group is currently developing a number of standards for the use of XR devices on the web (more details in Table 5). In addition, the working group is advancing a number of more detailed standardisation measures (see link in the footnote for more information)[230].

Table 5. Standardisation efforts by the immersive working group of W3

Name	Short Description	Status
WebXR Device API	Describes support for accessing virtual reality (VR) and augmented reality (AR) devices, including sensors and head-mounted displays via the web.	W3C Candidate Recommendation Draft
WebXR Gamepads Module – Level 1	Describes support for accessing button, trigger, thumb stick and touchpad data associated with virtual reality (VR) and augmented reality (AR) devices via the web.	W3C Working Draft
WebXR Augmented Reality Module – Level 1	The WebXR Augmented Reality module expands the WebXR Device API with the functionality available on AR hardware.	W3C Working Draft

Source: Authors’ own elaboration, based on https://www.w3.org/groups/wg/immersive-web.

A number of additional standardisations are relevant to the XR industry, including standards maintained by Web3D in relation to the creation and exchange of 3D visualisations. The first standard published by Web3D was the VRML (Virtual Reality Modelling Language) in 1997, which has since evolved into a number of more detailed standards. Also worth mentioning is an effort to provide a standard way of accessing and representing the physical world in the digital world, and vice versa. OARC (Open AR Cloud) was recently established to create open integration between the physical and digital worlds and thus propose open alternatives to, for example, Google Maps data for AR. The organisation has yet to publish its first work.

2.7. Vertical market breakdown

To understand how XR services and solutions are produced for private and business customers, we have broken down the XR market into the market segments presented in Table 6 below.

Table 6. Typology of the market segments analysed

Market segment	Description
Content-based services	End user experiences produced for specific use cases such as supporting remote surgery or providing a VR gaming experience.

[229] https://www.w3.org/immersive-web/
[230] See the full list here: https://www.w3.org/immersive-web/

Distribution platforms	Platforms involved in distributing content-based services to users. These are not XR-specific, but tap into existing distribution platforms for games such as PlayStation or Steam, as well as generic platforms such as Windows, Android or iOS. However, distribution platforms are emerging that are dedicated to VR/AR, such as Horizon Worlds and the Metaverse from Meta.
Authoring platforms	These platforms are used to author content-based services such as games and are very important for productivity in developing content-based services. These authoring platforms are typically not specific to XR, but are existing authoring platforms that are being extended to support the authoring of XR experiences such as games.
Devices and SDK	The core devices that provide VR/AR experiences to end users. These devices are assembled from procured components and include an SDK (Software Development Kit) that can be used by developers of content-based services. One important role of authoring platforms is that they provide an environment that does not have to be developed specifically to one device but can work across multiple, thus making development for a larger market less costly.
Device components	Components that go into the assembly of XR devices such as special screens and tracking devices that are essential to the functioning of the XR device.

Source: Visionary Analytics, 2022.

Each of these segments are analysed in more detail below, describing the nature of the segments and identifying the major players from a global and European perspective.

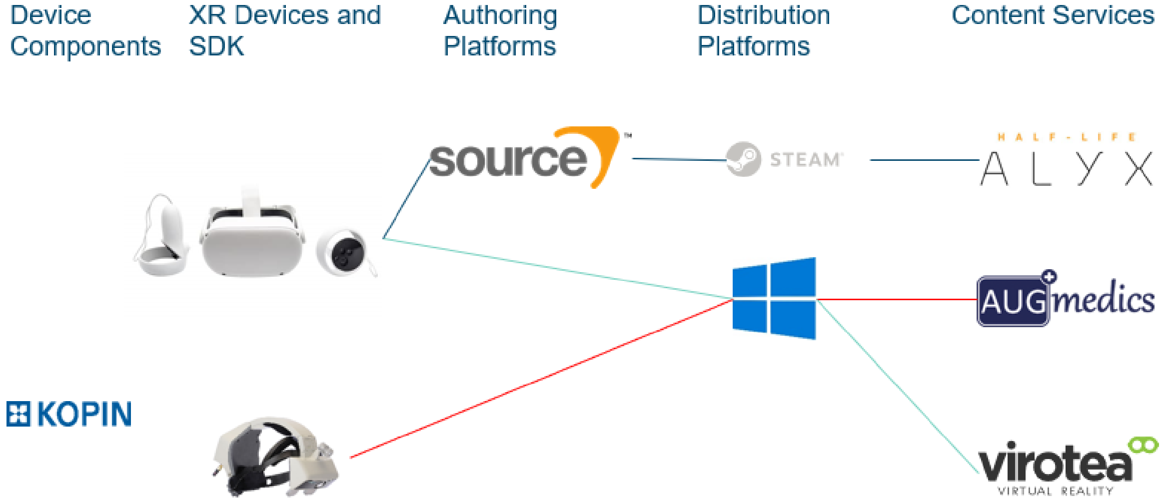
It must be noted that individual players may operate in different markets simultaneously. In addition, market segments are dependent on one another (see Figure 20). Devices and software frameworks (authoring platforms, SDKs) are used to produce specific solutions/experiences that are targeted at specific use cases and industries. The market segments involved are interrelated, and involve certain constraints. Companies providing XR solutions apply different strategies:

- **Creating constraints** by creating contractual or technological bindings. Using standard components for some part of a device or adopting industry standards, while using unique components for a few that are key to its competitive position and are constrained either by contracts or by in-house control. This is not unique to XR, but these generic mechanisms, observable in technology markets, also apply here. A popular strategy is the 'platform strategy', which is clearly also used for XR – most notably in the consumer space. An illustrative example is the Sony PlayStation platform. Sony manages the PlayStation gaming platform (a distribution platform) and produces PlayStation VR goggles designed for playing VR games (devices and SDK). This combination of device and distribution platform leads to a closed ecosystem for games.

- **Removing constraints**. A provider of content-based services can therefore choose to develop something designed for this PlayStation ecosystem. Other players such as the authoring platforms and technology standards (e.g. OpenXR) are countering this by helping content providers to write games that can be used on multiple platforms with little or no extra effort. Two other examples of more open distribution platforms are Steam and Windows. Both of these platforms allow multiple providers of devices and SDKs, as well as multiple authoring platforms, to be used to develop content on their distribution platforms.

The visual below illustrates a number of interconnections and dependencies. As an example, Virotea is a Swedish provider of VR solutions supporting the care of elderly people, which is sold as a service bundle including a VR device from Oculus and a software solution including content that is optimised for the Oculus device and requires a Windows PC. A second example, Augmedics, provides an AR solution to assist surgeons, which is built around the Windows platform and uses a headset developed specifically for this application. A third example is the Alyx Half-Life game, which has been developed as an evolution of the Half-Life gaming universe by the Valve Corporation. The Valve corporation has also built and currently operates the Source authoring platform (SDK) and distribution platform (Steam), which are also used by many other producers of games.

Figure 20. Examples of interconnection between different XR market segments



Source: Visionary Analytics, 2022..

2.7.1. Content-based services

The content-based services market segment covers a multitude of services and solutions that utilise XR technologies. Content-based services are delivered via a multitude of business models that make use of underlying market segments to varying degrees, but always depend on devices and SDKs from one of the XR device manufacturers (see Table 7 below).

In their content-based services, many companies provide not just XR experiences, but use XR technologies to enhance existing services or evolve new services that are related to successful existing ones. For example, organisations providing solutions for remote support of computers have now expanded this service to include remote support models in situations where laptops are not convenient, but a pair of AR glasses can be used to receive guidance remotely and access information in manuals, etc. Business models for content-based services are presented in Table 7 below. Business models are differentiated between those used to service business clients and those for consumers. None of the business models observed for the XR markets are new or unique, but are instead digital business models that are used in other markets such as the smartphone market.

Table 7. Business models used by XR content-based services

Business model	Description
Business models for companies working with business clients	
Subscription service	Providers of various subscription-based services that assume XR devices as a core element of the experience.
System integrator /custom content development	Providers of custom solutions that help to organisations to utilise XR technologies.
Games/simulators on distribution platforms	Providers of professional games/simulations delivered via distribution platforms, where the platform provides marketing, manages payments and supports the practical deployment and execution of the game.
Value-added to existing products and services	Companies that use XR technologies to enhance or improve existing service offerings using XR.
Business models for the consumer segment	
Unit purchase	The consumer procures access to a game, for example.
Subscription service	The consumer pays a monthly or yearly fee.
Freemium (Advertisement)	The software is free to use. The business model is driven by advertising revenue. This model is widely used in the smartphone app economy
Combined platform model	Platforms where providers of games, etc. can make their products available via the distribution platform and receive revenue either from payments by the customer or via advertising revenue. A share of the revenue is paid to the platform.

Source: Visionary Analytics, 2022..

Some examples of European content-based services providers are presented in Table 8 below.

Table 8. Case studies of content-based services in the EU

Anarky Labs

Anarky Labs, a Finnish company founded in 2020, has developed AirHUD, a software package that uses AR to revolutionise the way information is shown to drone pilots, and opens up new prospects for them. Through the use of AR, AirHUD provides drone pilots with useful data (e.g. the distance between an actual drone and a building). AirHUD can be applied to the inspection of wind turbines, oil and gas platforms, search and rescue operations, agricultural mapping, the generation of aerial terrain models for mining businesses, the remote inspection of buildings, as well as surveillance and evaluation, etc.

Currently, only HoloLens 2 is compatible with the software. AirHUD software is accessible to its customers on a subscription basis. The company currently only sells software and does not offer a full package (AR glasses, drone, software).

DC Smarter

DC Smarter is a product developed by FacITFixIT, a German company assisting companies in managing, fixing and solving problems relating to IT. DC Smarter is a piece of software that supports engineers at data centres through the use of AR. The solution is developed specifically for the data centre and telecommunication industries. DC Smarter creates a digital 'twin' of the physical world, and thus augments engineers with the information needed to make better informed decisions. At the same time, the software documents the work carried out by the engineers. The use of DC Smarter reduces human errors and increases efficiency for field engineers, accelerates the training and onboarding of staff and reduces the operational cost of data centre maintenance. The software is compatible with HoloLens 2. DC Smarter software is available to clients on a subscription basis.

Holo-Light

Holo-Light is a company based in Munich and Innsbruck, which offers an XR streaming platform that overcomes the performance limitations of XR hardware devices to create a high-quality engineering space for a range of industries. The company was founded in 2015. The company offers the following products:

- AR3S is a software application created by Holo-Light that is used to work on 3D CAD models using augmented reality. This allows engineers to place CAD designs in the real world and adapt, resize and rotate their work. It facilitates faster concept evaluation and identification of design flaws, thus creating a reliable platform that can be used for design reviews, training and the installation of machines.
- ISAR SDK is an interactive streaming platform that makes it possible to stream AR and VR applications and interact with high-quality visualisations. The capacity to render detailed visuals is often lost when using XR hardware devices such as the HoloLens 2; however, ISAR SDK overcomes these limitations to allow much more accurate evaluation, as well as providing access to external servers and the cloud. This platform has proved to be relevant to many different industries and offers immense potential, such as streaming CT scans and BIM data that would normally be too heavy for mobile devices.

The company has also launched Stylus XR, an AR/MR input device for head-mounted displays compatible with HoloLens 2. It offers the ability to sketch and design fully 3D holograms with precision and accuracy and intuitive interaction. However, this will eventually be outsourced, as the company's core business is software. In addition, the company is developing the platform 'XR Now' to allow companies to host AR/VR apps.

Holo-Light operates in the B2B market and runs on a subscription-based model in which customers pay an annual licence fee to access AR3S and ISAR. Access to cloud resources is available as a paid extra. The company's core markets are the automotive, mechanical engineering, healthcare, aerospace and defence sectors. At the moment, Holo-Light works mainly with engineers and product designers, though it is also open to interacting with other industries. In the short term, the company has no plans to explore the B2C market, although it remains open to this in the long term.

MeKiwi

MeKiwi was founded in Finland in 2014, and specialises in mobile applications. Since then, the company has provided a range of services for organisations such as VR, AR and MR development, graphic and 3D design, B2B training through XR solutions, software and mobile applications, gamification and more. MeKiwi helps companies to design AR platforms such as product catalogues that allow consumers to place virtual items into their own environment or to tell a story by creating an interactive interface, among many other applications. MeKiwi is also the largest XR game developer in Finland.

MeKiwi focuses on the following two lines of business:

- VR gaming and publishing
- B2B XR
    a. Training and simulations in MR and VR
    b. AR campaigns such as marketing applications for AR
    c. Entertainment
    d. Product user guides in AR

These products are created for use with different browsers, devices and operating systems.

Reapse Consulting

REAPSE is a consulting company specialising in AR. It works exclusively for end users of AR technologies. Its objective is to help end users develop and deploy AR solutions within their organisations. This is achieved by identifying the software and hardware that are best suited to the organisation's needs. In addition, REAPSE helps to implement these solutions in the workplace and addresses the constraints that arise from the introduction of AR solutions. In doing so, its goal is to help clients understand which AR solution is best suited to their individual needs, thus saving them time and money. REAPSE operates mainly in the industrial sector, but also works in arts and culture, retail and logistics.

Source: Visionary Analytics, 2022, based on interviews with company employees and information from website.

2.7.2. Distribution platforms

Distribution platforms are those platforms involved in distributing content-based services to users. They provide users with easy access to XR experiences, and user revenue to providers XR games, for example.

Distribution platforms are not XR-specific, but are often existing distribution platforms for games such as PlayStation or Steam, as well as generic platforms such as Windows, Android or iOS. Some specific platforms such Holo-Light have been developed specifically for XR, but link to existing device platforms. In addition, distribution platforms are emerging that are dedicated to VR/AR, such as Horizon Worlds and the Metaverse from Meta. These distribution platforms are still very immature and thus there is still uncertainty surrounding how the design and business models of such platforms will evolve in the future.

The distribution platforms observed are those tied to the consumer market segment. These are largely dominated by global technology players originating in the US, as is the case for the other consumer-oriented distribution platforms such as Google Play or Apple Store. The major global distribution platforms include Steam VR, PlayStation VR, Google Play Store, Apple store and Meta Quest Store. In addition, we identified some EU-based distribution platforms (see the box below). These platforms are niche and very small compared with the main global competitors.

Examples of EU-based XR distribution platforms

Viar360 is a platform that allows users to create interactive VR content based on 360-degree videos. Its intuitive design allows users to create, edit and format their own XR content. The company focuses on the training market in the US.

The platform itself operates on a self-service basis, allowing customers to build immersive training scenarios and training content. It draws on several components:

- Viar360 Stories enables users to create interactive immersive training scenarios with modern learning elements, and to score trainees on their performance. Users may also choose between creating linear or branched scenarios with videos, images, audio, quizzes and questions.
- Viar360 Rooms enables users to host group training sessions. By joining a hosted immersive training session through Viar360 Rooms, users can have full audio communication with the host and with other participants. The host guides you through an immersive training scenario, showing you all the interactions and available transitions.

Viar360 subscribers also enjoy the platform's user management system and analytics, among other features. Viar360 is able to provide specific experiences using XR, such as providing training for fire fighters or using VR to support learning targets.

Viar360 supports and is available on the following VR headsets:

- Oculus (meta)
- Pico

Viar360 qualifies as a distribution platform due to one of the modules on the platform being a distribution module, which allows users to transfer content to different platforms such as Google Play Store, Apple store and Oculus Store. Viar360 can also function as an authoring platform, and some customers use Viar360 solely for this purpose. They take the content they create and add it to their own learning management system (LMS) or another system via which host training. No specific standards for export are used, even though LMS systems often use SCORM, a standardised protocol to track completion.

Source: Visionary Analytics, 2022, based on interview with company employee and websites.

2.7.3. Authoring platforms

Authoring platforms are platforms used to author content-based services such as games. Such platforms focus on developer and engineering productivity. They provide attractive and efficient environments for quickly designing and operating revenue-generating content. They are therefore very important to productivity in the development of content-based services. As with distribution platforms, these authoring platforms are typically not specific to XR, but are existing authoring platforms that are extended to support the authoring of XR experiences such as games.

As with distribution platforms, the major global authoring platforms (e.g. Unity, Unreal, O3DE [the Open 3D Engine], React, Blender) are not EU-based[231]. EU-based platforms are somewhat niche and small compared with global ones. The main EU-based authoring platforms identified are presented in the table 9 below.

Table 9. EU-based authoring platforms identified

Name	Short description
VividWorks	Finland-based VividWorks develops a Visual Configure-Price-Quote (CPQ) technology that provides product customisation using 3D visuals and augmented reality for e-commerce. VividWorks offers four products: 3D Product Configurator, 3D Room Designer, 3D E-Commerce Configurator, and 3D Digital Showroom.
Viar360	Viar is a Slovenian start-up with an office in the United States. It develops virtual reality and augmented reality solutions that empower companies worldwide. Viar360 is a self-service platform that enables the creation of immersive training scenarios and materials. It is an intuitive authoring and publishing tool for interactive virtual reality content based on 360-degree films and photographs.
VRdirect	Based in Germany, VRdirect is a virtual reality platform that enables organisations to build use case-driven VR solutions that complement business processes and deliver concrete business value. Businesses can use the VRdirect platform to create and share VR projects with internal teams. To deliver solutions such as virtual showrooms, learning and training, and product presentations, the company provides a VR editor, mobile app, cloud-based infrastructure and browser-based player.
AR3S (by Holo-Light)	Holo-Light is an Austrian company working in the augmented and virtual reality enterprise market. Its product AR3S is an augmented and mixed reality engineering area designed to visualise and work with 3D CAD data. The tool can be used for design evaluations, machine installation, training and other purposes.

Source: Visionary Analytics, 2022. Information provided by company representatives during interviews, https://vividworks.com/, https://www.viar360.com/, https://www.vrdirect.com/.

2.7.4. Devices and SDK

From an industry perspective, XR devices are at the centre of the ecosystem. These devices provide the necessary visual, haptic and audio features that defines XR experiences.

For end users, the quality of cameras, eye tracking, haptic sensors and body movement sensing are key to the experience. However, equally important is the SDK[232] (software development kit), which enabling developers to program games or other content-based

[231] Although Unity is currently based in the US, it is of Danish origin.
[232] A software development kit is the API and the associated documentation, sample scripts, etc. that the device manufacturer creates to support developers in using the device in an efficient manner when developing software.

services that use the device. All XR devices therefore include an SDK, which ideally makes it easy for developers to program content. One of the key roles of authoring platforms is to wrap the SDKs made available to developers by device manufacturers and provide a layer that is agnostic of the actual device. This enables developers to build games that work with multiple devices and leaves the complexities of handling differences between device APIs to the authoring platform.

Other than goggles and smartphones, haptic devices are also important. Haptic devices create an experience of touch by applying forces, vibrations, or motions to the user. These devices enable more realistic interactions between the user and objects in virtual environments. Such devices come in quite different forms suited to different use cases, ranging from the controllers used by, for example, a Sony PlayStation, to advanced gloves that can track very delicate finger movements. The European examples of haptic devices identified are presented in Table 10.

Table 10. European haptic glove manufacturers

Magos
Magos is a Greek tech start-up that focuses on VR, developing both hardware and software to integrate a sense of touch into XR. The company's aim is to counter XR's current main focus, which according to Magos's perception is too closely related to audio-visual aspects of reality, resulting in XR experiences not being as well rounded as they otherwise could be. Magos's product is haptic gloves that bring integrated technology to the users' fingertips. The gloves closely resemble the anatomy of the human hand by featuring 16 joints and 22 degrees of freedom, as opposed to the 16 joints and 27 degrees of freedom in a real hand. This allows its product to use finger tracking using four sensors in every finger, as well as hand orientation, indoor hand localisation and haptic feedback to create a highly accurate and intuitive experience. In addition, the glove can record user motions and use them for feedback or to provide training validation. The more 'natural' architecture of Magos gloves means that they can provide more accurate and nuanced haptic feedback than conventional VR handsets. Hence, the gloves can and are being used in healthcare and patient rehabilitation, engineering, education and training, telerobotics, gaming and aeronautics. Importantly, Magos's glove is not a standalone technology and therefore needs to be used in conjunction with other VR devices, which Magos itself does not produce.
SenseGlove
SenseGlove is a Dutch company that originated from a student university project at TU Delft. Its first prototype was created in 2017 in conjunction with Volkswagen, which currently remains a partner. SenseGlove offers haptic Bluetooth gloves that enhance the XR experience and make digital interactions feel realistic and natural. Importantly, these gloves are compatible with standalone headsets. The haptic glove, called Nova, provides users with the ability to touch, grab, hold and feel VR interactions as if they occur in the real world. It allows users to feel textures, stiffness, impacts and resistance from virtual objects and thereby provides a more accurate and intuitive experience. The feedback system in the glove can exert 20 Newtons of resistance within 10 milliseconds, making objects feel real. This makes Nova well-suited to training, marketing, research and prototype development.

Source: Visionary Analytics, 2022, based on interviews with company employees and websites.

In terms of devices and SDKs, the market is currently dominated by a small number of global, non-European players – Meta (Oculus), HTC, Google, Microsoft, PICO headsets, RealWear, Vuzix, LLVision, and Glass Enterprise. European companies tend to be niche players directed at specialised use cases with high requirements that cater to the business segment involved in simulations, advanced design activities, etc. The European device manufacturers identified are based in Austria, Belgium, the Czech Republic, Finland, France, Greece, Latvia, Romania, Spain and the Netherlands. We identified no device manufacturers in other EU countries (see Figure 22 for more details). .

2.7.5. Device components

XR devices are assembled and marketed on the basis of a number of key components, and include software that enables them to be used to create realistic experiences for the user. Some of the key technologies include the small screens (displays) and lenses used in goggles, as well as cameras and associated software for tracking eye movements, location technology for tracking the movement of the person wearing the goggles, and processing units. These technologies are presented in detail in Table 11.

Table 11. Key technologies involved in XR devices

Technology	Key technological concepts	Examples
Display technology	Screens are used to project computer-generated images to the user. Together with the optics, these are the key components of the visual experience.	• LCD (Liquid Crystal Displays) • OLED (Organic Light Emitting Diode) – either PMOLED (Passive Matrix) or AMOLED (Active Matrix) • Digital Light Projector (DLP) microdisplay • Liquid Crystal on Silicon (LCoS) microdisplay
Lenses (optics)	Optics, used to produce a good visual experience for the user, are a key component alongside the display used.	• Aspheric lenses • Fresnel optics
Cameras	Used for eye tracking, 6DOF tracking of the user in physical space, and for generating mixed reality images that combine input from cameras and computer-generated images.	• Eye tracking • 6DOF tracking
Location technology	Various means are used to track the location of the user.	• Lighthouse Base Stations • Inside-out tracking
Movement	A device needs to track the movement in physical space of the user and uses different techniques for that.	• IMU (Inertial Measurement Unit) • gyroscopes • accelerometers • magnetometers
Processing unit	All devices have built-in processing units of different sizes and capacities.	• CPU • GPU

Source: Visionary Analytics, 2022, based on desk research.

Our desk research identified companies in the EU producing components that could potentially be used for XR. A Google search was carried out for companies in the EU that manufacture technologies and employ concepts required for XR devices. This used keywords relating to certain technologies and concepts (provided in Table 11, above). In addition, during the interviews with XR device manufacturers, interviewees were asked to name any component providers that come from the EU. To clarify if these companies manufacture components for XR devices, companies were contacted by email and phone. A list was generated of 15 companies that confirmed they manufacture XR devices; a further 37 companies contacted. These 37 companies may produce components (e.g. OLED screens) only for other devices, and may not produce components for XR. Based on the companies that responded, it could be expected that around half manufacture components for XR devices. Some examples of European companies manufacturing components for XR devices are presented in Table 12 below. Figure 21 illustrates the geographical distribution of both confirmed and non-confirmed device manufacturers.

Figure 21. Map of component manufacturers in Europe

Figure 22. Map of European device manufacturers

Note: * - refers to companies that are joint companies of two countries. In one case it is France-Italy company. In other case it is Belgium-Netherlands company.
Source: Visionary Analytics, 2022, based on XR company mapping.

Most of the 15 confirmed companies are based in Italy (4), Germany (4) and France (3). Breaking down the identified companies by technology, the majority focus on lenses (optics) (7) and display technologies (4). There were also some companies manufacturing cameras and processing units. No companies manufacturing movement or location technology were confirmed as manufacturing components for XR devices.

Table 12. European XR component manufacturers

Microoled
MICROOLED is a French company based in Grenoble, and is associated with the Micatec Campus, an international research hub for micro and nanotechnology. The company manufactures near-eye AMOLED displays (NEDs) and modules for a variety of products ranging from digital camera viewfinders to AR glasses. Microoled uses technology that is both high luminance and very low in power consumption, thus enabling AR glasses to be both lightweight and high-quality. In addition, the company's displays are used for medical devices, outdoor and sports optics and defence. Importantly, these displays are not produced exclusively for the AR market. Key use cases include high-end binoculars, digital night vision, thermal imaging and fusion imaging. Microleed is one of the only suppliers of OLED microdisplays in Europe. Other large manufacturers are based in Japan, the US and China. In addition to its main product (near-eye AMOLED displays), Microoled, has developed its own brand of AR glasses called ActiveLook. These constitute an open platform and offer a web interface, meaning that any developer can send data to the glasses. The glasses are created for various kinds of applications, including sports, navigation and industrial use. The glasses are good-looking, lightweight and comfortable, with long battery life.
Raytrix
Founded in Germany in 2008, Raytrix has been selling 3D light field cameras for professional applications and research for the past 12 years. Its cameras provide input for XR applications and help replicate real-life environments in VR. The company has also created software, Light Field Engine, that helps process and control raw light field data to produce images and 3D maps. Raytrix cameras work by capturing a standard image alongside depth information from a scene. They function by placing a micro lens array (MLA) in front of the image sensor of a standard

camera. Hence, only a single camera is needed, using standard lighting and a single exposure. In addition, the measurement volume is chosen by the main lens, so cameras can be used with a telecentric lens, standard lens, microscope or telescope. Whichever lens is used, Raytrix cameras offer a large depth of field in comparison to other devices. Images are then processed using the GPU of a PC, as the cameras or the MLAs themselves produce only a raw image. Their main applications are automated optical inspection, volumetric particle velocimetry, plant phenotyping, and microscopy.

The value of Raytrix products is in the upper high-resolution segment, as the product combines very high fidelity 3D with video. Its business model focuses on industrial applications. Raytrix maintains a stock of cameras and will typically make one such camera available to the customer, along with the MLA. Raytrix also provides the software needed to process the images taken. Currently, its technology is used to provide 3D images for the generation of XR-relevant data. Importantly, the images are not part of any VR headset, although it is conceivable that such an application may be developed in the future.

Tecnottica

Tecnottica Consonni is an Italian company based just outside Milan. Established in 1957, the company has more than 60 years' expertise in optical components and systems for industrial applications. It works with a number of other companies within the field of XR to supply custom optical components. Tecnottica mainly focuses on manufacturing lenses (spherical, aspherical), achromats, prisms, optical filters, beamsplitters, optical mirrors and light guides. It also provides services such as optical design, optomechanical design and optical testing. Its core business is producing high-quality parts, dedicated to high-technology markets such as aerospace, AR/VR and biomedical.

Source: Visionary Analytics, 2022, based on interview with company employee and websites.

2.8. Economic impacts

This section provides an assessment of the direct economic impacts of various segments of the EU XR market. This includes what proportions of the estimated market may be attributed as European value-added. Indirect economic impacts are described in Section 1.2.1.

Direct economic impacts of XR are defined as the value contribution from the European XR industry. The value contribution is identified by the revenue generated through XR devices, solutions and services in Europe. Some of this revenue will consist of value originating from outside Europe. As an example, devices for XR are almost exclusively produced outside Europe and the price of these should therefore be deducted from the revenue to identify the value contributed by the European XR industry.

The economic impact of XR on Europe is observed in a number of different market segments. Table 13 below identifies and assesses the impacts of different market segments in terms of their direct economic impacts on the European economy. The table identifies direct impacts on the EU economy as revenue generated in the EU and involving employment in the EU. It also provides, where possible, an assessment of the estimated market share of EU revenue and employees. The identification of these impacts leads to an overall expert assessment of the size of the impact on the EU economy of the various market segments.

Table 13. Estimates of the direct economic impacts of various segments of the EU XR market

Market	Direct Impacts on EU economy[233]	Size of Impact[234]
Content-based services	• Revenue and employment from building and marketing games and other XR-based experiences • Estimated market share of EU companies: 25-50%	Medium
Content-based services	• Revenue and employment from using XR devices and XR experiences to innovate existing products and services. • Estimated market share of EU companies: 50-75%	Large
Content-based services	• Revenue and employment from building and marketing new services based on XR technologies for the professional segment. • Estimated market share of EU companies: 50-75%	Large
Distribution Platforms	• Revenue and employment from niche authoring platforms for the professional market. • No qualified data for market share assessment.	Small
Distribution Platforms	• Revenue and employment from IT infrastructure used by distribution platforms. • No qualified data for market share assessment.	Small
Authoring Platforms	• Revenue and employment from niche authoring platforms for the professional market. • No qualified data for market share assessment.	Small
Devices and SDK	• Revenue and employment for niche device manufacturers (e.g. Varjo, etc.). • Estimated market share of EU companies 1-5% • Revenue and employment from sales and support services for global device brands in European markets. • Estimated EU share of foreign companies' revenue in the EU: 10-25%.	Small

Source: Visionary Analytics, 2022, based on desk research, published market research, as well as survey and interview results.

The major direct contribution to the EU economy is expected to come from content-based services, in particular the professional segment of these. This is based on the EU companies identified during the course of the desk research.

[233] The estimated market shares for EU companies have been assessed on the basis of surveys, interviews and expert assessments by the study team. For authoring and distribution platforms, no valid data points for assessment were available.
[234] This is an overall expert assessment of the impact, based on a combined assessment of the market share of EU companies and the relative economic size of this impact.

3. Conclusions

This report describes the state of the art, and provides an assessment of the strengths and weaknesses of the results of existing research linked to the use of extended reality (XR) technologies in the healthcare and education sectors. This includes an analysis of how XR can assist the daily lives of vulnerable groups (children and adults with disabilities), as well as the challenges that such groups face when using these technologies. In addition, the report provides a market analysis of XR applications in Europe.

The study is mainly based on secondary data (an extensive and systemic review of the available literature). The study findings are further supported by the following primary data, collected during this project:

- Two online surveys: 1) one with representatives of XR companies and XR researchers/academics (106 complete, and 23 partial responses); and 2) a survey about the XR education programmes offered by higher education institutions across Europe (33 responses, of which 16 were complete).
- 78 interviews with representatives of XR companies (e.g. CEOs, CTOs); academics and researchers in the field of XR; practitioners and industry representatives; policymakers/government officials; representatives of end users of XR technologies (particularly vulnerable groups, but also others such as teachers).
- 11 case studies of European XR companies across different vertical market segments to illustrate the different types and business models of European XR players.
- Success stories of XR companies focusing on the sectors of healthcare (AMA), education (Varjo); engineering and manufacturing (Holo-Light); and logistics and manufacturing (TeamViewer).
- Online workshops with XR stakeholders in the sectors of healthcare (11 participants) and education (27 participants). Both workshops yielded information and ideas to inform the recommendations provided in this report on how to address current barriers and maximise the potential impact of XR.

The findings of the study are presented below. First, these conclusions present an analysis of the applications and affordances of XR technologies in healthcare, education, and other sectors covered under the success stories. Second, the economic and social impacts of XR are presented, followed by the barriers to be addressed, research gaps, and the overall landscape of the European XR market.

Applications of XR technologies in the healthcare sector

Extended reality-based applications for healthcare can be broadly categorised in two separate areas, depending on the user group:

- Applications used by medical professionals and students:
  - **XR applications in surgery**, including (a) preoperative planning to allow the creation of an optimal surgery design in 3D; (b) intraoperative navigation to allow the visualisation of a patient's anatomy in real time; and (c) telepresence-enabled remote guidance for medical staff.
  - **XR-assisted analysis and diagnosis,** covering the detection of diseases via 3D imaging and the detection and assessment of disorders by observing patients in virtual reality (VR) environments.
  - **Learning in healthcare.** Training for medical staff and students using XR (e.g. studying anatomy, practising surgery, training for medical emergency).
- Applications used by patients or the general population:

- **Patient and caregiver education,** including (a) the visualisation of medical procedures, helping users to understand the nature and purpose of the proposed procedure, its potential risks and benefits; and (b) simulating the experience of having a certain health condition.
- **Pain management**– for example, to alleviate acute and chronic pain, such as from burns, cancer-related pain or labour contractions.
- **Treatments and therapies for patients with mental health problems or disorders,** including (a) cognitive behavioural therapy and exposure therapy in virtual environments; (b) virtual self-counselling to treat conditions such as anxiety, depression and PTSD; and (c) embodiment using a virtual body to treat eating disorders and others.
- **Rehabilitation and cognitive enhancement**, including (a) cognitive rehabilitation to improve memory (e.g. for dementia patients); (b) treatments to aid neurological and functional recovery such as improving motor and language skills after a stroke; (c) sustaining the attention of people with learning difficulties (e.g. attention deficit hyperactivity disorder) through the use of serious VR games; (d) helping people with cognitive disabilities (e.g. autism spectrum disorders) to understand what other people are feeling, pay attention to people's faces, improve their reading and conversation skills, and reduce repetitive motor behaviours and underlying stress.
- **Assistance for people with physical disabilities.** This includes aid for (a) visually impaired people, through sight enhancement and machine vision; (b) hearing impaired people (no commercially available solutions exist as yet, but research is already being carried out in this area; (c) people with mobility challenges – for example, by incorporating eye tracking into augmented reality (AR) devices, allowing individuals to control and communicate remotely with their home appliances.
- **Improving well-being and promoting healthy lifestyles**, including the promotion of physical activity by increasing motivation to exercise through AR/VR-based 'exergaming' (exercising while gaming), and improving psychological and emotional well-being through VR solutions designed to aid relaxation, stress management and anxiety reduction, or simply through the generalised improvement of mood.

Affordances of XR technologies in the education sector

The affordances of XR in the education sector (i.e. the possible applications supported by XR technologies) can be summarised from two different perspectives:

- The aims of the intervention:
  - **Procedural training,** in which XR ensures safer and more effective skills development (through VR-based simulators) for both the technical and soft skills required in areas such as aviation, maritime, armed and the security forces, firefighting and train operation.
  - **Development of soft skills** using XR – for example, through virtual scenarios and virtual platforms – allows a more efficient and enjoyable learning process while addressing widespread challenges in traditional learning (e.g. shame, and the fear of mistakes that have real-life consequences). However, despite its positive effects, the application of XR is fairly limited in this field due to insufficient digital skills, high costs, and the lack of research demonstrating the positive effects of soft skills training.
  - **Awareness raising.** This encompasses the use of XR technologies to teach students about subjects such as environmental and racial issues in an engaging manner (i.e. through virtual emergency and/or instructive scenarios), which can

have a stronger positive effect on student awareness (including empathy towards ethnic minorities or persons with disabilities) than traditional learning approaches.

- **Art and design**, in which XR allows students of architecture, design and art to expand their creative opportunities. Students can create or explore clothes, architectural designs or paintings in a virtual environment, thus promoting greater creative freedom.
- **Computational thinking** skills, which can be developed through virtual scenarios and AR-based video games. These address the challenges inherent in traditional learning approaches, enabling problems to be visualised more effectively to increase learning performance compared with more traditional basic descriptions.
- **Collaborative XR learning**, including within virtual learning environments, helps to expand the opportunities provided by traditional learning approaches via the following affordances of XR: (a) opportunities to collaborate on problem-solving tasks (including for children with autism); (b) communication platforms for increased interactivity (e.g. communicating using virtual sticky notes, 3D paintings and video presentations); (c) virtual laboratories (for chemistry, physics, etc.), which expand the opportunities for scientific experimentation, provide virtual assistance to students, and ensure a safe learning environment; (d) opportunities for distance learning, i.e. virtual participation in the learning process for those who are unable to physically attend due to health conditions.
- **Physical training** as an affordance of XR allows a variety of physical activity, improving students' skills and tracking progress through VR-based simulators. Despite their positive effects, XR technologies are rarely used for physical training. This is mainly because XR cannot replace traditional approaches to physical training as it is more expensive, and educational institutions usually lack the necessary equipment.
- **Language learning** using XR technologies can take place in both formal and informal settings – that is, in educational institutions and workplaces. This ensures less stressful training, a smoother and more effective learning process, and more interactive learning opportunities, thus increasing the engagement and motivation of learners.

- Instructional approaches:
  - **Visualisation,** including visualising difficult scientific processes in AR and/or 3D settings. This is particularly applicable in the fields of engineering, STEM, anatomy and chemistry. Visualisation makes the learning process easier and more entertaining, ensures student engagement, and contributes to higher learning outcomes.
  - **Virtual field trips** to museums and galleries, or travelling geographically or through time (including into space) using head-mounted displays (HMDs) or smart glasses, 2D or 3D VR simulators, creates a more engaging learning experience. This is particularly true for learners who are less able to physically attend places due to health conditions.
  - **Storytelling and/or annotation.** This includes interactive storytelling, which allows the generation of stories based on both pre-prepared content and the interactions of the player or user in the story world. This is useful for (a) language learning and speech development (especially among people with learning difficulties and/or health impairments); (b) fostering communication and interactivity.

Application of XR technologies in other sectors

Beyond the healthcare and education sectors, XR technologies are also being actively applied in a range of fields, as demonstrated by the success stories of Holo-Light and

TeamViewer. These include sectors such as logistics, manufacturing, engineering and architecture:

- In **Logistics**, XR technologies include digital solutions (smart glasses with AR functionality), which allow workers to view all relevant information within their field of vision. This allows the automation of manual processes for workers in the logistics sector.
- In **Manufacturing**, XR enables workers using smart glasses with AR functionality to have all relevant information about the production process in their field of vision, and to virtually consult with experts about the working processes and/or technical problems that occur.
- In **Engineering/architecture**, the application of XR enables engineers and industrial designers to use mixed reality (MR) based tools and software (e.g. AR3S) to visualise, edit and share CAD (computer-aided design) data as 3D holograms in a natural environment. This results in more active collaboration, optimises workflows, increases efficiency, and reduces time and costs.

In all of these cases, XR allows the automation and digitalisation of work processes, which in turn minimises manual work and fosters work efficiency.

XR's impact on the healthcare and education sectors

The study observed both positive and negative impacts of XR on the economy, the social environment and vulnerable groups (children and adults with disabilities).

From a **cross-sectoral perspective** (overlapping aspects of the healthcare and education sectors), the application of XR increases cost-efficiency in treatment and learning processes, as well as allowing the development of unique skills and ensuring flexibility for medical staff and teachers/students. In addition, XR demonstrates positive behavioural effects (providing a safe environment for learning and practising soft skills); psychological gains (making learning and health procedures more engaging); and ethical benefits for students, medical personnel and patients (helping to overcome discrimination, harassment and violence; fostering tolerance and moral values). Furthermore, it also enables the increased inclusion of people with disabilities, as it ensures opportunities for such groups to participate in learning activities or attend procedures virtually. However, in addition to these positive impacts, the application of XR also has some possible negative effects: (a) content-related risks for users (e.g. unsuitable content, which can result in trauma symptoms, altered personal identity or in personal isolation*)*; (b) ethical and privacy risks (e.g. the manipulation of agency, identity hacking, data exploitation, etc.), (c) risks to medical safety (e.g. hygiene risks, motion sickness, temporary modification of sensorimotor and perceptual capacities); and (d) harmful social interactions (e.g. fraud, harassment and bullying).

Looking specifically at the **healthcare sector**, the application of XR can ensure greater accuracy and precision in treating patients, increased accessibility and affordability of healthcare services, and more durable and lasting treatment outcomes for patients. This is mainly possible due to expanded learning and treatment opportunities (e.g. analysing computerised tomography (CT) and/or magnetic resonance imaging (MRI) scans in 3D), as well as opportunities to provide and receive healthcare consultations online.

In addition, the application of XR in the health sector offers potential for generally positive effects on the population, such as enhanced therapy and rehabilitation outcomes, improved well-being, and reduced pain perception and anxiety. With regard to vulnerable groups, XR technologies allow novel treatment and therapy opportunities, support the daily life functions of people with disabilities, and improve quality of life for the elderly. However, the accessibility of XR treatments for people with disabilities and children remains limited due to the difficulty of adjusting visual contrasts and text size, as well as the heavy reliance on audible cues of experiences in virtual world. Moreover, paediatric care units are reluctant to use VR due to the size and weight of the headsets, as well as the fact that interpupillary distance[235] of most XR devices is designed for older children and adults.

In the **education sector**, XR has positive impacts on vulnerable groups (especially those with cognitive disorders, learning disabilities, and/or physical disabilities), as it enables increases in student comprehension, reading and spelling skills, as well as boosting their physical activity. The application of XR also allows the promotion and teaching of empathy and moral values to students, which may help to prevent or mitigate (potential) violent behaviour. Despite these positive effects, the application of XR also raises concerns with regard to potential inequality among educational institutions (i.e. unequal financial opportunities to afford and apply XR technologies), as well as negative impacts on vulnerable groups such as possible harmful content, especially given the greater emotional vulnerability of people with disabilities. Access to XR technologies may also be limited, as in the case of individuals with cognitive or physical disabilities (e.g. difficulties in using XR tools, navigating in a virtual environment, etc.*)*.

Barriers to be addressed

The study observed market-related barriers, technical limitations, and other barriers (e.g. those relating to ethical considerations or the legal environment).

From a **cross-sectoral perspective** (overlapping aspects of the health and education sectors)**,** the key market-related barriers observed are a lack of awareness and acceptance of XR technologies, as well as financial constraints and the lack of skilled XR professionals in the market. The first of these barriers, lack of awareness, refers to outdated or rudimentary understandings of what XR is and how it can be applied to increase effectiveness and efficiency at work. The second barrier, financial constraints, relates to the high cost for both individual users and institutions of purchasing XR software and devices, as well as the lack of (or difficulty in securing) funding for research institutions and companies to innovate and/or develop XR solutions. Lastly, the lack of skilled professionals for XR development also poses a substantial obstacle, with a need for more XR designers, content creators and developers. Furthermore, in most cases, teachers lack necessary XR skills. This partly stems from a lack of education opportunities in the field of XR (including those for healthcare professionals), especially within formal education.

Cross-sectoral technical limitations encompass four key areas:

- XR devices are not yet sufficiently ergonomic (e.g. due to their size and weight), especially when they have to be worn for longer periods of time (e.g. during a surgery). In addition, the experience of using XR devices is not yet smooth enough; there is a need for wireless and standalone headsets, as well as frictionless and non-disruptive technology.
- Low image resolution results in a lack of precision and realism. A lack of precision may negatively affect the use of AR hardware in surgical navigation, for example.
- The limited processing power and battery life of head-mounted displays (HMDs) and their controllers can negatively affect their usability and the experience provided by XR equipment.
- Health concerns, such as simulation sickness, dizziness, headaches, nausea and eye strain pose a barrier to the wider uptake of XR in both sectors.

Barriers in terms of government policies and the regulation of XR are also pertinent to this discussion. For the health sector, this barrier relates to difficulties in certifying XR products as medical devices, as well as the absence – or in some cases an illogical system – of compensation for XR treatments by state insurance. In the education sector, regulatory

[235] The distance between the centres of a person's two eyes.

barriers include the potential complexity of applying the General Data Protection Regulation to certain XR scenarios, as well as a lack of guidelines or unified national policies that could help to create a guiding framework for educational institutions to adopt XR in the classroom more easily.

Lastly, ethical and privacy issues stem from problems relating to the collection of large volumes of data, including personal, biometric and cognitive data, as well as data about the users' surroundings – all of which may be subject to potential misuse. Other ethical barriers relate to users' physical and psychological safety, due to being distracted by XR experiences. In the healthcare sector, the psychological impacts of XR on a user must be carefully considered, especially for children. This special concern for children is also prominent when using XR in education, as the collection of data from underaged individuals will reduce the likelihood of parents giving their approval to the use of such technologies in a classroom setting.

The present study has identified three main market-related barriers specific to the **healthcare** sector. First, research groups and companies are not consolidated, and healthcare systems in Europe remain fragmented. Furthermore, the adoption of XR devices is also unequally distributed, with the highest uptake seen in high-income countries. The second market-related barrier is the limited availability of XR content and its low quality, with applications for specific medical conditions that are also customisable being rare. The unsuitability of software also relates to a third barrier – because most commercially available software comes from the US, many XR applications are only available in English, making them inapplicable to people who do not speak the language.

The technical limitation of XR that relates to the healthcare sector entails a lack of realism. XR tools are not always capable of simulating real-life situations, which may make accurate diagnoses difficult to perform.

Lastly, a major market-related barrier in the **education** sector is the lack of availability of European XR devices. This is problematic, due to the current market-leading (non-EU) devices being intricately linked with, or locked to, specific XR ecosystems or software, thus posing the risk of obstacles to the more streamlined application of such technologies for educational purposes.

Research gaps

Despite a growing number of publications on the application of XR in the healthcare and education sectors, a number of research gaps remain. Notably, technical advances are rapid, and as a result new research cannot keep abreast of these developments.

- **Cross-sectoral** (applicable to both healthcare and education sectors). The absence of large-scale and longitudinal research; insufficient research into sensory augmentation and neurophysiological changes; insufficient focus on potentially negative effects in relation to vulnerable groups (children and adults with disabilities) and ethical considerations.
- **Healthcare** sector. Human relationships with avatars have not yet been sufficiently well investigated; research on the integration of XR with AI and machine learning remains limited.
- **Education** sector. There is a scarcity of research in the following areas: case studies on new affordances (only limited research has been dedicated to domains other than science, technology, engineering and mathematics [STEM]); the application of XR in primary education, as well as vocational education and training (VET); the impact of the use of XR on students' psychological health, including motivation and behavioural changes; the impact of XR applications on students' learning performance; the integration of XR into the natural setting of a classroom; addressing the data protection

issues involved in XR use; the negative impacts of XR use; the economic impacts of XR use in education.

European XR market

This part of the report provides an overview of the European XR market, and presents data gathered on how it is expected to evolve. It provides a breakdown of the market in the various vertical market segments that are involved in delivering XR experiences to end users. It also presents the expected direct economic impacts in different EU XR market segments.

The European XR market (valued at EUR 7.95 billion in 2021, and expected to grow to EUR 88.87 billion by 2030) represents around one-third of the global XR market. However, the majority (84%) of revenue in the core European XR market is generated by the top 10 players, all of which are based outside the EU, as the market overall is strongly dominated by US and Asian companies.

Although Europe manages to produce strong research results, lower awareness and demand for applications and/or investment in XR compared with that in US and Asian countries limits the ability of European XR companies to scale up without relocating outside the European market. Some of the businesses interviewed that are currently based in the EU are focusing their resources on growth in the US market. For example, one of the major authoring platforms, Unity, despite originating in Denmark, chose to relocate to the US. In addition, European companies face difficulties in attracting XR professionals due to both competition with global non-EU XR players that offer more attractive working conditions, as well as competition from other related sectors (in particular, the conventional gaming industry).

Europe hosts a relatively small number of niche players in core XR market segments such as devices, authoring platforms and distribution platforms. While niche EU players exist within each of the aforementioned market segments, the largest market potential for EU companies lies in the content-based services market segment. In this segment, an understanding of the use context and user preferences through geographical, cultural and linguistic proximity is more important for delivering services than in other market segments. In addition, niche EU authoring and distribution platforms have been identified and have market potential.

Europe’s position in the global healthcare and education XR market

Although the key focus of this report is on the applications of XR in Europe, it also presents the authors’ short assessment on the position of Europe in the global XR market for both the healthcare and education sectors. This assessment is based on expert opinion, due to a lack of sufficient primary evidence on this specific question, which was not collected for the purpose of this study. Thus, the assessment should be considered with caution and validated through future research.

Overall, the European healthcare sector uses up-to-date XR solutions, but lags behind the US, the UK, and countries in Asia in terms of XR adoption rate and access to finance. First, Europe appears to be using up-to-date XR solutions in healthcare. Examples have been identified of applications of XR in Europe in most of the areas of application investigated in this study. Second, anecdotal evidence from a limited number of interviews suggests that the rate of XR adoption in the European healthcare sector is somewhat lower than in some of its main competitors, such as the US. This is mostly due to the lower awareness and uptake of XR solutions in Europe. A limited number of interviewees noted that this is the result of cultural differences between Europe and the US, as Europe is considered as having a more conservative approach towards innovation, as well as stricter and more diverse regulations (often varying between EU countries – for example, with regard to the assessment of health technologies or to cost reimbursement practices). Such characteristics impede the easy dissemination of XR solutions to the European market. Third, compared with the US, the UK, and countries in Asia, the accessibility of funding for the development of XR solutions is lower in Europe. This relates to the willingness of private investors to invest in XR solutions, challenges regarding the conditions for commercialising research results, as well as for compensating treatments that use XR under health insurance.

The European educational XR industry appears to be developing across all areas of application identified within this report, however it lags behind the US, the UK, and countries in Asia in a number of fields. First, according to several interviewees, Europe lags behind in terms of XR hardware. While the main European players are *Varjo* and *Lynx*, American and Asian headsets dominate the market in terms of breadth of choice as well as low pricing. Second, Europe appears to lag behind in terms of the share of teachers who are interested and proactively experimenting with XR, as most content in relation to XR experiences, teacher blogs, websites, etc. comes from the US. Third, although the European research landscape is booming, the majority of XR-related research in education stems from US and Asia-based research centres and universities. Part of the reason for this is the limited funding available in Europe for research in this field – a similar challenge to that faced in the health sector. Lastly, while the availability of XR professionals (developers and content creators) is low globally, it appears to be lower still in Europe. This could be result of the 'brain drain' of existing professionals to other, better-established XR education sectors in the US and Asia (see Section 1.3.1 for more details).

4. Recommendations

This chapter presents the study recommendations. Recommendations are divided into the following three groups:

- Suggested policy interventions: creating optimal conditions and strengthening ecosystems;
- Suggested policy interventions: providing financial support;
- Potential research and innovation areas.

The recommendations in each group are presented in order of priority. Groups of recommendations are, in turn, also presented in order of priority. Recommendations have been prioritised on the basis of expert opinion, which requires further validation, for example, by surveying wider groups of relevant stakeholders.

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
		Suggested policy interventions: creating optimal conditions and strengthening ecosystems			
1.	Cross-sectoral (concerning both healthcare and education sectors)	A lack of skilled professionals such as XR content creators and developers creates an obstacle to the expansion of the XR industry in healthcare and education in Europe	1.3.3	• Include plans to exploit the affordances XR technologies offered by the healthcare and education sectors as a strategic objective in official government policies/roadmaps, especially in national policies devised by the relevant ministries (health and education or labour/work/economy) of the Member States.[236] DG Connect could develop a blueprint framework suggesting how XR could be integrated within strategies on digital healthcare and education, guiding and encouraging national governments as well as providing successful examples such as the one mentioned in the last footnote. The blueprint framework could be widely disseminated within existing networks such as the European Digital Education Hub.	EC incl. DG Connect, national governments

[236] One example is the XR Action Plan by the Ministry of Education in Flanders, which is spending EUR 5.5 million on XR for education, building on four elements: hardware, software, professional development initiatives for teachers, and practically oriented research, creating a comprehensive framework for a wide, government-coordinated uptake of XR in schools.

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				• Provide funding to further develop and strengthen existing XR-related programmes/subjects or establish new ones at tertiary education institutions in the EU at all levels – Bachelor's, Master's, and PhD (elaborated upon in recommendation no. 6).	
2.	Cross-sectoral (concerning both healthcare and education sectors)	• Lack of skilled professionals, i.e. teachers and healthcare professionals who are able to adopt XR technologies and apply them in educational and medical environments. • Lack of awareness among teachers and healthcare professionals about opportunities for the application of XR and its benefits. This lack of awareness about XR and its capabilities also results in greater scepticism among such groups concerning the use of XR in their daily practice.	1.3.1	• Short-term: prepare training on the use of XR applications and technologies: ○ Associations of healthcare professionals could be responsible for preparing such courses (with support from academia), selecting professionals, as well as teaching and training them to use the technology as a part of their existing ongoing efforts to offer continuous education. This may also fall under the European Board for Accreditation of Continuing Education for Health Professionals[237], and may be required for licensing. In this case, a study of the medical education and continuing medical education (CME) in Europe would be required, as well as a further harmonisation of CME systems across Europe. ○ Implement teacher training for the delivery of education via XR (upskilling/certifications as well as integration of XR elements in existing pedagogical curricula). An example of such training would be the 'Create with VR for Educators' beginner course by Unity. The training could include the following modules: a) the affordances of XR for educational purposes; b) technical requirements; c) software setup; d) XR device technical setup; and e) XR content and lesson plan creation – this would also include guidelines on how to integrate XR into	EC incl. DG Connect, associations of healthcare professionals, teachers' associations, national governments

[237] http://www.ebac-cme.org/

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				existing curricula, and increasing accessibility. Other than training, selected web-based authoring platforms (e.g. CoSpaces[238]) could become a part of an accredited list of platforms in a given Member State that would function as a standardised, user-friendly method for teachers to create XR experiences for classroom settings in a variety of subjects. Prepared materials and templates should be developed and made open-access, to serve as a toolkit for teachers. • Long-term: develop a model and guidelines for integrating XR as a part of the education of healthcare students and future educators. DG Connect could initiate and encourage such developments. Overall, policymakers, educational institutions, student representatives, researchers, associations of healthcare professionals, teachers' associations, practitioners and industry representatives should be involved and consulted in the process of developing the model, to ensure the consistency and comprehensiveness of results. ○ For healthcare professionals, the model should be connected to a framework for the certification of healthcare professionals (Directive on the recognition of professional qualifications[239]), so it would be clear which practitioners are competent to use XR in treatments. DG Connect could initiate a call/ project to develop both the measures suggested above, as well as possibly other short-	

[238] https://cospaces.io/edu/
[239] Directive 2005/36/EC of the European Parliament and of the Council of 7 September 2005 on the recognition of professional qualifications.

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				and long-term sectoral and/ or cross-sectoral measures under the Erasmus+ or other EU support programme.	
3.	Education	A general lack of access to XR technologies by institutions due to inadequate funding and lack of awareness, as well as a lack of guidance on which tools would bring the most value added, and how they can be applied most effectively for the benefit of both teachers and students.	1.3.3	• First, outline the needs of end users (teachers, educational institutions, students) throughout the learning and education administration process to see where XR could bring the most value. Second, design a general framework for evaluating XR tools intended for educational institutions, and put out calls for submissions to address the needs identified. Following this, evaluate (through submitted demos and proposals) the existing commercialised XR tools according to a predetermined set of criteria (e.g. xAPI and OpenXR). Finally, recommend technologies (whether hardware or software) to educational institutions by issuing official recommendations concerning which XR tools are 'verified' or 'approved' for use in various educational settings. The above will provide the MSs with general guidelines, while affording them the flexibility to design their own systems. This will also help to ensure some degree of harmonisation across Europe with regard to these guidelines, and help to minimise further market fragmentation. The body or bodies (cf. supra) responsible for the above should function in close cooperation with the developers of solutions, to ensure an effective process and outcome. This means that the state body must communicate with industry representatives (independent consultants and researchers with expertise in the field) about the identified needs, and in return expect to receive feedback about the feasibility of implementing solutions that address those needs. This is important, in order to create funding calls that: 1) are feasible; 2) are useful and necessary in practice; 3) create synergies with the existing systems and teaching guidelines already in place. This is also important in order to minimise bureaucracy	EC incl. DG Connect, national governments

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				and carefully consider the intended end users' preferences and industry standards. The results can be made available in open-access via a centralised database, and disseminated across the relevant sectors. • Provide a national education funds for the purchase/rental of XR software, high-end smartphones for AR, and VR headsets for institutions The option to rent is especially important as schools do not require headsets all the time. Moreover, renting will allow experimentation and familiarisation with XR by the institutions. DG Connect could also carry this out via the Digital Europe (DIGITAL) programme.[240] • Create and support an XR strand within the European Digital Education Hub (e.g. within a network of national advisory services; a Support, Advanced Learning and Training Opportunities (SALTO) resource centre; and possibly a wider community for cooperation). This strand could promote good practices on the possible ways to apply XR in a sustainable manner for educational purposes, as well as approaches to creating or adapting XR solutions in various educational and training settings, and the necessary standards in relation to privacy, harassment, morality and inclusion. This would both help to encourage national policymaking in the area, as well as guiding practitioners in their day-to-day work.	
4.	Healthcare	• The fragmentation of various healthcare systems across Europe is a barrier to utilising XR healthcare technologies in hospitals across different countries and regions. Each country often has a different healthcare model, and legal	1.2.1, 1.3.1, 1.3.2	Create a regulatory policy body (working group) focusing on emerging technologies such as XR (or integrate functions mentioned below into existing body(-ies) such as the eHealth network, medical devices expert panel, or new committee in the European Medicines Agency for European Medical Device Regulation). The body would focus on	EC incl. DG Connect

[240] The Digital Europe Programme, per the 2021-2022 Work Programme, targets educational institutions (specifically primary, secondary and vocational schools) for a wide scale uptake of effective digital content and platforms, including large-scale pilots and deployment activities.

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
		environments vary (e.g. with regard to the collection and storage of data), as well as different processes for the procurement, reimbursement and use of digital health services. • Ethical concerns regarding the dual use[241] of information technology also apply to XR. The persuasive capabilities of XR technologies may produce positive and negative effects in healthcare applications.		providing guidelines/roadmaps for companies and practitioners detailing the procedures to be followed when testing/developing/validating/distributing/applying solutions involving new technologies (including ethical, legal, data protection issues, and those relating to vulnerable groups). In addition, the body could provide guidelines for national governments on investing in digital health solutions and in streamlining the compensation of digital health solutions. This could ensure that legislation and policy are not (far) behind developments in XR and, furthermore, that they do not hinder the development of XR technologies. DG Connect could keep in touch with the existing bodies mentioned above and discuss if they would have any interest in taking on any of the functions suggested above.	
5.	Cross-sectoral (concerning both healthcare and education sectors)	While the overarching goals of policies and directives related to harassment can certainly be extended to AR/VR devices and applications, the mechanisms to achieve those objectives laid out in current laws do not directly apply to immersive experiences. As a result, laws on harassment in the XR cyberspace, particularly those concerning mechanisms of punishment and the enforcement of rules, are also unclear.	1.2, 1.3	Propose extensions to the policies and directives that address issues relating to harassment (e.g. the Digital Services Act and the Directive on combating violence against women and domestic violence) so as to encompass the idiosyncrasies presented by cyberspace and XR environments, along with rules and related punishment mechanisms in the event of violations. DG Connect could raise harassment-related issues with the relevant bodies, such as European Digital Rights (EDRi) and other DGs – DG JUST[242] and DG HOME,[243] to raise awareness and draw attention to this issue and encourage collaborative action.	EC incl. DG Connect, national governments
		Suggested policy interventions: providing financial support			

[241] Potentially having both positive and negative effects, depending on application.
[242] Due to their work on the Code of Conduct – Illegal online hate speech.
[243] Due to their work on legislation fighting child sexual abuse, including online.

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
6.	Cross-sectoral (concerning both healthcare and education sectors)	A lack of skilled professionals such as XR content creators and developers creates an obstacle to the expansion of the XR industry in healthcare and education across Europe. Currently, there is no specialisation or discipline that combines health and education disciplinary education with the teaching of XR technologies. Brain drain to the more established XR industries in the US and Asia is also taking place.	1.3.1, 1.3.3.	Provide funding to further develop and strengthen existing XR-related programmes/subjects or establish new ones at tertiary education institutions in the EU at all levels – certificates and diplomas, Bachelor's, Master's and PhD. DG Connect could allocate funding for XR-related study programmes/subjects in the current and next Digital Europe work programme (under Strategic Objective 4) and/or through the Erasmus+ programme. Such programmes could cover the whole range from enabling technologies to the final user experience of XR applications, while also finding their way into applications for industry. The key areas for education include: • Art and design • Programming • Application development. The key target groups include: • Professionals aiming to work in the XR sector • Users (e.g. healthcare professionals applying XR technologies in their practice or teachers in schools). The XR-related programmes/subjects could take the form of: • Formal education that leads to a qualification or certification • Non-formal education • Continuing medical education courses for re-licensing. In addition, agreements with industry for traineeships after the end of the XR-related programme/course should be promoted, perhaps through the existing Erasmus+ programme.	EC incl. DG Connect, national governments

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
7.	Cross-sectoral (concerning both healthcare and education sectors)	Although Europe manages to produce strong research results, research teams and start-ups still face difficulties when trying to commercialise their products. This mostly relates to a lack of funding and the difficult certification process. Private investors in the EU are reluctant to fund XR solutions and especially hardware, due to a lack of knowledge about it. In the survey of XR company representatives and XR researchers/academics, barriers relating to a lack of funding were ranked among the top barriers to expanding XR businesses. Without the growth and improvement of commercially available XR software, it will be impossible to encourage the widespread use of XR technologies.	1.3.1	Provide funding for the creation of a European venture capital fund dedicated to investments in XR companies. This fund could be set up and administered by the European Investment Bank, which manages similar measures funded through the European Regional Development Fund (e.g. the JEREMIE initiative[244]). An example of an XR-specific venture capital fund is the WXR venture fund in the US, which invests in gender-diverse seed stage companies that are transforming business and human interactions with spatial computing (VR/AR) and artificial intelligence (AI).[245] DG Connect should liaise with the EIB to raise this issue and present this recommendation. A working group consisting of DG Connect, the EIB, DG RTD and other relevant DGs could also be set up to either develop a new funding instrument, or to set up an XR-focused fund within the currently available funding instrument(s).	EC incl. DG Connect, EIB
8.	Cross-sectoral (concerning both healthcare and education sectors)	Independent and inclusive access to XR technologies and affordances for people with disabilities remain limited in wider education and training, as well as in healthcare settings. Specifically, a heavy emphasis on motion controls, the use of the body to control the experience, and sometimes requiring the user to be in a certain position (e.g. standing) all pose potential accessibility challenges.	1.2.1, 1.2.2, 1.2.3, 1.5	• Focus on accessibility during the design and implementation of new XR tools, rather than incorporating accessibility requirements into existing products, as this will be easier and more cost-effective. This could be achieved by encouraging the integration of accessibility features and guiding principles for universal design into the design and programming tools used by developers. For example, accessibility requirements and guidelines could be ingrained into EU XR research and solutions calls for XR both software and hardware. DG Connect could suggest accessibility features as a horizontal requirement in XR-related calls during the discussions about the next Horizon Europe work programme. The	EC incl. DG Connect, national governments

[244] http://www.eif.europa.eu/what_we_do/resources/jeremie/index.htm
[245] https://www.wxrfund.com/

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				inclusion of accessibility features could be required in order for a project to receive EU funding from calls funding XR product development (e.g. in a similar way to the requirement to have a Gender Equality Plan for most organisations participating in Horizon Europe calls). Accessibility requirements can be adapted from existing guidelines, such as those produced by the World Wide Web Consortium (W3C), XR Association, and Microsoft's Inclusive Design Toolkit, which provide actionable advice on inclusion when designing XR tools and planning accessible XR collaborations. Some elements to consider include, but are not limited to: ○ Immersive semantics and customisation of an XR environment to the user's needs ○ Motion-agnostic interactions ○ Immersive personalisation (support symbols, ability to turn off non-critical content) ○ Voice commands ○ Colour changes ○ Screen magnification ○ Gestural interfaces and interactions ○ Signing videos, spatial audio tracks, text-to-speech and captioning features ○ Avatar options that represent the full range of human diversity (including visible disabilities) for enhanced nonverbal communication ○ Inclusive designs of headsets/HMDs (more flexible and ergonomic) that would allow the user to use the device comfortably ○ Platforms that allow access via multiple types of devices.	

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
				• Involve people with disabilities (end users, experts, industry professionals, etc.) to consult on implementing the requirements and reviewing procedures. • During research and/or funding calls (recommendations no. 11, 12, 7, 10) or when assessing tools to issue an official approval (recommendation no. 3), include an accessibility score.	
9.	Healthcare	Large-scale validation is crucial for new XR products before they are offered to the market. Large-scale clinical trials are very expensive; thus, some companies opt for smaller-scale trials that are less reliable. Hence, uncertainty among healthcare professionals remains as to the validity of such tools, due to a lack of large-scale clinical trials, resulting in scepticism and mistrust of XR among healthcare professionals.	1.3.1, 1.5	Supporting large-scale clinical trials of successful XR applications. This could be carried out by the European Commission and/or national governments by creating specific calls under their current funding programmes. DG Connect could raise the issue of large-scale clinical trials during discussions about the next Horizon Europe work programmes. In addition, DG Connect Unit G2 could initiate an internal working group to discuss how clinical trials could be supported through current EU funding programmes.	EC incl. DG Connect, national governments
10.	Cross-sectoral (concerning both healthcare and education sectors)	• There is a lack of XR content and scenarios (multimodal data, non-linear interactive storytelling, annotation, etc.) relating to under-researched areas of education, such as physical training, construction and manufacturing. • Most XR applications for healthcare available on the market consist of games, while more serious applications that address specific medical conditions and can be easily personalised for each patient remain rare in the EU. These validated tools have been developed more widely in the US and Asia.	1.3.3	Create XR content-specific a) incubation programmes; b) acceleration programmes; c) hackathons; and d) European funding calls focusing on SMEs/early-stage start-ups and research institutions. This includes follow-up programmes for the above, in order to scale up businesses. The focus could be on the following: • Producing content for under-represented fields of education, such as physical training, construction and manufacturing. • Producing XR programmes and content that can be applied in the healthcare sector. DG Connect could initiate such funding instruments under Horizon Europe or other EU programme.	EC incl. DG Connect, national governments
Potential research and innovation areas					

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
11.	Cross-sectoral (concerning both healthcare and education sectors)	Potential negative effects and ethical considerations of using XR have not yet been sufficiently investigated. Knowledge remains insufficient as to the effects of XR on human cognitive processes. For example, it is still not known precisely how XR is able to modify emotional experiences. In addition, there is a lack of evidence about the long-term effects of XR.	1.2	Launch further research calls relating to the potential negative effects and ethical considerations concerning of XR and how to alleviate or accommodate them (some calls could ask or be dedicated to developing concrete recommendations for EU policy). This could be done by the European Commission and/or national governments, by creating specific calls under their current funding programmes (including those Horizon Europe calls for which DG Connect is responsible). The topics of such calls could include the ethical effects and considerations for using XR; the psychological effects of long-term immersion (differentiating between different age groups); the effects of XR on human cognitive processes; the capabilities of XR to alter perceptions and personal identities; how to reduce cybersickness; how to improve accessibility for vulnerable people; how to maintain moral subjectivity; the impact of XR on real-life social relationships; the use and misuse of personal data in relation to XR interactions; how to use XR for promoting empathy, etc. Based on the needs of the XR community, and as suggested by experts, further research into three specific thematic areas could take priority: a) the psychological effects of long-term immersion in XR (differentiating between different age groups); b) improving the accessibility of XR for vulnerable people; and c) the use and misuse of personal data in relation to XR interactions.	EC incl. DG Connect, national governments
12.	Cross-sectoral (concerning both healthcare and education sectors)	Despite a growing number of publications and clinical evidence, several research gaps remain, namely: limited research on sensory	1.5	Launch, or support the launching of, further European and/or national research calls, bearing in mind the caveats listed in the previous recommendation, on the following topics:	EC incl. DG Connect, national governments

No	Sector	Context/challenge	Chapter/ Section	Related recommendation	Intended recipient
		augmentation[246] and neurophysiological changes; human-avatar relations; insufficient research on integrating XR with AI (including machine learning); the new affordances that could be provided by new devices; data protection issues; and the relationship between the features of immersive systems and learning performance.		• Health: a) the collection and use of biofeedback[247] and neurofeedback[248] data during XR treatments, providing an objective metric of success/lack of success; b) enabling tactile stimuli and haptic feedback in XR solutions to provide more realistic experiences; c) opportunities for using data from virtual environments, d) human relations with avatars; e) linkages between AI and XR data to support ethical patient-centred goals in healthcare, e.g. using heart rate to drive the VR experience and create an individualised experience for each patient. • Education: a) XR affordances, especially in the education areas of construction, engineering, manufacturing and physical training; b) whether and how XR-based intergroup interactions with outgroup members (e.g. minority groups, people with cognitive and/or physical disabilities, neurodiverse populations), represented by avatars, increase trainees' empathy towards different parts of society; c) the learning performance of school students when using XR; d) further opportunities for using visualisation tools to improve learning outcomes; e) the experiences of educational institutions when using XR technologies in terms of data protection or security issues; f) cyber-security risks, vulnerabilities and potential personal harm to users brought about by the use of XR in educational settings.	

Source: Visionary Analytics.

[246] Sensory augmentation is augmentation of the body's sensory apparatus with the aim of extending the body's ability to sense aspects of the environment or body that are not normally perceivable (e.g. skin temperature, muscle tension, sweat level).
[247] Biofeedback refers to physiological signals from the human body (e.g. breathing, heart rate, sweat, muscle movement and tension, skin temperature, brain waves) collected through sensors.
[248] Neurofeedback is a type of biofeedback received by measuring brain waves and producing a feedback signal.

Annexes

Annex 1. Abbreviations

ADHD	Attention deficit hyperactivity disorder
AI	Artificial intelligence
API	Application programming interface
AR	Augmented reality
ASD	Autism spectrum disorder
CAGR	Compound annual growth rate
CBT	Cognitive behavioural therapy
CE	Conformité Européenne
CEO	Chief executive officer
CIVE	Collaborative immersive virtual environments
CSA	Coordination and support actions
CT	Computerised tomography
CTA	Computed tomography angiography
CWA	CEN Workshop Agreement
EIT	European Institute for Innovation and Technology
EU	European Union
EU MSs	Member State of the European Union
GDPR	General Data Protection Regulation
HMD	Head-mounted display
IA	Innovation actions
ICT	Information and communications technology
LVC	Live-Virtual-Constructive
MLD	Mathematical learning disability
MR	Mixed reality
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
NDD	Neurodevelopmental disabilities
PBIS	Positive behaviour interventions and supports
PTSD	Post-traumatic stress disorder
RIA	Research and innovation actions
STEM	Science, technology, engineering and mathematics
UK	United Kingdom
US	United States
VET	Vocational Education and Training
VR	Virtual reality
XR	Extended reality

Annex 2. Bibliography

List of sources used in healthcare sector analysis

1. ABI Research, & Qualcomm. (2017). Augmented and Virtual Reality: The First Wave of 5G Killer Apps | Qualcomm. https://www.qualcomm.com/documents/augmented-and-virtual-reality-first-wave-5g-killer-apps
2. Ahmadpour, N., Randall, H., Choksi, H., Gao, A., Vaughan, C., & Poronnik, P. (2019). Virtual Reality interventions for acute and chronic pain management. The International Journal of Biochemistry & Cell Biology, 114. https://doi.org/10.1016/j.biocel.2019.105568
3. Alfonso-Garcia, A., Bec, J., Sridharan Weaver, S., Hartl, B., Unger, J., Bobinski, M., Lechpammer, M., Girgis, F., Boggan, J., & Marcu, L. (2020). Real-time augmented reality for delineation of surgical margins during neurosurgery using autofluorescence lifetime contrast. Journal of Biophotonics, 13(1), e201900108. https://doi.org/10.1002/JBIO.201900108
4. Alqudimat, M., Mesaroli, G., Lalloo, C., Stinson, J., & Matava, C. (2021). State of the Art: Immersive Technologies for Perioperative Anxiety, Acute, and Chronic Pain Management in Pediatric Patients. Current Anesthesiology Reports, 11(3). https://doi.org/10.1007/s40140-021-00472-3
5. Amini, N., Lim, J. S., Mohammadi, F., Thodos, C., Braun, B., Ghasemzadeh, H., Chun, M. W., & Nouri-Mahdavi, K. (2020, September 12). Design and evaluation of a wearable assistive technology for hemianopic stroke patients. Proceedings of the 2020 International Symposium on Wearable Computers. https://doi.org/10.1145/3410531.3414296
6. Andersen, D., Popescu, V., Cabrera, M. E., Shanghavi, A., Mullis, B., Marley, S., Gomez, G., & Wachs, J. P. (2017). An Augmented Reality-Based Approach for Surgical Telementoring in Austere Environments. Military Medicine, 182(S1), 310–315. https://doi.org/10.7205/MILMED-D-16-00051
7. ANSES. (2021). Expositions aux technologies de réalité virtuelle et/ou augmentée Avis de l'Anses Rapport d'expertise collective. www.anses.fr
8. Arane, K., Behboudi, A., & Goldman, R. D. (2017). Virtual reality for pain and anxiety management in children. Canadian Family Physician, 63(12).
9. Ayoub, A., & Pulijala, Y. (2019). The application of virtual reality and augmented reality in Oral & Maxillofacial Surgery. BMC Oral Health, 19(1), 1–8. https://doi.org/10.1186/S12903-019-0937-8/FIGURES/2
10. Aziz, H. A. (2018). Virtual Reality Programs Applications in Healthcare. https://doi.org/10.4172/2157-7420.1000305
11. Baños, R. M., Escobar, P., Cebolla, A., Guixeres, J., Alvarez Pitti, J., Lisón, J. F., & Botella, C. (2016). Using Virtual Reality to Distract Overweight Children from Bodily Sensations During Exercise. Cyberpsychology, Behavior and Social Networking, 19(2), 115–119. https://doi.org/10.1089/CYBER.2015.0283
12. Barteit, S., Lanfermann, L., Bärnighausen, T., Neuhann, F., & Beiersmann, C. (2021). Augmented, Mixed, and Virtual Reality-Based Head-Mounted Devices for Medical Education: Systematic Review. JMIR Serious Games, 9(3). https://doi.org/10.2196/29080
13. Bashiri, A., Ghazisaeedi, M., & Shahmoradi, L. (2017). The opportunities of virtual reality in the rehabilitation of children with attention deficit hyperactivity disorder: a literature review. Korean Journal of Pediatrics, 60(11). https://doi.org/10.3345/kjp.2017.60.11.337
14. Bell, B. (2019). Benefits of Sensory Rooms & Spaces in Schools and Homes. https://enablingdevices.com/blog/benefits-sensory-rooms-special-needs/

15. Benaich, N. (2021). Universities in the UK and Europe have a start-up problem. Financial Times. https://www.ft.com/content/fd038300-f09a-4afc-9f7d-c0e3d6965243

16. Bermudez i Badia, S., Quintero, L. V., Cameirao, M. S., Chirico, A., Triberti, S., Cipresso, P., & Gaggioli, A. (2019). Toward Emotionally Adaptive Virtual Reality for Mental Health Applications. IEEE Journal of Biomedical and Health Informatics, 23(5). https://doi.org/10.1109/JBHI.2018.2878846

17. Blum, D. (2021, June 3). Virtual Reality Therapy Plunges Patients Back Into Trauma. Here Is Why Some Swear by It. - The New York Times. https://www.nytimes.com/2021/06/03/well/mind/vr-therapy.html

18. Boeldt, D., McMahon, E., McFaul, M., & Greenleaf, W. (2019). Using Virtual Reality Exposure Therapy to Enhance Treatment of Anxiety Disorders: Identifying Areas of Clinical Adoption and Potential Obstacles. Frontiers in Psychiatry, 10. https://doi.org/10.3389/fpsyt.2019.00773

19. Bona, S., Donvito, G., Cozza, F., Malberti, I., Vaccari, P., Lizio, A., Greco, L., Carraro, E., Sansone, V. A., & Lunetta, C. (2021). The development of an augmented reality device for the autonomous management of the electric bed and the electric wheelchair for patients with amyotrophic lateral sclerosis: a pilot study. Disability and Rehabilitation: Assistive Technology, 16(5), 513–519. https://doi.org/10.1080/17483107.2019.1683237/SUPPL_FILE/IIDT_A_1683237_SM6967.DOCX

20. Bond, S., Laddu, D. R., Ozemek, C., Lavie, C. J., & Arena, R. (2021). Exergaming and Virtual Reality for Health: Implications for Cardiac Rehabilitation. Current Problems in Cardiology, 46(3), 100472. https://doi.org/10.1016/J.CPCARDIOL.2019.100472

21. Brütsch, K., Schuler, T., Koenig, A., Zimmerli, L., Koeneke, S. M., Lünenburger, L., Riener, R., Jäncke, L., & Meyer-Heim, A. (2010). Influence of virtual reality soccer game on walking performance in robotic assisted gait training for children. Journal of NeuroEngineering and Rehabilitation, 7(1), 1–9. https://doi.org/10.1186/1743-0003-7-15/FIGURES/5

22. Calin Riley-Missouri. (2019, June 26). Virtual reality could soon let your doctor 'step inside' your blood sample | World Economic Forum. https://www.weforum.org/agenda/2019/06/doctor-to-step-inside-biopsy-samples-with-vr/

23. Cao, Y., Huang, X., Zhang, B., Kranz, G. S., Zhang, D., Li, X., & Chang, J. (2021). Effects of virtual reality in post-stroke aphasia: a systematic review and meta-analysis. Neurological Sciences 2021, 1–11. https://doi.org/10.1007/S10072-021-05202-5

24. Caserman, P., Garcia-Agundez, A., Gámez Zerban, A., & Göbel, S. (2021). Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Reality, 25(4), 1153–1170. https://doi.org/10.1007/S10055-021-00513-6/FIGURES/1

25. Cerritelli, F., Chiera, M., Abbro, M., Megale, V., Esteves, J., Gallace, A., & Manzotti, A. (2021). The Challenges and Perspectives of the Integration Between Virtual and Augmented Reality and Manual Therapies. Frontiers in Neurology, 12. https://doi.org/10.3389/fneur.2021.700211

26. Chan, J., Pangal, D. J., Cardinal, T., Kugener, G., Zhu, Y., Roshannai, A., Markarian, N., Sinha, A., Anandkumar, A., Hung, A., Zada, G., & Donoho, D. A. (2021). A systematic review of virtual reality for the assessment of technical skills in neurosurgery. Neurosurgical Focus, 51(2). https://doi.org/10.3171/2021.5.FOCUS21210

27. Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. Https://Doi.Org/10.1080/10447318.2020.1778351, 1658–1682. https://doi.org/10.1080/10447318.2020.1778351

28. Chawla, V. (2022). Where is the money in digital health? The roadmap to digital health app reimbursement in Europe. Research2Guidance. https://research2guidance.com/where-is-the-money-in-digital-health-the-roadmap-to-digital-health-app-reimbursement-in-europe/

29. Chen, P.-H. C., Gadepalli, K., MacDonald, R., Liu, Y., Kadowaki, S., Nagpal, K., Kohlberger, T., Dean, J., Corrado, G. S., Hipp, J. D., Mermel, C. H., & Stumpe, M. C. (2019). An augmented reality microscope with real-time artificial intelligence integration for cancer diagnosis. Nature Medicine, 25(9). https://doi.org/10.1038/s41591-019-0539-7

30. Cieślik, B., Mazurek, J., Rutkowski, S., Kiper, P., Turolla, A., & Szczepańska-Gieracha, J. (2020). Virtual reality in psychiatric disorders: A systematic review of reviews. Complementary Therapies in Medicine, 52. https://doi.org/10.1016/j.ctim.2020.102480

31. Cogné, M., Taillade, M., N'Kaoua, B., Tarruella, A., Klinger, E., Larrue, F., Sauzéon, H., Joseph, P. A., & Sorita, E. (2017). The contribution of virtual reality to the diagnosis of spatial navigation disorders and to the study of the role of navigational aids: A systematic literature review. Annals of Physical and Rehabilitation Medicine, 60(3), 164–176. https://doi.org/10.1016/J.REHAB.2015.12.004

32. Cortese, M., & Outlaw, J. (2021). The IEEE Global Initiative on Ethics of Extended Reality (XR) Report: Social and Multi-User Spaces In VR: Trolling, Harassment, and Online Safety. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9650825

33. Dechant, M., Trimpl, S., Wolff, C., Mühlberger, A., & Shiban, Y. (2017). Potential of virtual reality as a diagnostic tool for social anxiety: A pilot study. Computers in Human Behavior, 76, 128–134. https://doi.org/10.1016/J.CHB.2017.07.005

34. Delshad, S. D., Almario, C. v., Fuller, G., Luong, D., & Spiegel, B. M. R. (2018). Economic analysis of implementing virtual reality therapy for pain among hospitalized patients. Npj Digital Medicine, 1(1). https://doi.org/10.1038/S41746-018-0026-4

35. Dennler, C., Jaberg, L., Spirig, J., Agten, C., Götschi, T., Fürnstahl, P., & Farshad, M. (n.d.). Augmented reality-based navigation increases precision of pedicle screw insertion. https://doi.org/10.1186/s13018-020-01690-x

36. Dombrowski, M., Smith, P. A., Manero, A., & Sparkman, J. (2019a). Designing Inclusive Virtual Reality Experiences. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11574 LNCS, 33–43. https://doi.org/10.1007/978-3-030-21607-8_3

37. Dombrowski, M., Smith, P. A., Manero, A., & Sparkman, J. (2019b). Designing Inclusive Virtual Reality Experiences. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11574 LNCS, 33–43. https://doi.org/10.1007/978-3-030-21607-8_3

38. Douglas, D. B., Boone, J. M., Petricoin, E., Liotta, L., & Wilson, E. (2016). Augmented Reality Imaging System: 3D Viewing of a Breast Cancer. Journal of Nature and Science, 2(9). /pmc/articles/PMC5074083/

39. Ebner, F., de Gregorio, A., Schochter, F., Bekes, I., Janni, W., & Lato, K. (2019). Effect of an Augmented Reality Ultrasound Trainer App on the Motor Skills Needed for a Kidney Ultrasound: Prospective Trial. JMIR Serious Games 2019;7(2):E12713 Https://Games.Jmir.Org/2019/2/E12713, 7(2), e12713. https://doi.org/10.2196/12713

40. Ehrlich, J. R., Ojeda, L. v., Wicker, D., Day, S., Howson, A., Lakshminarayanan, V., & Moroi, S. E. (2017). Head-Mounted Display Technology for Low-Vision Rehabilitation and Vision Enhancement. American Journal of Ophthalmology, 176, 26–32. https://doi.org/10.1016/j.ajo.2016.12.021

41. Ellis, L. A., Lee, M. D., Ijaz, K., Smith, J., Braithwaite, J., & Yin, K. (2020). COVID-19 as 'Game Changer' for the Physical Activity and Mental Well-Being of Augmented Reality

Game Players During the Pandemic: Mixed Methods Survey Study. Journal of Medical Internet Research, 22(12). https://doi.org/10.2196/25117

42. Ellysse Dick. (2021). Balancing User Privacy and Innovation in Augmented and Virtual Reality. ITIF. https://itif.org/publications/2021/03/04/balancing-user-privacy-and-innovation-augmented-and-virtual-reality

43. Elmi-Terander, A., Nachabe, R., Skulason, H., Pedersen, K., Söderman, M., Racadio, J., Babic, D., Gerdhem, P., & Edström, E. (2018). Feasibility and Accuracy of Thoracolumbar Minimally Invasive Pedicle Screw Placement With Augmented Reality Navigation Technology. Spine, 43(14), 1018–1023. https://doi.org/10.1097/BRS.0000000000002502

44. Emil Gejrot, Sara Kjellstrand, & Susanna Laurin. (2021). New Realities: Unlocking the Potential of XR for Persons with Disabilities. In Commissioned by Facebook under agreement "Research on Accessibility Benefits of AR and VR Technology." https://www.funka.com/contentassets/0efed77304a3467aa7fdd7e181c7b47b/new_realities_xr_for_pwd.pdf

45. Evans, J. et al. (2022). The IEEE Global Initiative on Ethics of Extended Reality (XR) Report. Ethics in Medicine. https://standards.ieee.org/about/bog/iccom/.

46. Fernández-Alvarez, J., Grassi, M., Colombo, D., Botella, C., Cipresso, P., Perna, G., & Riva, G. (2021). Efficacy of bio- and neurofeedback for depression: a meta-analysis. Psychological Medicine. https://doi.org/10.1017/S0033291721004396

47. Fertleman, C., Aubugeau-Williams, P., Sher, C., Lim, A. N., Lumley, S., Delacroix, S., & Pan, X. (2018). A discussion of virtual reality as a new tool for training healthcare professionals. Frontiers in Public Health, 6(FEB), 44. https://doi.org/10.3389/FPUBH.2018.00044/BIBTEX

48. Foerster, R. M., Poth, C. H., Behler, C., Botsch, M., & Schneider, W. X. (2016). Using the virtual reality device Oculus Rift for neuropsychological assessment of visual processing capabilities. Scientific Reports 2016 6:1, 6(1), 1–10. https://doi.org/10.1038/srep37016

49. Fox, D., Li, A., Pandey, A., & Kar, R. (2019). Augmented Reality for Visually Impaired People (AR for VIPs).

50. Freeman, D., J, B., A, A., E, B., N, D., N, E., E, Č., B, S., F, W., G, D., M, S., & DM, C. (2016). Virtual reality in the treatment of persecutory delusions: randomised controlled experimental study testing how to reduce delusional conviction. The British Journal of Psychiatry : The Journal of Mental Science, 209(1), 62–67. https://doi.org/10.1192/BJP.BP.115.176438

51. García-Betances, R. I., Jiménez-Mixco, V., Arredondo, M. T., & Cabrera-Umpiérrez, M. F. (2015). Using Virtual Reality for Cognitive Training of the Elderly. American Journal of Alzheimer's Disease & Other Dementias, 30(1). https://doi.org/10.1177/1533317514545866

52. Goo, H. W., Park, S. J., & Yoo, S. J. (2020). Advanced Medical Use of Three-Dimensional Imaging in Congenital Heart Disease: Augmented Reality, Mixed Reality, Virtual Reality, and Three-Dimensional Printing. Korean Journal of Radiology, 21(2), 133–145. https://doi.org/10.3348/KJR.2019.0625

53. Gorman, C., & Gustafsson, L. (2020). The use of augmented reality for rehabilitation after stroke: a narrative review. Https://Doi.Org/10.1080/17483107.2020.1791264, 1–9. https://doi.org/10.1080/17483107.2020.1791264

54. Grechuta, K., Rubio Ballester, B., Espín Munne, R., Usabiaga Bernal, T., Molina Hervás, B., Mohr, B., Pulvermüller, F., San Segundo, R., & Verschure, P. (2019). Augmented Dyadic Therapy Boosts Recovery of Language Function in Patients With Nonfluent Aphasia: A Randomized Controlled Trial. Stroke, 50(5), 1270–1274. https://doi.org/10.1161/STROKEAHA.118.023729

55. Guarino, D., la Paglia, F., Daino, M., Maiorca, V., Zichichi, S., Guccione, F., Pintabona, A., Wiederhold, M. D., Riva, G., Wiederhold, B. K., & la Barbera, D. (2017). Chronic Pain Treatment Through Virtual Reality. Annual Review of Cybertherapy and Telemedicine, 15.

56. Hamacher, A., Kim, S. J., Cho, S. T., Pardeshi, S., Lee, S. H., Eun, S. J., & Whangbo, T. K. (2016). Application of Virtual, Augmented, and Mixed Reality to Urology. International Neurourology Journal, 20(3), 172. https://doi.org/10.5213/INJ.1632714.357

57. Häuser, W., Buchser, E., Finn, D. P., Dom, G., Fors, E., Heiskanen, T., Jarlbaek, L., Knaggs, R. D., Kosek, E., Krcevski-Škvarč, N., Pakkonen, K., Perrot, S., Trouvin, A. P., & Morlion, B. (2021). Is Europe also facing an opioid crisis?-A survey of European Pain Federation chapters. European Journal of Pain (London, England), 25(8), 1760–1769. https://doi.org/10.1002/EJP.1786

58. Heinrich, F., Schmidt, G., Hansen, C., & Jungmann, F. (2019). Augmented reality visualisation concepts to support intraoperative distance estimation. Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST. https://doi.org/10.1145/3359996.3364818

59. Huang, J., Kinateder, M., Dunn, M. J., Jarosz, W., Yang, X. D., & Cooper, E. A. (2019). An augmented reality sign-reading assistant for users with reduced vision. PLOS ONE, 14(1), e0210630. https://doi.org/10.1371/JOURNAL.PONE.0210630

60. Huang, X., Funsch, K. M., Park, E. C., Conway, P., Franklin, J. C., & Ribeiro, J. D. (2021). Longitudinal studies support the safety and ethics of virtual reality suicide as a research method. Scientific Reports 2021 11:1, 11(1), 1–12. https://doi.org/10.1038/s41598-021-89152-0

61. Iqbal, S., Farooq, S., Shahzad, K., Malik, A. W., Hamayun, M. M., & Hasan, O. (2019). SecureSurgiNET: A framework for ensuring security in telesurgery: Https://Doi.Org/10.1177/1550147719873811, 15(9). https://doi.org/10.1177/1550147719873811

62. Islam, M. K., & Brunner, I. (2019). Cost-analysis of virtual reality training based on the Virtual Reality for Upper Extremity in Subacute stroke (VIRTUES) trial. International Journal of Technology Assessment in Health Care, 35(5), 373–378. https://doi.org/10.1017/S026646231900059X

63. Jeffs, D., Dorman, D., Brown, S., Files, A., Graves, T., Kirk, E., Meredith-Neve, S., Sanders, J., White, B., & Swearingen, C. J. (2014). Effect of Virtual Reality on Adolescent Pain During Burn Wound Care. Journal of Burn Care & Research, 35(5). https://doi.org/10.1097/BCR.0000000000000019

64. Jones, P. R., Somoskeöy, T., Chow-Wing-Bom, H., & Crabb, D. P. (2020). Seeing other perspectives: evaluating the use of virtual and augmented reality to simulate visual impairments (OpenVisSim). Npj Digital Medicine 2020 3:1, 3(1), 1–9. https://doi.org/10.1038/s41746-020-0242-6

65. Khor, W. S., Baker, B., Amin, K., Chan, A., Patel, K., & Wong, J. (2016). Augmented and virtual reality in surgery—the digital surgical environment: applications, limitations and legal pitfalls. Annals of Translational Medicine, 4(23). https://doi.org/10.21037/ATM.2016.12.23

66. Kim, O., Pang, Y., & Kim, J.-H. (2019). The effectiveness of virtual reality for people with mild cognitive impairment or dementia: a meta-analysis. BMC Psychiatry, 19(1). https://doi.org/10.1186/s12888-019-2180-x

67. Kordali, P. (2021, May 21). Transformational Impact of XR Technologies on Medical Education - AIXR. https://aixr.org/insights/transformational-impact-of-xr-technologies-on-medical-education/

68. Ku, J., & Kang, Y. J. (2018). Novel Virtual Reality Application in Field of Neurorehabilitation. Brain & Neurorehabilitation, 11(1). https://doi.org/10.12786/BN.2018.11.E5

69. Lachmeijer, R. (2022). Guntur Sandino: “Angststoornissen verdwijnen sneller en goedkoper met virtual reality.” Change Inc. https://www.change.inc/ict/guntur-sandino-maakt-mensen-sneller-geestelijk-gezond-met-vr-37959

70. Laver, K. E., Lange, B., George, S., Deutsch, J. E., Saposnik, G., & Crotty, M. (2017). Virtual reality for stroke rehabilitation. The Cochrane Database of Systematic Reviews, 11(11). https://doi.org/10.1002/14651858.CD008349.PUB4

71. Lee, J., Mullarkey, M. C., & Weisz, J. R. (2019). Virtual Reality and Web-Based Growth Mindset Interventions for Adolescent Depression: Protocol for a Three-Arm Randomized Trial. JMIR Res Protoc 2019;8(7):E13368 Https://Www.Researchprotocols.Org/2019/7/E13368, 8(7), e13368. https://doi.org/10.2196/13368

72. Lemley, M., & Volokh, E. (2018). Law, Virtual Reality, and Augmented Reality. University of Pennsylvania Law Review, 166(5). https://scholarship.law.upenn.edu/penn_law_review/vol166/iss5/1

73. Li, T., Li, C., Zhang, X., Liang, W., Chen, Y., Ye, Y., & Lin, H. (2021). Augmented Reality in Ophthalmology: Applications and Challenges. Frontiers in Medicine, 0, 2548. https://doi.org/10.3389/FMED.2021.733241

74. Ligthart, S., Meynen, G., Biller-Andorno, N., Kooijmans, T., & Kellmeyer, P. (2021). Is Virtually Everything Possible? The Relevance of Ethics and Human Rights for Introducing Extended Reality in Forensic Psychiatry. Https://Doi.Org/10.1080/21507740.2021.1898489. https://doi.org/10.1080/21507740.2021.1898489

75. Lin, C. X., Lee, C., Lally, D., & Coughlin, J. F. (2018). Impact of Virtual Reality (VR) Experience on Older Adults’ Well-Being. https://doi.org/10.1007/978-3-319-92037-5_8

76. Lindner, P., Hamilton, W., Miloff, A., & Carlbring, P. (2019). How to Treat Depression With Low-Intensity Virtual Reality Interventions: Perspectives on Translating Cognitive Behavioral Techniques Into the Virtual Reality Modality and How to Make Anti-Depressive Use of Virtual Reality–Unique Experiences. Frontiers in Psychiatry, 0(OCT), 792. https://doi.org/10.3389/FPSYT.2019.00792

77. Liu, X., Tao, H., Xiao, X., Guo, B., Xu, S., Sun, N., Li, M., Xie, L., & Wu, C. (2018). Use of the stereoscopic virtual reality display system for the detection and characterization of intracranial aneurysms: A comparison with conventional computed tomography workstation and 3D rotational angiography. Clinical Neurology and Neurosurgery, 170, 93–98. https://doi.org/10.1016/j.clineuro.2018.04.034

78. Logeswaran, A., Munsch, C., Chong, Y. J., Ralph, N., & McCrossnan, J. (2021). The role of extended reality technology in healthcare education: Towards a learner-centred approach. Future Healthcare Journal, 8(1), e79. https://doi.org/10.7861/FHJ.2020-0112

79. Ma, L., Mor, S., Anderson, P. L., Baños, R. M., Botella, C., Bouchard, S., Cárdenas-López, G., Donker, T., Fernández-Álvarez, J., Lindner, P., Mühlberger, A., Powers, M. B., Quero, S., Rothbaum, B., Wiederhold, B. K., & Carlbring, P. (2021). Integrating virtual realities and psychotherapy: SWOT analysis on VR and MR based treatments of anxiety and stress-related disorders. Https://Doi.Org/10.1080/16506073.2021.1939410, 50(6), 509–526. https://doi.org/10.1080/16506073.2021.1939410

80. Madary, M., & Metzinger, T. K. (2016). Real virtuality: A code of ethical conduct. Recommendations for good scientific practice and the consumers of VR-technology. Frontiers Robotics AI, 3(FEB), 3. https://doi.org/10.3389/FROBT.2016.00003/BIBTEX

81. Madison, D. (2018). The future of augmented reality in healthcare. 18(1), 41–45. https://healthmanagement.org/uploads/article_attachment/the-future-of-augmented-reality-in-healthcare.pdf

82. Mäkinen, H., Haavisto, E., Havola, S., & Koivisto, J. M. (2020). User experiences of virtual reality technologies for healthcare in learning: an integrative review. Https://Doi.Org/10.1080/0144929X.2020.1788162, 1–17. https://doi.org/10.1080/0144929X.2020.1788162

83. Mantovani, E., Zucchella, C., Bottiroli, S., Federico, A., Giugno, R., Sandrini, G., Chiamulera, C., & Tamburin, S. (2020). Telemedicine and Virtual Reality for Cognitive Rehabilitation: A Roadmap for the COVID-19 Pandemic. Frontiers in Neurology, 11, 926. https://doi.org/10.3389/FNEUR.2020.00926/BIBTEX

84. Marín-Morales, J., Higuera-Trujillo, J. L., Greco, A., Guixeres, J., Llinares, C., Scilingo, E. P., Alcañiz, M., & Valenza, G. (2018). Affective computing in virtual reality: emotion recognition from brain and heartbeat dynamics using wearable sensors. Scientific Reports 2018 8:1, 8(1), 1–15. https://doi.org/10.1038/s41598-018-32063-4

85. Márquez-Caraveo, M. E., Rodríguez-Valentín, R., Pérez-Barrón, V., Vázquez-Salas, R. A., Sánchez-Ferrer, J. C., de Castro, F., Allen-Leigh, B., & Lazcano-Ponce, E. (2021). Children and adolescents with neurodevelopmental disorders show cognitive heterogeneity and require a person-centered approach. Scientific Reports 2021 11:1, 11(1), 1–14. https://doi.org/10.1038/s41598-021-97551-6

86. Mason, R. O. (1986). Four ethical issues of the information age. MIS Quarterly: Management Information Systems, 10(1), 5–12. https://doi.org/10.2307/248873

87. McCahill, R. J., Nagle, C., & Clarke, P. (2021). Use of Virtual Reality for minor procedures in the Emergency Department: A scoping review. Australasian Emergency Care, 24(3), 174–178. https://doi.org/10.1016/j.auec.2020.06.006

88. Mehra, R., Brimijoin, O., Robinson, P., & Lunner, T. (2020). Potential of Augmented Reality Platforms to Improve Individual Hearing Aids and to Support More Ecologically Valid Research. Ear and Hearing, 41, 140S-146S. https://doi.org/10.1097/AUD.0000000000000961

89. Meldrum, D., Herdman, S., Vance, R., Murray, D., Malone, K., Duffy, D., Glennon, A., & McConn-Walsh, R. (2015). Effectiveness of conventional versus virtual reality-based balance exercises in vestibular rehabilitation for unilateral peripheral vestibular loss: results of a randomized controlled trial. Archives of Physical Medicine and Rehabilitation, 96(7), 1319-1328.e1. https://doi.org/10.1016/J.APMR.2015.02.032

90. Miller, I. T., Miller, C. S., Wiederhold, M. D., Dolga, M., & Wiederhold, B. K. (2019). Autism Spectrum Disorder and the Use of Virtual Reality Technologies to Address Core Social Communication Deficits-A Statement of Position. Global Journal of Intellectual & Developmental Disabilities, 6(2), 1–5. https://doi.org/10.19080/GJIDD.2019.06.555683

91. Miller, K. K., Porter, R. E., DeBaun-Sprague, E., van Puymbroeck, M., & Schmid, A. A. (2016). Exercise after Stroke: Patient Adherence and Beliefs after Discharge from Rehabilitation. Http://Dx.Doi.Org/10.1080/10749357.2016.1200292, 24(2), 142–148. https://doi.org/10.1080/10749357.2016.1200292

92. Molinari, E., Vincelli, F., Riva, G., Choi, Y. H., & Wiederhold, B. (2002). Multi-Center Study for the Treatment of Panic Disorders with Agoraphobia. Cognitive Psychotherapy Toward a New Millennium, 335–342. https://doi.org/10.1007/978-1-4615-0567-9_57

93. Mosso-Vázquez, J. L., Wiederhold, B. K., Miller, I., & Wiederhold, M. D. (2017). Virtual Reality Assisted Anesthesia--A report of 115 Cases. European Medical Journal Innov, 1(1), 75–82. https://www.emjreviews.com/innovations/article/virtual-reality-assisted-anaesthesia-during-upper-gastrointestinal-endoscopy-report-of-115-cases/

94. Nilufar, Chitale, V., Hlasnik, A., Stemmet, L., Liang, H.-N., & Porter, R. (2021). Virtual Reality for Supporting the Treatment of Depression and Anxiety: Scoping Review. JMIR Ment Health 2021;8(9):E29681 Https://Mental.Jmir.Org/2021/9/E29681, 8(9), e29681. https://doi.org/10.2196/29681

95. O'Brolcháin, F., Jacquemard, T., Monaghan, D., O'Connor, N., Novitzky, P., & Gordijn, B. (2016). The Convergence of Virtual Reality and Social Networks: Threats to Privacy and Autonomy. Science and Engineering Ethics, 22(1), 1–29. https://doi.org/10.1007/s11948-014-9621-1

96. Ong, T., Wilczewski, H., Paige, S. R., Soni, H., Welch, B. M., & Bunnell, B. E. (2021). Extended Reality for Enhanced Telehealth During and Beyond COVID-19: Viewpoint. JMIR Serious Games, 9(3), e26520. https://doi.org/10.2196/26520

97. Orlosky, J., Itoh, Y., Ranchet, M., Kiyokawa, K., Morgan, J., & Devos, H. (2017). Emulation of Physician Tasks in Eye-Tracked Virtual Reality for Remote Diagnosis of Neurodegenerative Disease. IEEE Transactions on Visualization and Computer Graphics, 23(4), 1302–1311. https://doi.org/10.1109/TVCG.2017.2657018

98. Pallesen, H., Andersen, M. B., Hansen, G. M., Lundquist, C. B., & Brunner, I. (2018). Patients' and Health Professionals' Experiences of Using Virtual Reality Technology for Upper Limb Training after Stroke: A Qualitative Substudy. Rehabilitation Research and Practice, 2018, 1–11. https://doi.org/10.1155/2018/4318678

99. Panachakel, J. T., Ramakrishnan, A. G., & Manjunath, K. P. (2020). VR Glasses based Measurement of Responses to Dichoptic Stimuli: A Potential Tool for Quantifying Amblyopia? Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, 2020-July, 5106–5110. https://doi.org/10.1109/EMBC44109.2020.9176510

100. Pelanis, E., Kumar, R. P., Aghayan, D. L., Palomar, R., Fretland, Å. A., Brun, H., Elle, O. J., & Edwin, B. (2019). Use of mixed reality for improved spatial understanding of liver anatomy. Https://Doi.Org/10.1080/13645706.2019.1616558, 29(3), 154–160. https://doi.org/10.1080/13645706.2019.1616558

101. Pérez-Pachón, L., Poyade, M., Lowe, T., & Gröning, F. (2020). Image Overlay Surgery Based on Augmented Reality: A Systematic Review. https://doi.org/10.1007/978-3-030-47483-6_10

102. Pericot-Valverde, I., Secades-Villa, R., Gutiérrez-Maldonado, J., & García-Rodríguez, O. (2014). Effects of Systematic Cue Exposure Through Virtual Reality on Cigarette Craving. Nicotine & Tobacco Research, 16(11), 1470–1477. https://doi.org/10.1093/NTR/NTU104

103. Perin, A., Galbiati, T. F., Ayadi, R., Gambatesa, E., Orena, E. F., Riker, N. I., Silberberg, H., Sgubin, D., Meling, T. R., & DiMeco, F. (2021). Informed consent through 3D virtual reality: a randomized clinical trial. Acta Neurochirurgica, 163(2). https://doi.org/10.1007/s00701-020-04303-y

104. Piron, L., Turolla, A., Agostini, M., Zucconi, C., Cortese, F., Zampolini, M., Zannini, M., Dam, M., Ventura, L., Battauz, M., & Tonin, P. (2009). Exercises for paretic upper limb after stroke: A combined virtual-reality and telemedicine approach. Journal of Rehabilitation Medicine, 41(12), 1016–1020. https://doi.org/10.2340/16501977-0459

105. Porras, D. C. (2021). Virtual reality (VR) trends in healthcare. SOCRATES Blog. https://socratesvr.eu/virtual-reality-vr-trends-in-healthcare/

106. Pot-Kolder, R. M. C. A., Geraets, C. N. W., Veling, W., van Beilen, M., Staring, A. B. P., Gijsman, H. J., Delespaul, P. A. E. G., & van der Gaag, M. (2018). Virtual-reality-based cognitive behavioural therapy versus waiting list control for paranoid ideation and social

avoidance in patients with psychotic disorders: a single-blind randomised controlled trial. The Lancet Psychiatry, 5(3). https://doi.org/10.1016/S2215-0366(18)30053-1

107. Pot-Kolder, R., Veling, W., Geraets, C., Lokkerbol, J., Smit, F., Jongeneel, A., Ising, H., & van der Gaag, M. (2020a). Cost-effectiveness of virtual reality cognitive behavioral therapy for psychosis: Health-economic evaluation within a randomized controlled trial. Journal of Medical Internet Research, 22(5). https://doi.org/10.2196/17098

108. Pottle, J. (2019). Virtual reality and the transformation of medical education. Future Healthcare Journal, 6(3), 181. https://doi.org/10.7861/FHJ.2019-0036

109. Primack, B. A., Shensa, A., Sidani, J. E., Whaite, E. O., Lin, L. yi, Rosen, D., Colditz, J. B., Radovic, A., & Miller, E. (2017). Social Media Use and Perceived Social Isolation Among Young Adults in the U.S. American Journal of Preventive Medicine, 53(1), 1–8. https://doi.org/10.1016/J.AMEPRE.2017.01.010

110. Ramirez, E. J. (2021). The Ethics of Virtual and Augmented Reality : Building Worlds. In The Ethics of Virtual and Augmented Reality (1st Edition). Routledge. https://doi.org/10.4324/9781003042228

111. Ramirez, E. J., Elliott, M., & Milam, P. E. (2021). What it’s like to be a _____: why it’s (often) unethical to use VR as an empathy nudging tool. Ethics and Information Technology 2021 23:3, 23(3), 527–542. https://doi.org/10.1007/S10676-021-09594-Y

112. Ratclife, J., Soave, F., Bryan-Kinns, N., Tokarchuk, L., & Farkhatdinov, I. (2021). Extended reality (xr) remote research: A survey of drawbacks and opportunities. Conference on Human Factors in Computing Systems - Proceedings. https://doi.org/10.1145/3411764.3445170

113. Raz, G. (2022). Rage against the empathy machine revisited: The ethics of empathy-related affordances of virtual reality: Https://Doi.Org/10.1177/13548565221086406, 135485652210864. https://doi.org/10.1177/13548565221086406

114. Reiners, D., Davahli, M. R., Karwowski, W., & Cruz-Neira, C. (2021). The Combination of Artificial Intelligence and Extended Reality: A Systematic Review. Frontiers in Virtual Reality, 0, 114. https://doi.org/10.3389/FRVIR.2021.721933

115. Repetto, C., Paolillo, M. P., Tuena, C., Bellinzona, F., & Riva, G. (2020). Innovative technology-based interventions in aphasia rehabilitation: a systematic review. Https://Doi.Org/10.1080/02687038.2020.1819957. https://doi.org/10.1080/02687038.2020.1819957

116. Riva, G., Bernardelli, L., Castelnuovo, G., di Lernia, D., Tuena, C., Clementi, A., Pedroli, E., Malighetti, C., Sforza, F., Wiederhold, B. K., & Serino, S. (2021). A Virtual Reality-Based Self-Help Intervention for Dealing with the Psychological Distress Associated with the COVID-19 Lockdown: An Effectiveness Study with a Two-Week Follow-Up. International Journal of Environmental Research and Public Health 2021, Vol. 18, Page 8188, 18(15), 8188. https://doi.org/10.3390/IJERPH18158188

117. Riva, G., la Paglia, F., Daino, M., Guarino, D., Zichichi, S., Wiederhold, B. K., & la Barbera, D. (2018). Virtual Reality environments to reduce dental anxiety. Annual Review of CyberTherapy and Telemedicine, 16, 175–178. https://doi.org/10.2/JQUERY.MIN.JS

118. Riva, G., Malighetti, C., & Serino, | Silvia. (2021). Virtual reality in the treatment of eating disorders. https://doi.org/10.1002/cpp.2622

119. Rizzo, A., Lucas, G., Gratch, J., Stratou, G., Morency, L.-P., Chavez, K., Shilling, R., & Scherer, S. (2016). Automatic Behavior Analysis During a Clinical Interview with a Virtual Human. Studies in Health Technology and Informatics, 220, 316–322. https://doi.org/10.3233/978-1-61499-625-5-316

120. Robertson, A. (2022). Meta is adding a ‘personal boundary’ to VR avatars to stop harassment - The Verge. https://www.theverge.com/2022/2/4/22917722/meta-horizon-worlds-venues-metaverse-harassment-groping-personal-boundary-feature

121. Robitzki, D. (2019, January 8). How virtual reality tumours could help cure cancer | World Economic Forum. https://www.weforum.org/agenda/2019/01/virtual-reality-tumors-could-help-lead-to-new-cancer-treatments/

122. Rockstroh, C., Blum, J., & Göritz, A. S. (2021). A mobile VR-based respiratory biofeedback game to foster diaphragmatic breathing. Virtual Reality, 25(2), 539–552. https://doi.org/10.1007/S10055-020-00471-5/FIGURES/9

123. Saab, M. M., Landers, M., Murphy, D., O’Mahony, B., Cooke, E., O’Driscoll, M., & Hegarty, J. (2021). Nursing students’ views of using virtual reality in healthcare: A qualitative study. Journal of Clinical Nursing, 00, 1–15. https://doi.org/10.1111/JOCN.15978

124. Sahin, N., Keshav, N., Salisbury, J., & Vahabzadeh, A. (2018). Safety and Lack of Negative Effects of Wearable Augmented-Reality Social Communication Aid for Children and Adults with Autism. Journal of Clinical Medicine, 7(8). https://doi.org/10.3390/jcm7080188

125. Sánchez-Margallo, J. A., Plaza de Miguel, C., Fernández Anzules, R. A., & Sánchez-Margallo, F. M. (2021). Application of Mixed Reality in Medical Training and Surgical Planning Focused on Minimally Invasive Surgery. Frontiers in Virtual Reality, 0, 144. https://doi.org/10.3389/FRVIR.2021.692641

126. Schulze, S., Pence, T., Irvine, N., & Guinn, C. (2019). The Effects of Embodiment in Virtual Reality on Implicit Gender Bias. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11574 LNCS, 361–374. https://doi.org/10.1007/978-3-030-21607-8_28

127. Segawa, T., Baudry, T., Bourla, A., Blanc, J.-V., Peretti, C.-S., Mouchabac, S., & Ferreri, F. (2020). Virtual Reality (VR) in Assessment and Treatment of Addictive Disorders: A Systematic Review. Frontiers in Neuroscience, 0, 1409. https://doi.org/10.3389/FNINS.2019.01409

128. Segovia, K. Y., & Bailenson, J. N. (2009). Virtually True: Children’s Acquisition of False Memories in Virtual Reality. Https://Doi.Org/10.1080/15213260903287267, 12(4), 371–393. https://doi.org/10.1080/15213260903287267

129. Shluzas, L. A., Aldaz, G., & Leifer, L. (2016). Design Thinking Health: Telepresence for Remote Teams with Mobile Augmented Reality. Design Thinking Research: Making Design Thinking Foundational, 53–66. https://doi.org/10.1007/978-3-319-19641-1_5

130. Slater, M. (2021). Beyond Speculation About the Ethics of Virtual Reality: The Need for Empirical Results. Frontiers in Virtual Reality, 0, 81. https://doi.org/10.3389/FRVIR.2021.687609

131. Slater, M., Gonzalez-Liencres, C., Haggard, P., Vinkers, C., Gregory-Clarke, R., Jelley, S., Watson, Z., Breen, G., Schwarz, R., Steptoe, W., Szostak, D., Halan, S., Fox, D., & Silver, J. (2020). The Ethics of Realism in Virtual and Augmented Reality. Frontiers in Virtual Reality, 0, 1. https://doi.org/10.3389/FRVIR.2020.00001

132. Sobnath, D., Rehman, I. U., & Nasralla, M. M. (2020). Smart Cities to Improve Mobility and Quality of Life of the Visually Impaired. https://doi.org/10.1007/978-3-030-16450-8_1

133. Spiegel, B. (2020). VRx : how virtual therapeutics will revolutionize medicine. Basic Books.

134. Spiegel, J. S. (2018). The Ethics of Virtual Reality Technology: Social Hazards and Public Policy Recommendations. Science and Engineering Ethics 2017 24:5, 24(5), 1537–1550. https://doi.org/10.1007/S11948-017-9979-Y

135. Stretton, T., Cochrane, T., & Narayan, V. (2018). Exploring mobile mixed reality in healthcare higher education: A systematic review. Research in Learning Technology, 26. https://doi.org/10.25304/rlt.v26.2131

136. Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. Computers in Human Behavior, 86, 77–90. https://doi.org/10.1016/J.CHB.2018.04.019

137. Tabbaa, L., Ang, C. S., Rose, V., Siriaraya, P., Stewart, I., Jenkins, K. G., & Matsangidou, M. (2019, May 2). Bring the Outside In: Providing Accessible Experiences Through VR for People with Dementia in Locked Psychiatric Hospitals. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3290605.3300466

138. Tang, L. Z. W., Ang, K. S., Amirul, M., Yusoff, M. B. M., Tng, C. K., Alyas, M. D. B. M., Lim, J. G., Kyaw, P. K., & Folianto, F. (2015, April). Augmented reality control home (ARCH) for disabled and elderlies. 2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP). https://doi.org/10.1109/ISSNIP.2015.7106975

139. Thieme, H., Morkisch, N., Mehrholz, J., Pohl, M., Behrens, J., Borgetto, B., & Dohle, C. (2018). Mirror therapy for improving motor function after stroke. Cochrane Database of Systematic Reviews, 2018(7). https://doi.org/10.1002/14651858.CD008449.PUB3/EPDF/ABSTRACT

140. Tromp, J., Le, C., Le, B., & Le, D.-N. (2018). Massively Multi-user Online Social Virtual Reality Systems: Ethical Issues and Risks for Long-Term Use. In Social Networks Science: Design, Implementation, Security, and Challenges. Springer International Publishing. https://doi.org/10.1007/978-3-319-90059-9_7

141. Ullberg, T., Zia, E., Petersson, J., & Norrving, B. (2016). Perceived Unmet Rehabilitation Needs 1 Year after Stroke: An Observational Study from the Swedish Stroke Register. Stroke, 47(2), 539–541. https://doi.org/10.1161/STROKEAHA.115.011670

142. University of Cambridge. (2019, June 5). This VR device could let you know the early warning signs for Alzheimer’s | World Economic Forum. https://www.weforum.org/agenda/2019/06/virtual-reality-can-spot-navigation-problems-in-early-alzheimer-s-disease/

143. Usclade, A., Blanc, N., Kohlmuller, M., Torres, A., Siret, S., Tachet, C., Favard, B., Merlin, E., Pereira, B., & Rochette, E. (2021). Infrared augmented reality device versus standard procedure for peripheral venous catheterisation in children less than 3 years old: A quasi-experimental cluster randomised controlled trial. Journal of Clinical Nursing. https://doi.org/10.1111/jocn.16017

144. van Bennekom, M. J., de Koning, P. P., & Denys, D. (2017). Virtual reality objectifies the diagnosis of psychiatric disorders: A literature review. Frontiers in Psychiatry, 8(SEP), 163. https://doi.org/10.3389/FPSYT.2017.00163/BIBTEX

145. Vávra, P., Roman, J., Zonča, P., Ihnát, P., Němec, M., Kumar, J., Habib, N., & El-Gendi, A. (2017). Recent Development of Augmented Reality in Surgery: A Review. Journal of Healthcare Engineering, 2017. https://doi.org/10.1155/2017/4574172

146. Vayena, E. (2021). Value from health data: European opportunity to catalyse progress in digital health. The Lancet, 397(10275). https://doi.org/10.1016/S0140-6736(21)00203-8

147. Vincelli, F., Anolli, L., Bouchard, S., Wiederhold, B. K., Zurloni, V., & Riva, G. (2003). Experiential cognitive therapy in the treatment of panic disorders with agoraphobia: a controlled study. Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society, 6(3), 321–328. https://doi.org/10.1089/109493103322011632

148. Vincelli, F., Choi, Y. H., Molinari, E., Wiederhold, B. K., & Riva, G. (2001). A VR-Based Multicomponent Treatment For Panic Disorders With Agoraphobia. Studies in Health Technology and Informatics, 81, 544–550. https://doi.org/10.3233/978-1-60750-925-7-544

149. Wellens, L. M., Meulstee, J., van de Ven, C. P., Terwisscha Van Scheltinga, C. E. J., Littooij, A. S., van den Heuvel-Eibrink, M. M., Fiocco, M., Rios, A. C., Maal, T., & Wijnen, M. H. W. A. (2019). Comparison of 3-Dimensional and Augmented Reality Kidney Models With Conventional Imaging Data in the Preoperative Assessment of Children With Wilms Tumors. JAMA Network Open, 2(4), e192633–e192633. https://doi.org/10.1001/JAMANETWORKOPEN.2019.2633

150. Wiederhold, B. K., & Wiederhold, M. D. (2003). Three-year follow-up for virtual reality exposure for fear of flying. Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society, 6(4), 441–445. https://doi.org/10.1089/109493103322278844

151. Wiederhold Brenda K. and Miller, I. and W. M. D. (2018). Augmenting Behavioral Healthcare: Mobilizing Services with Virtual Reality and Augmented Reality. In K. Rivas Homero and Wac (Ed.), Digital Health: Scaling Healthcare to the World (pp. 123–137). Springer International Publishing. https://doi.org/10.1007/978-3-319-61446-5_9

152. Wijma, E. M., Veerbeek, M. A., Prins, M., Pot, A. M., & Willemse, B. M. (2018). A virtual reality intervention to improve the understanding and empathy for people with dementia in informal caregivers: results of a pilot study. Aging & Mental Health, 22(9), 1115–1123. https://doi.org/10.1080/13607863.2017.1348470

153. World Health Organization. (2019). Leading causes of death and disability 2000-2019: A visual summary. https://www.who.int/data/stories/leading-causes-of-death-and-disability-2000-2019-a-visual-summary

154. XR4ALL. (2020, February 18). The Ultimate Guide to the European XR Healthcare Investing Scene | by XR4ALL | Medium. https://xr4all.medium.com/the-ultimate-guide-to-the-european-xr-healthcare-investing-scene-9c53e6f4f6c3

155. Zhu, M., Liu, F., Chai, G., Pan, J. J., Jiang, T., Lin, L., Xin, Y., Zhang, Y., & Li, Q. (2017). A novel augmented reality system for displaying inferior alveolar nerve bundles in maxillofacial surgery. Scientific Reports 2017 7:1, 7(1), 1–11. https://doi.org/10.1038/srep42365

156. Zweifach, S. M., & Triola, M. M. (2019). Extended Reality in Medical Education: Driving Adoption through Provider-Centered Design. Digital Biomarkers, 3(1), 14–21. https://doi.org/10.1159/000498923

List of sources used in education sector analysis

1. Abdinejad M., Talaie B., Qorbani H. and Dalili S., (2020), Student perceptions using augmented reality and 3D visualization technologies in chemistry education, *J. Sci. Educ. Technol.*

2. Accenture Extended Reality. (n.d.). Immersive Learning for the Future Workforce. URL: https://www.accenture.com/_acnmedia/pdf-86/accenture-extended-reality-immersive-training.pdf

3. Achuthan K., Kolil V. and Diwakar S., (2018), Using virtual laboratories in chemistry classrooms as interactive tools towards modifying alternate conceptions in molecular symmetry, *Educ. Inf. Technol.*, 23(6), 2499–2515.
4. Acosta, J. L. B., Navarro, S. M. B., Gesa, R. F., & Kinshuk, K. (2019). Framework for designing motivational augmented reality applications in vocational education and training. Australasian Journal of Educational Technology, 35(3).
5. Adam, A. (2019). Effects of Gamification with Virtual Reality: Explaining Convolutional Neural Nets (Doctoral dissertation, Tilburg University).
6. Adams, D., Bah, A., Barwulor, C., Musaby, N., Pitkin, K., & Redmiles, E. M. (2018). Ethics emerging: the story of privacy and security perceptions in virtual reality. In Fourteenth Symposium on Usable Privacy and Security (SOUPS 2018) (pp. 427-442).
7. Agbo, Friday Joseph, et al. "iThinkSmart: Immersive Virtual Reality Mini Games to Facilitate Students' Computational Thinking Skills." Koli Calling'21: 21st Koli Calling International Conference on Computing Education Research, November 18-21, 2021, Joensuu, Finland. Association for Computing Machinery, 2021.
8. Akbaş, A., Marszałek, W., Kamieniarz, A., Polechoński, J., Słomka, K. J., & Juras, G. (2019). Application of virtual reality in competitive athletes–A review. *Journal of human kinetics*, *69*(1), 5-16.
9. Alamäki, A., Dirin, A., Suomala, J., & Rhee, C. (2021). Students' Experiences of 2D and 360° Videos With or Without a Low-Cost VR Headset: An Experimental Study in Higher Education.
10. Alcañiz, M., Bigné, E., & Guixeres, J. (2019). Virtual reality in marketing: a framework, review, and research agenda. *Frontiers in psychology*, 1530.
11. Ali, A., Pigou, D., Clarke, L., & McLachlan, C. (2017). Literature review on motor skill and physical activity in preschool children in New Zealand.
12. Allcoat, D., & von Mühlenen, A. (2018). Learning in virtual reality: Effects on performance, emotion and engagement. *Research in Learning Technology*, *26*.
13. Allcoat, D., Hatchard, T., Azmat, F., Stansfield, K., Watson, D., & von Mühlenen, A. (2021). Education in the digital age: Learning experience in virtual and mixed realities. Journal of Educational Computing Research, 59(5), 795-816.
14. Alomair, Y., & Hammami, S. (2019). A review of gamified techniques for foreign language learning. Journal of Educational Research and Reviews, 7(11), 223-238
15. Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R. (2020). The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses—Theoretical background and empirical results. British Journal of Educational Technology, 51(3), 611-628.
16. Araiza-Alba, Paola, et al. "Immersive virtual reality as a tool to learn problem-solving skills." *Computers & Education* 164 (2021): 104121.
17. ARETE (n.d.), Retrieved 20 April 2022, from https://www.areteproject.eu/pilots/.
18. Artese, F. (2020). Virtual Reality: The Future of Military Training. European Army Interoperability Centre. Available at: https://finabel.org/virtual-reality-the-future-of-military-training/.
19. Aylward, Katie, et al. "Using operational scenarios in a virtual reality enhanced design process." Education Sciences 11.8 (2021): 448.
20. Aziz, Tahera. "Designing an'Immersive'Story Environment: Racism and the Sonic Representation of the Stephen Lawrence Murder." DIGICOM: International Conference on Design and Digital Communication. 2019.

21. BAA Training (2021). BAA Training Starts Virtual Reality-Based Pilot Training. Available at: https://www.baatraining.com/baa-training-starts-virtual-reality-based-pilot-training/

22. Bäck, Regina, et al. "Mixed reality in art education." 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE, 2019.

23. Bahadoran Baghbadorani, Afsoon. VR Based Aviation Training Application for Avoiding Severe Thunderstorms. Diss. University of Akron, 2021.

24. Barteit, S., Lanfermann, L., Bärnighausen, T., Neuhann, F., & Beiersmann, C. (2021). Augmented, mixed, and virtual reality-based head-mounted devices for medical education: systematic review. JMIR serious games, 9(3), e29080.

25. Bastos, Susana, et al. "Soft-digital skills in higher education curricula." Proc. 18th Eur. Conf. E-Learn.. 2019.

26. Benda, P., Ulman, M., & Šmejkalová, M. (2015). Augmented reality as a working aid for intellectually disabled persons for work in horticulture. *AGRIS on-line Papers in Economics and Informatics*, *7*(665-2016-45075), 31-37.

27. Berenguer, C, et al. (2020) 'Exploring the impact of augmented reality in children and adolescents with autism spectrum disorder: a systematic review.' *International Journal of Environmental Research and Public Health* 17.17, 6143.

28. Bernard, Fabien, et al. "Digital simulation tools in aviation maintainability training." Computer Applications in Engineering Education 30.2 (2022): 384-395.

29. Bernholt, S., Broman, K., Siebert, S., & Parchmann, I. (2019). Digitising teaching and learning–Additional perspectives for chemistry education. *Israel Journal of Chemistry*, *59*(6-7), 554-564.

30. Berns, A., & Reyes Sánchez, S. (2021). A review of virtual reality-based language learning apps.

31. Bertrand, P., Guegan, J., Robieux, L., McCall, C. A., & Zenasni, F. (2018). Learning empathy through virtual reality: multiple strategies for training empathy-related abilities using body ownership illusions in embodied virtual reality. *Frontiers in Robotics and AI*, 26.

32. Bezegová, E., Ledgard, M.A., Molemaker, R.-J., Oberč, B.P. and Vigkos, A. (2017), Virtual Reality and Its Potential for Europe, Ecorys, Brussels, available at https://1jzp3z22udm91mv3si18pugq-wpengine.netdna-ssl.com/wpcontent/uploads/2017/11/1Ecorys_Potential_of_VR_v05_DoublePages_Bleed.pdf

33. Bhugra, D., Tasman, A., Pathare, S., Priebe, S., Smith, S., Torous, J., ... & Ventriglio, A. (2017). The WPA-lancet psychiatry commission on the future of psychiatry. The Lancet Psychiatry, 4(10), 775-818.

34. Boel, C., et al. "Six years after google cardboard: what has happened in the classroom? A scoping review of empirical research on the use of immersive virtual reality in secondary education." EDULEARN21 Proceedings. 2021.

35. Bogomolova, K., Sam, A. H., Misky, A. T., Gupte, C. M., Strutton, P. H., Hurkxkens, T. J., & Hierck, B. P. (2021). Development of a virtual three-dimensional assessment scenario for anatomical education. Anatomical sciences education, 14(3), 385-393.

36. Bohné, T., Heine, I., Gürerk, Ö., Rieger, C., Kemmer, L., & Cao, L. Y. (2021). Perception Engineering Learning With Virtual Reality. IEEE Transactions on Learning Technologies, 14(4), 500-514.

37. Bork, F., Stratmann, L., Enssle, S., Eck, U., Navab, N., Waschke, J., & Kugelmann, D. (2019). The benefits of an augmented reality magic mirror system for integrated radiology teaching in gross anatomy. Anatomical sciences education, 12(6), 585-598. ISO 690

38. Bos, D. (2021). Geography and virtual reality. Geography Compass, 15(9), e12590.

39. Bos, D., Miller, S., & Bull, E. (2021). Using virtual reality (VR) for teaching and learning in geography: Fieldwork, analytical skills, and employability. Journal of Geography in Higher Education, 1-10.

40. Bucea-Manea-Țoniş, Rocsana, et al. (2020). 'Sustainability in higher education: The relationship between work-life balance and XR e-learning facilities.' Sustainability 12.14, 5872.

41. Bujdosó, G., Jász, E., Császár, Z. M., Farsang, A., Kapusi, J., Molnár, E., & Teperics, K. (2019). Virtual Reality in Teaching Geography. In 12th International Conference of Education, Research, and Innovation. Sevilla, Spain. International Academy of Technology, Education and Development (IATED) (pp. 659-665).

42. Cabero-Almenara, J., Barroso-Osuna, J., Llorente-Cejudo, C., & Fernández Martínez, M. D. M. (2019). Educational uses of augmented reality (AR): Experiences in educational science. Sustainability, 11(18), 4990.

43. Cabero-Almenara, Julio, Julio Barroso-Osuna, and Rosabel Martinez-Roig. "Mixed, augmented and virtual, reality applied to the teaching of mathematics for architects." Applied Sciences 11.15 (2021): 7125.

44. Calabuig-Moreno, F., González-Serrano, M. H., Fombona, J., & García-Tascón, M. (2020). The emergence of technology in physical education: A general bibliometric analysis with a focus on virtual and augmented reality. Sustainability, 12(7), 2728.

45. Campos, G. (2018), '5G connectivity will boost AR and VR use in industry', AV Magazine, 11 July, available at https://www.avinteractive.com/news/virtual-augmented-mixed/5gconnectivity-will-boost-ar-and-vr-use-in-industry-11-07-2018/

46. Carbonell-Carrera, C., Saorin, J. L., & Jaeger, A. J. (2021). Navigation Tasks in Desktop VR Environments to Improve the Spatial Orientation Skill of Building Engineers. Buildings, 11(10), 492.

47. Carlton, Bobby, Examining the Relationship between VR, Soft Skills Training and KPI's, 2019. https://aixr.org/insights/vr-will-completely-change-the-landscape-for-soft-skills-and-kpis/

48. Casañ-Pitarch, R., & Gong, J. (2021). Testing ImmerseMe with Chinese students: acquisition of foreign language forms and vocabulary in Spanish. *Language Learning in Higher Education*, *11*(1), 219-233.

49. Cercenelli, L., De Stefano, A., Billi, A. M., Ruggeri, A., Marcelli, E., Marchetti, C., ... & Badiali, G. (2022). AEducaAR, Anatomical Education in Augmented Reality: A Pilot Experience of an Innovative Educational Tool Combining AR Technology and 3D Printing. International Journal of Environmental Research and Public Health, 19(3), 1024.

50. Chan, P., Van Gerven, T., Dubois, J. L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers and Education Open*, *2*, 100053.

51. Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual reality sickness: a review of causes and measurements. International Journal of Human–Computer Interaction, 36(17), 1658-1682.

52. Checa, D., & Bustillo, A. (2020). A review of immersive virtual reality serious games to enhance learning and training. Multimedia Tools and Applications, 79(9–10), 5501–5527

53. Christopoulos, A., Mystakidis, S., Pellas, N., & Laakso, M. J. (2021). ARLEAN: An Augmented Reality Learning Analytics Ethical Framework. Computers, 10(8), 92.
54. Cieri, R. L., Turner, M. L., Carney, R. M., Falkingham, P. L., Kirk, A. M., Wang, T., ... & Farmer, C. G. (2021). Virtual and augmented reality: New tools for visualizing, analyzing, and communicating complex morphology. Journal of Morphology, 282(12), 1785-1800.
55. Cleto, B., Moura, J. M., Ferreira, L., & Sylla, C. (2018). Codecubes-playing with cubes and learning to code. In Interactivity, Game Creation, Design, Learning, and Innovation (pp. 538-543). Springer, Cham.
56. Cleto, B., Sylla, C., Ferreira, L., & Moura, J. M. (2019, October). “Play and Learn”: Exploring CodeCubes. In *EAI International Conference on Technology, Innovation, Entrepreneurship and Education* (pp. 34-42). Springer, Cham.
57. Cognizant (2016), Disrupting reality: Taking virtual & augmented reality to the enterprise, Cognizant, Teaneck, NJ, available at https://www.cognizant.com/whitepapers/disruptingreality-taking-virtual-augmented-reality-to-the-enterprise-codex2124.pdf
58. Cristea, M. (2020). KLM trains its crew with virtual reality and plans to develop VR programs to replace theoretical training. Business Review. Available at: https://business-review.eu/future-of-work/klm-trains-its-crew-with-virtual-reality-and-plans-to-develop-vr-programs-to-replace-theoretical-training-215715
59. Cruse, D. T., & Brereton, P. (2018). Integrating QR codes into ELT materials. Language teaching in a global age: Shaping the classroom, shaping the world. Tokyo: JALT.
60. Cvetkovski, G., Petkovska, L., Di Barba, P., Mognaschi, M. E., Kaminska, D., Firych-Nowacka, A., ... & Lefik, M. (2019). ViMeLa Project: An innovative concept for teaching mechatronics using virtual reality. Przeglad Elektrotechniczny, 95(5), 18-21.
61. Dahl, Tone Lise. "A Preliminary Scoping Review of Immersive Virtual Soft Skills Learning and Training of Employees." 2021 7th International Conference of the Immersive Learning Research Network (iLRN). IEEE, 2021.
62. De Guzman, J. A., Thilakarathna, K., & Seneviratne, A. (2019). Security and privacy approaches in mixed reality: A literature survey. ACM Computing Surveys (CSUR), 52(6), 1-37.
63. de Oliveira Malaquias, Fernanda Francielle and Malaquias, Rodrigo Fernandes. (2016). ‘The Role of Virtual Reality in the Learning Process of Individuals with Intellectual Disabilities’. Pp. 133 – 138.
64. Delgado, Isidro Navarro, and David Fonseca Escudero. "Nuevas tecnologías de visualización para mejorar la representación de arquitectura en la educación." ACE: Arquitectura, Ciudad y Entorno (2017).
65. Deloitte (2018). Utilizing virtual reality to drive supply chain innovation. A series exploring Industry 4.0 technologies and their potential impact for enabling digital supply networks in manufacturing. Available at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/process-and-operations/us-cons-utilizing-virtual-reality-to-drive-supply-chain-innovation.pdf
66. Dengel, A. (2018). "Seeking the treasures of theoretical computer science education: Towards educational virtual reality for the visualization of finite state machines." *IEEE international conference on teaching, assessment, and learning for engineering (TALE)*.
67. Di Natale, Anna Flavia, et al. "Immersive virtual reality in K-12 and higher education: A 10-year systematic review of empirical research." British Journal of Educational Technology 51.6 (2020): 2006-2033.

68. Diaz-Orueta, U., Hopper, L., & Konstantinidis, E. (2020). Shaping technologies for older adults with and without dementia: Reflections on ethics and preferences. *Health informatics journal*, *26*(4), 3215-3230.

69. Dinis, F. M., Guimarães, A. S., Carvalho, B. R., & Martins, J. P. P. (2017, April). Development of virtual reality game-based interfaces for civil engineering education. In 2017 IEEE global engineering education conference (EDUCON) (pp. 1195-1202). IEEE.

70. Divekar*, R. R., Drozdal*, J., Chabot*, S., Zhou, Y., Su, H., Chen, Y., ... & Braasch, J. (2021). Foreign language acquisition via artificial intelligence and extended reality: design and evaluation. Computer Assisted Language Learning, 1-29.

71. Du, Sijia. (2021). 'Discussion on the Reform of Teaching Mode of Art Design Specialty VR Virtual Reality Technology.' International Conference on Application of Intelligent Systems in Multi-modal Information Analytics. Springer, Cham.

72. EduChem. (n.d.). http://educhem-vr.com/webVR/index.html

73. Edwards B., Bielawski K., Prada R. and Cheok A., (2019), Haptic virtual reality and immersive learning for enhanced organic chemistry instruction, *Virt. Real.*, 23(4), 363–373 .

74. Emanuel, Federica, et al. (2021). 'Make soft skills stronger? An online enhancement platform for higher education.' International Journal of Educational Research Open 2, 100096.

75. European Commission. (2018). Automated Serious Game Scenario Generator for Mixed Reality Training. https://cordis.europa.eu/project/id/653590

76. European Commission. (2021). Horizon Europe Work Programme 2021-2022: 7. Digital, Industry and Space; European Commission Decision C(2021)9128 of 15 December 2021. https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-7-digital-industry-and-space_horizon-2021-2022_en.pdf

77. European Parliament and Council of the European Union. (2016). Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation) (Text with EEA relevance). https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32016R0679

78. European Universities Initiative faces many barriers. (2021). University World News. https://www.universityworldnews.com/post.php?story=20220111103551 63

79. Farič, N., Smith, L., Hon, A., Potts, H. W., Newby, K., Steptoe, A., & Fisher, A. (2021). A virtual reality exergame to engage adolescents in physical activity: Mixed methods study describing the formative intervention development process. *Journal of medical Internet research*, *23*(2), e18161.

80. Faure, C., Limballe, A., Bideau, B., & Kulpa, R. (2020). Virtual reality to assess and train team ball sports performance: A scoping review. *Journal of sports Sciences*, *38*(2), 192-205.

81. Fejdyś, Marzena, et al. "Mathematical algorithm for risk assessment of police officer in VR training simulation." Applied Sciences 12.4 (2022): 2169.

82. Ferguson, Linda, 6 Inventive Examples of VR in Education. (2021). https://www.theglimpsegroup.com/6-inventive-examples-of-vr-in-education/

83. Fernandes, H. S., Cerqueira, N. M., & Sousa, S. F. (2021). Developing and using BioSIMAR, an augmented reality program to visualize and learn about chemical structures in a virtual environment on any internet-connected device.

84. Fernandez, M. (2017). Augmented virtual reality: How to improve education systems. *Higher Learning Research Communications*, *7*(1), 1-15.

85. Fernández-Batanero, J. M., Montenegro-Rueda, M., & Fernández-Cerero, J. (2022). Use of Augmented Reality for Students with Educational Needs: A Systematic Review (2016–2021). Societies, 12(2), 36.

86. Flores-Gallegos, R., Rodríguez-Leis, P., & Fernández, T. (2021). Effects of a virtual reality training program on visual attention and motor performance in children with reading learning disability. International Journal of Child-Computer Interaction, 100394.

87. Fokides, E., Chronopoulou, M. I., & Kaimara, P. (2019). Comparing videos and a 3D virtual environment for teaching school-related functional skills and behaviors to students with ADHD or developmental dyslexia, displaying challenging behaviors: a case study. *Research and Practice in Technology Enhanced Learning*, *14*(1), 1-19.

88. Fombona-Pascual, A., Fombona, J., & Vázquez-Cano, E. (2022). VR in chemistry, a review of scientific research on advanced atomic/molecular visualization. *Chemistry Education Research and Practice*. https://pubs.rsc.org/en/content/articlehtml/2022/rp/d1rp00317h

89. Fracaro, S. G., Glassey, J., Bernaerts, K., & Wilk, M. (2022). Immersive technologies for the training of operators in the process industry: A Systematic Literature Review. Computers & Chemical Engineering, 107691.

90. Frolli, A., Savarese, G., Di Carmine, F., Bosco, A., Saviano, E., Rega, A., ... & Ricci, M. C. (2022). Children on the Autism Spectrum and the Use of Virtual Reality for Supporting Social Skills. *Children*, *9*(2), 181.

91. Fussell, S. G., & Truong, D. (2020). Preliminary results of a study investigating aviation student's intentions to use virtual reality for flight training. *International Journal of Aviation, Aeronautics, and Aerospace*, *7*(3), 2.

92. García, Mercedes García, et al. (2016). "Development and evaluation of the team work skill in university contexts. Are virtual environments effective?." *International Journal of Educational Technology in Higher Education* 13.1, pp. 1-11.

93. Garcia, S., Kauer, R., Laesker, D., Nguyen, J., & Andujar, M. (2019, May). A virtual reality experience for learning languages. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-4).

94. Gardeli, Anna, and Spyros Vosinakis. "ARQuest: A tangible augmented reality approach to developing computational thinking skills." 2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games). IEEE, 2019.

95. Garzón, J., Pavón, J., & Baldiris, S. (2019). Systematic review and meta-analysis of augmented reality in educational settings. Virtual Reality, 23(4), 447-459.

96. Garzotto, Franca, et al. (2017). "Wearable immersive virtual reality for children with disability: a case study." *Proceedings of the 2017 Conference on Interaction Design and Children*.

97. Gelsomini, M. (2016, October). An affordable virtual reality learning framework for children with neuro-developmental disorder. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility* (pp. 343-344).

98. Ghobadi, M., Sepasgozar, S. M., Ghobadi, M., & Sepasgozar, S. M. E. (2020). An investigation of virtual reality technology adoption in the construction industry. Smart Cities and Construction Technologies, 157.

99. Goddard T., Brilliant A., Skillman, T., Vergenz S., Tyrwhitt-Drake J., Meng E. and Ferrin T., (2018), Molecular visualization on the Holodeck, *J. Mol. Biol.*, 430(21), 3982–3996.

100. Gold Lotus (n.d.), Retrieved 20 April 2022, from https://www.goldlotus.co.

101. Grabowski, Andrzej. "Practical skills training in enclosure fires: An experimental study with cadets and firefighters using CAVE and HMD-based virtual training simulators." Fire Safety Journal 125 (2021): 103440.

102. Greenwald, Scott W., et al. (2017). ‘Technology and applications for collaborative learning in virtual reality.’ Philadelphia, PA: International Society of the Learning Sciences.

103. Gros, B., & García-Peñalvo, F. J. (2016). Future trends in the design strategies and technological affordances of e-learning. Springer.

104. Guo, X.; Guo, Y.; Liu, Y. (2021). The Development of Extended Reality in Education: Inspiration from the Research Literature. Sustainability 13, 13776. https://doi.org/ 10.3390/su132413776

105. Gutowski, P., & Kłos-Adamkiewicz, Z. (2020). Development of e-service virtual museum tours in Poland during the SARS-CoV-2 pandemic. Procedia computer science, 176, 2375-2383.

106. Haas, B., Kreis, Y., & Lavicza, Z. (2021). Case study on augmented reality, digital and physical modelling with mathematical learning disabilities students in an elementary school in Luxemburg. *The International Journal for Technology in Mathematics Education*.

107. Hamilton, David, et al. "Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design." Journal of Computers in Education 8.1 (2021): 1-32.

108. Hammady, R., Ma, M., & Strathearn, C. (2020). Ambient information visualisation and visitors’ technology acceptance of mixed reality in museums. Journal on Computing and Cultural Heritage (JOCCH), 13(2), 1-22.

109. Han, I. (2021). Immersive virtual field trips and elementary students’ perceptions. British Journal of Educational Technology, 52(1), 179-195.

110. Happa, J., Glencross, M., & Steed, A. (2019). Cyber security threats and challenges in collaborative mixed-reality. Frontiers in ICT, 6, 5.

111. Harris, David J., et al. "Assessing the learning and transfer of gaze behaviours in immersive virtual reality." Virtual Reality 25.4 (2021): 961-973.

112. Hasler, B. S., Spanlang, B., & Slater, M. (2017). Virtual race transformation reverses racial in-group bias. *PloS one*, *12*(4), e0174965.

113. Hasler, Béatrice S., Bernhard Spanlang, and Mel Slater. "Virtual race transformation reverses racial in-group bias." PloS one 12.4 (2017): e0174965.

114. Hemminki-Reijonen, U. (2022). Virtuaalitodellisuus Oppimisessa. Opas opettajalle. https://www.oph.fi/sites/default/files/documents/Virtuaalitodellisuus_oppimisessa.pdf

115. Hu, Na. ‘Research on the Application of VR Technology in Clothing Design Teaching.’ The Sixth International Conference on Information Management and Technology. 2021.

116. Hui, Jing, et al. (2022). ‘Research on Art Teaching Practice Supported by Virtual Reality (VR) Technology in the Primary Schools.’ Sustainability 14.3, 1246.

117. Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. Computers & Education, 123, 109-123.

118. ICAROS (n.d.). Retrieved 18 April 2022, from https://www.icaros.com/experiences/.

119. Ilić, M. P., Păun, D., Popović Šević, N., Hadžić, A., & Jianu, A. (2021). Needs and Performance Analysis for Changes in Higher Education and Implementation of Artificial Intelligence, Machine Learning, and Extended Reality. Education Sciences, 11(10), 568.

120. Ivascu, S., Moldoveanu, A., Moldoveanu, F., Morar, A., & Balan, O. (2019). Virtual Interaction for Visually Impaired and Sighted People. *eLearning & Software for Education*, *1*.

121. Jamah, Ahmed & Alnagrat, Ahmed & Ismail, R.C. & Syed Idrus, Syed Zulkarnain. (2020). Extended Reality (XR) in Virtual Laboratories: A Review of Challenges and Future Training Directions.

122. Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. Education and Information Technologies, 23(4), 1515-1529.

123. Jerome, J., & Greenberg, J. (2021). Augmented Reality + Virtual Reality: Privacy & autonomy Considerations in Emerging, Immersive Digital Worlds. Future of Privacy Forum. https://fpf.org/wp-content/uploads/2021/04/FPF-ARVR-Report-4.16.21-Digital.pdf

124. Jetter, J., Eimecke, J., & Rese, A. (2018). Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits?. Computers in Human Behavior, 87, 18-33.

125. Jochecová, K., Černý, M., Stachoň, Z., Švedová, H., Káčová, N., Chmelík, J., ... & Šašinka, Č. (2022). Geography Education in a Collaborative Virtual Environment: A Qualitative Study on Geography Teachers. ISPRS International Journal of Geo-Information, 11(3), 180.

126. K. Zhang and S. -J. Liu, 'The application of virtual reality technology in physical education teaching and training,' (2016). IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI), pp. 245-248, doi: 10.1109/SOLI.2016.7551695

127. Kallioniemi, P., Ronkainen, K., Karhu, J., Sharma, S., Hakulinen, J., & Turunen, M. (2019, September). CityCompass VR-a collaborative virtual language learning environment. In *IFIP Conference on Human-Computer Interaction* (pp. 540-543). Springer, Cham.

128. Kamińska, D., Sapiński, T., Aitken, N., Rocca, A. D., Barańska, M. and Wietsma, R. (2017). 'Virtual reality as a new trend in mechanical and electrical engineering education' *Open Physics*, vol. 15, no. 1, pp. 936-941. https://doi.org/10.1515/phys-2017-0114

129. Kang, Sunyoung, and Seungae Kang. "The study on the application of virtual reality in adapted physical education." *Cluster computing* 22.1 (2019): 2351-23

130. Kaplan-Rakowski, R., & Wojdynski, T. (2018). Students' attitudes toward high-immersion virtual reality assisted language learning. *Future-Proof CALL: language learning as exploration and encounters–short Papers from EUROCALL*, *2018*, 124-129.

131. Ke, Fengfeng, and Sungwoong Lee. (2016): 'Virtual reality based collaborative design by children with high-functioning autism: Design-based flexibility, identity, and norm construction.' Interactive Learning Environments 24.7, pp. 1511-1533.

132. Keep Talking and Nobody Explodes - Defuse a bomb with your friends. (2021, May 26). Keep Talking and Nobody Explodes. https://keeptalkinggame.com./

133. Kenwright, B. (2018). Virtual reality: ethical challenges and dangers [Opinion]. IEEE Technology and Society Magazine, 37(4), 20-25.

134. Kharvari, Farzam, and Wolfgang Höhl. "The role of serious gaming using virtual reality applications for 3D architectural visualization." 2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games). IEEE, 2019.

135. Kic-Drgasm Joanna, Development of soft skills as a part of an LSP course, 'e-mentor' . (2018). Pp. 27–36, http://dx.doi.org/10.15219/em74.1349.

136. Kirsch, Breanne. ‘Virtual Reality.’ Information Technology and Libraries 38.4 (2019): 4-5.

137. Klimova, B. (2021). Use of Virtual Reality in Non-Native Language Learning and Teaching. *Procedia Computer Science*, *192*, 1385-1392.

138. Knack, A., Deshpande, A., Hoorens, S., and Gunashekar, S. (2019). Virtual and augmented reality: Implications of game-changing technologies in the services sector in Europe. Working Paper. Eurofound. https://euagenda.eu/upload/publications/untitled-262817-ea.pdf

139. Koutsopoulos, K., Doukas, K., & Kotsanis, Y. (2017). Handbook of Research on Educational Design and Cloud Computing in Modern Classroom Settings.

140. Kuleto, V.; P., M.I.; Stanescu, M.; Rankovi´c, M.; Ševi´c, N.P.; P ˘aun, D.; Teodorescu, S. (2021). Extended Reality in Higher Education, a Responsible Innovation Approach for Generation Y and Generation Z. Sustainability 13, 11814. https://doi.org/10.3390/su132111814

141. Kurniawati, Arik, Ari Kusumaningsih, and Imam Hasan. (2019). "Class VR: Learning Class Environment for Special Educational Needs using Virtual Reality Games." International Conference on Computer Engineering, Network, and Intelligent Multimedia (CENIM). IEEE.

142. Labedan, P., Darodes-De-Tailly, N., Dehais, F., & Peysakhovich, V. (2021). Virtual Reality for Pilot Training: Study of Cardiac Activity. In VISIGRAPP (2: HUCAPP) (pp. 81-88).

143. Labedan, P., Dehais, F., & Peysakhovich, V. (2018, October). Evaluation de l’expérience de pilotage d’un avion léger en réalité virtuelle. In *ERGO'IA 2018* (pp. 1-10).

144. Lai, Ying-Hsun, et al. (2021). ‘Study on enhancing AIoT computational thinking skills by plot image-based VR.’ Interactive Learning Environments 29.3, pp. 482-495.

145. LaMotte, S. C. (2017, December 13). *Virtual reality has some very real health dangers*. CNN. https://edition.cnn.com/2017/12/13/health/virtual-reality-vr-dangers-safety/index.html

146. Léa Paule. (2020). When virtual reality raises awareness of our impact on the environment. https://blog.laval-virtual.com/en/when-virtual-reality-raises-awarness-of-our-impact-on-the-environment/

147. Leovaridis, C. and Bahna, M. (2017), ‘Aspects regarding virtual reality as innovation in creative industries’, Revista Romana de Sociologie, Vol. 28. http://www.revistadesociologie.ro/sites/default/files/02-cleovaridis.pdf

148. Lepaya, Whitepaper "Could Virtual Reality be a L&D solution or is it jus a cool gimmick?", 2021

149. Li, D., Yi, C., & Gu, Y. (2021). Research on college physical education and sports training based on virtual reality technology. Mathematical Problems in Engineering, 2021.

150. Li, Wenfang. ‘Application analysis of VR virtual technology in environmental art design teaching.’ Journal of Physics: Conference Series. Vol. 1744. No. 4. IOP Publishing, 2021.

151. Liagkou, V., Salmas, D., & Stylios, C. (2019). Realizing virtual reality learning environment for industry 4.0. *Procedia Cirp*, *79*, 712-717.

152. Lin, Y. J., & Wang, H. C. (2021). Using virtual reality to facilitate learners’ creative self-efficacy and intrinsic motivation in an EFL classroom. Education and Information Technologies, 26(4), 4487-4505.

153. Lin, Yu-Shan, et al. ‘Exploring computational thinking skills training through augmented reality and AIoT learning.’ Frontiers in Psychology (2021): 318.

154. Liu, H. (2019). Application of virtual reality technology in college physical education teaching and training. In Journal of Physics: Conference Series (Vol. 1213, No. 4, p. 042044). IOP Publishing

155. Liu, P., & Lan, L. (2021). Museum as multisensorial site: story co-making and the affective interrelationship between museum visitors, heritage space, and digital storytelling. Museum Management and Curatorship, 36(4), 403-426.

156. Liu, X., Zhang, J., Hou, G., & Wang, Z. (2018, July). Virtual reality and its application in military. In IOP Conference Series: Earth and Environmental Science (Vol. 170, No. 3, p. 032155). IOP Publishing.

157. Loia, V., & Orciuoli, F. (2019). ICTs for exercise and sport science: focus on augmented reality. *Journal of Physical Education and Sport*, *19*, 1740-1747.

158. Lukačević, F., Škec, S., Perišić, M. M., Horvat, N., & Štorga, M. (2020). Spatial perception of 3D CAD model dimensions and affordances in virtual environments. IEEE Access, 8, 174587-174604.

159. Maas, Melanie J., and Janette M. Hughes. "Virtual, augmented and mixed reality in K–12 education: A review of the literature." Technology, Pedagogy and Education 29.2 (2020): 231-249.

160. Macariu, C., Iftene, A., & Gîfu, D. (2020). Learn chemistry with augmented reality. *Procedia Computer Science*, *176*, 2133-2142.

161. Madary, M., & Metzinger, T. K. (2016). Real virtuality: A code of ethical conduct. Recommendations for good scientific practice and the consumers of VR-technology. Frontiers Robotics AI, 3(FEB), 3. https://doi.org/10.3389/FROBT.2016.00003/BIBTEX

162. Maister, Lara, et al. "Changing bodies changes minds: owning another body affects social cognition." Trends in cognitive sciences 19.1 (2015): 6-12.

163. Makransky, Guido, and Lau Lilleholt. "A structural equation modeling investigation of the emotional value of immersive virtual reality in education." Educational Technology Research and Development 66.5 (2018): 1141-1164.

164. Makransky, Guido, and Sara Klingenberg. "Virtual reality enhances safety training in the maritime industry: An organizational training experiment with a non-WEIRD sample." Journal of Computer Assisted Learning (2022).

165. Makransky, Guido, Stefan Borre-Gude, and Richard E. Mayer. "Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments." Journal of Computer Assisted Learning 35.6 (2019): 691-707.

166. Mallam, Steven C., Salman Nazir, and Sathiya Kumar Renganayagalu. ‘Rethinking maritime education, training, and operations in the digital era: applications for emerging immersive technologies.’ Journal of Marine Science and Engineering 7.12 (2019): 428

167. Margetis, G., Apostolakis, K. C., Ntoa, S., Papagiannakis, G., & Stephanidis, C. (2020). X-reality museums: unifying the virtual and real world towards realistic virtual museums. Applied Sciences, 11(1), 338.

168. Marino, E., Barbieri, L., Colacino, B., Fleri, A. K., & Bruno, F. (2021). An Augmented Reality inspection tool to support workers in Industry 4.0 environments. Computers in Industry, 127, 103412.

169. Markopoulos, Evangelos, and Mika Luimula. "Immersive safe oceans technology: developing virtual onboard training episodes for maritime safety." Future Internet 12.5 (2020): 80.

170. Markopoulos, Evangelos, et al. ‘Maritime safety education with VR technology (MarSEVR).’ 2019 10th IEEE International Conference on Cognitive Infocommunications (CogInfoCom). IEEE, 2019.

171. Martin-Gutierrez, Jorge & Mora, Carlos & Añorbe, Beatriz & González-Marrero, Antonio. (2017). Virtual Technologies Trends in Education. Eurasia Journal of Mathematics, Science and Technology Education. 13. 469-486.

172. Martín-Gutiérrez, Jorge, et al. ‘Augmented reality to promote collaborative and autonomous learning in higher education.’ Computers in human behavior 51 (2015): 752-761.

173. Martí-Testón, A.; Muñoz, A.; Solanes, J.E.; Gracia, L.; Tornero, J. A Methodology to Produce Augmented-Reality Guided Tours in Museums for Mixed-Reality Headsets. Electronics 2021, 10, 2956. https://doi.org/10.3390/ electronics10232956

174. Mastroianni, C. (2015). The 7 e-Affordances in eLearning. eLearning Industry. https://elearningindustry.com/7-e-affordances-elearning

175. Mawas, N. E., Tal, I., Moldovan, A. N., Bogusevschi, D., Andrews, J., Muntean, G. M., & Muntean, C. H. (2018). Improving STEM learning experience in primary school by using NEWTON project innovative technologies. In International Conference on Computer Supported Education (pp. 214-230). Springer, Cham.

176. McGinity, Matthew. "Immersive media for environmental awareness." 2018 IEEE Workshop on Augmented and Virtual Realities for Good (VAR4Good). IEEE, 2018.

177. McMorrine, J. (2017). Digital participation amongst people with disabilities: Barriers that need to be overcome to increase digital participation. https://peopleknowhow.org/wp-content/uploads/2017/12/Digital-Participation-Amongst-people-with-Disabilities.pdf.

178. Mead, C., Buxner, S., Bruce, G., Taylor, W., Semken, S., & Anbar, A. D. (2019). Immersive, interactive virtual field trips promote science learning. Journal of Geoscience Education, 67(2), 131-142.

179. Meijer J., & Batalas N. (2020). Exploring visuo-tactile embodiment in a social Virtual Reality setting with a physical wheelchair for training empathy towards social disability barriers. In Cross-Reality (XR) Interaction, ACM ISS 2020 (International Workshop on XR Interaction 2020)

180. Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29-40.

181. Meyran-Martinez, C., & Spanghero-Gaillard, N. (2021). L’enseignement de l’anglais avec la réalité virtuelle. *Mélanges CRAPEL*, *42*(2).

182. Michela, Abele, et al. "Deep-breathing biofeedback trainability in a virtual-reality action game: A single-case design study with police trainers." (2022).

183. Mihai-Alexandru Cristea. KLM trains its crew with virtual reality and plans to develop VR programs to replace theoretical training, 2020, https://business-review.eu/future-of-work/klm-trains-its-crew-with-virtual-reality-and-plans-to-develop-vr-programs-to-replace-theoretical-training-215715

184. Modolin, S., & Grace, S. (2018). Virtual Reality Games for Team Building Interventions: Comparison of team building interventions for university students.

185. Modolin, Sarah, and Sekwao Grace. "Virtual Reality Games for Team Building Interventions: Comparison of team building interventions for university students." (2018).

186. Mondly (n.d.), Retrieved 13 April 2022, from https://www.mondly.com

187. Munafo, J., Diedrick, M. and Stoffregen, T.A. (2017), 'The virtual reality head-mounted display Meta Rift induces motion sickness and is sexist in its effects', Experimental Brain Research, Vol. 235, No. 3, pp. 889–901.

188. Muséum national d'Histoire naturelle. (2021). Revivre, les animaux disparus en réalité augmentée. *YouTube.* https://www.youtube.com/watch?v=So_4UzvyPO4&feature=emb_title&ab_channel=Mus%C3%A9umnationald%27Histoirenaturelle

189. Mystakidis, S., Christopoulos, A., & Pellas, N. (2021). A systematic mapping review of augmented reality applications to support STEM learning in higher education. Education and Information Technologies, 1-45.

190. Mystakidis, S., Fragkaki, M., & Filippousis, G. (2021). Ready Teacher One: Virtual and Augmented Reality Online Professional Development for K-12 School Teachers. Computers, 10(10), 134.

191. Nelson, Katherine M., Eva Anggraini, and Achim Schlüter. "Virtual reality as a tool for environmental conservation and fundraising." Plos one 15.4 (2020): e0223631.

192. Nesenbergs, K., Abolins, V., Ormanis, J., & Mednis, A. (2020). Use of augmented and virtual reality in remote higher education: A systematic umbrella review. Education Sciences, 11(1), 8.

193. Newman, D. (2018), '4 Reasons 5G is critical for mass adoption of AR and VR', Forbes, 27 May. https://www.forbes.com/sites/danielnewman/2018/03/27/4-reasons-5g-iscritical-for-mass-adoption-of-ar-and-vr/

194. Nicolaidou, I., Pissas, P., & Boglou, D. (2021). Comparing immersive Virtual Reality to mobile applications in foreign language learning in higher education: a quasi-experiment. Interactive Learning Environments, 1-15.

195. Nikolaou, Alina. "Attitude Change in Immersive Virtual Environments." 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW). IEEE, 2021.

196. Nisha, Bobby. "The pedagogic value of learning design with virtual reality." Educational Psychology 39.10 (2019): 1233-1254.

197. Nóbrega, R., Jacob, J., Coelho, A., Weber, J., Ribeiro, J., & Ferreira, S. (2017, October). Mobile location-based augmented reality applications for urban tourism storytelling. In 2017 24º Encontro Português de Computação Gráfica e Interação (EPCGI) (pp. 1-8). IEEE.

198. Núñez, M., Quirós, R., Núñez, I., Carda, J. B., Camahort, E., & Mauri, J. L. (2008, July). Collaborative augmented reality for inorganic chemistry education. In *WSEAS international conference. Proceedings. Mathematics and computers in science and engineering* (Vol. 5, pp. 271-277). WSEAS.

199. O'Brolcháin, F., Jacquemard, T., Monaghan, D., O'Connor, N., Novitzky, P., & Gordijn, B. (2016). The Convergence of Virtual Reality and Social Networks: Threats to Privacy and Autonomy. Science and Engineering Ethics, 22(1), 1–29. https://doi.org/10.1007/s11948-014-9621-1

200. Okanovic, V., Ivkovic-Kihic, I., Boskovic, D., Mijatovic, B., Prazina, I., Skaljo, E., & Rizvic, S. (2022). Interaction in eXtended Reality Applications for Cultural Heritage. *Applied Sciences*, *12*(3), 1241.

201. Pagano, A., Palombini, A., Bozzelli, G., De Nino, M., Cerato, I., & Ricciardi, S. (2020). Arkaevision vr game: User experience research between real and virtual paestum. Applied Sciences, 10(9), 3182.

202. Panagiotidis, P. (2021). Augmented and Mixed Reality in Language Learning. European Journal of Education, 4(2), 28–44. https://doi.org/10.26417/501ibq23c.

203. Papanastasiou, G., Drigas, A., Skianis, C., Lytras, M., & Papanastasiou, E. (2019). Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills. *Virtual Reality*, *23*(4), 425-436.

204. Parmaxi, A. (2020). Virtual reality in language learning: A systematic review and implications for research and practice. Interactive learning environments, 1-13.

205. Parmaxi, A., & Demetriou, A. A. (2020). Augmented reality in language learning: A state-of-the-art review of 2014–2019. Journal of Computer Assisted Learning, 36(6), 861-875.

206. Pedaste, M., Mitt, G., & Jürivete, T. (2020). What is the effect of using mobile augmented reality in K12 inquiry-based learning?. Education Sciences, 10(4), 94.

207. Pegrum, M. (2019). Mobile lenses on learning: Languages and literacies on the move. Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-15-1240-7

208. Pegrum, M., & Lan, Y. J. (2021). Call for papers for a special issue on Extended Reality (XR) in Language Learning. Language Learning & Technology, 25(3), 40-42.

209. Pellas, N., Dengel, A. & Christopoulos, A. (2020). A Scoping Review of Immersive Virtual Reality in STEM education. IEEE Transactions on Learning Technologies. DOI: 10.1109/TLT.2020.3019405

210. Perry, B. (2015). Gamifying French language learning: A case study examining a quest-based, augmented reality mobile learning-tool. Procedia-Social and Behavioral Sciences, 174, 2308-2315.

211. Pietikäinen, O., Hämäläinen, P., Lehtinen, J., & Karttunen, A. J. (2021). VRChem: A virtual reality molecular builder. *Applied Sciences*, *11*(22), 10767.

212. Pinto, R. D., Peixoto, B., Melo, M., Cabral, L., & Bessa, M. (2021). Foreign language learning gamification using Virtual Reality—A systematic review of empirical research. *Education Sciences*, *11*(5), 222.

213. Pirker, Johanna, and Andreas Dengel. "The potential of 360-degree virtual reality videos and real VR for education-A literature review." IEEE Computer Graphics and Applications (2021).

214. Play2Speak (n.d.), Retrieved 20 April 2022, from https://www.seedrs.com/play2speak.

215. Pletz, C. (2021). Which Factors Promote and Inhibit the Technology Acceptance of Immersive Virtual Reality Technology in Teaching-Learning Contexts? Results of an Expert Survey. International Journal of Emerging Technologies in Learning (iJET), 16(13), 248-272.

216. Golf Monthly (2019). The PuttView has made it onto the Golf Monthly Tech 50 2019/20 list. https://www.golfmonthly.com/tech50/putt-view-162871

217. Qualcomm Technologies Inc. (2018), 'VR and AR pushing connectivity limits'. https://www.qualcomm.com/media/documents/files/vr-and-ar-pushing-connectivity-limits.pdf

218. Quintero, J., Baldiris, S., Rubira, R., Cerón, J., & Velez, G. (2019). Augmented reality in educational inclusion. A systematic review on the last decade. Frontiers in psychology, 10, 1835.

219. Radianti, Jaziar, et al. "A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda." Computers & Education 147 (2020): 103778.

220. Rae, J.; Edwards, L. (2016). Virtual reality at the British Museum: What is the value of virtual reality environments for learning by children and young people, schools, and families. In Proceedings of the Annual Conference of Museums and the Web, Los Angeles, CA, USA (pp. 6-9). https://mw2016.museumsandtheweb.com/ paper/virtual-reality-at-the-british-museum-what-is-the-value-of-virtual-reality-environments-for-learning-by-childrenand-young-people-schools-and-families/

221. Rajan, A. V., Nassiri, N., Akre, V., Ravikumar, R., Nabeel, A., Buti, M., & Salah, F. (2018, November). Virtual reality gaming addiction. In *2018 Fifth HCT Information Technology Trends (ITT)* (pp. 358-363). IEEE.

222. Recupero, A., Talamo, A., Triberti, S., & Modesti, C. (2019). Bridging museum mission to visitors' experience: activity, meanings, interactions, technology. *Frontiers in psychology*, *10*, 2092.

223.Ređep, T., & Hajdin, G. (2021). Use of Augmented Reality with Game Elements in Education–Literature Review. Journal of Information and Organizational Sciences, 45(2), 473-494.

224. Renganayagalu, S. K., S. C. Mallam, and M. Hernes. "Maritime Education and Training in the COVID-19 Era and Beyond." environment 17 (2022): 25.

225. Repetto, C., Di Natale, A. F., Villani, D., Triberti, S., Germagnoli, S., & Riva, G. (2021). The use of immersive 360° videos for foreign language learning: a study on usage and efficacy among high-school students. *Interactive Learning Environments*, 1-16.

226. Reuters. (2016). HoloLens to help improve museum experience. https://www.reuters.com/video/watch/hololens-to-help-improve-museum-experien-id370256067

227. Rivu, R., Mäkelä, V., Prange, S., Rodriguez, S. D., Piening, R., Zhou, Y., ... & Alt, F. (2021). Remote VR Studies--A Framework for Running Virtual Reality Studies Remotely Via Participant-Owned HMDs. arXiv preprint arXiv:2102.11207.

228. Rizvic, S. (2018). Digitalna Prezentacija Kulturnog Naslijeđa Bosne i Hercegovine; TDP Sarajevo: Sarajevo, Bosnia and Herzegovina. https://people.etf.unsa.ba/~srizvic/Digitalna_prezentacija_kulturnog_naslijedja_BiH.pdf

229. Rizvić, S., Bošković, D., Okanović, V., Kihić, I. I., Prazina, I., & Mijatović, B. (2021). Time Travel to the Past of Bosnia and Herzegovina through Virtual and Augmented Reality. Applied Sciences, 11(8), 3711.

230. Rodríguez-Cano, Sonia, et al. "Design of a virtual reality software to promote the learning of students with dyslexia." *Sustainability* 13.15 (2021): 8425.

231. Rodríguez-Cano, Sonia, Vanesa Delgado-Benito, and Vanesa Ausín-Villaverde. "Áreas de desarrollo para intervención en dislexia: una propuesta de realidad virtual." *Ocnos. Revista de estudios sobre lectura* 21.1 (2022).

232. Rogers, S. L. (2020). Cheap, accessible, and virtual experiences as tools for immersive study: a proof of concept study. *Research in Learning Technology*, *28*.

233. Roitsch, Jane, et al. "Writing instruction for students with learning disabilities: Quality appraisal of systematic reviews and meta-analyses." Reading & Writing Quarterly 37.1 (2021): 32-44.

234. Roitsch, Jane, Robert L. Moore, and Annemarie L. Horn. "Lessons learned: what the COVID-19 global pandemic has taught us about teaching, technology, and students with autism spectrum disorder." *Journal of Enabling Technologies* (2021).

235. Román-González, M., Pérez-González, J. C., & Jiménez-Fernández, C. (2017). Which cognitive abilities underlie computational thinking? Criterion validity of the Computational Thinking Test. *Computers in human behavior*, *72*, 678-691.

236. Roswell, Robert O., et al. ‘Cultivating empathy through virtual reality: advancing conversations about racism, inequity, and climate in medicine.’ Academic Medicine 95.12 (2020): 1882-1886.

237. Ryoo K., Bedell K. and Swearingen A., (2018), Promoting linguistically diverse students’ short-term and long-term understanding of chemical phenomena using visualizations, *J. Technol. Sci. Educ.*, 27(6), 508–522.

238. S. F. Ali, S. A. Azmat, A. U. Noor, H. Siddiqui and S. Noor, ‘Virtual reality as a tool for physical training,’ 2017 First International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT), 2017, pp. 1-6, doi: 10.1109/INTELLECT.2017.8277617.

239. Sadiku, A. (2018). The Effects of Virtual Worlds on Improving Students’ Communication and Collaboration Skills. *International Journal of Sciences: Basic and Applied Research, 42*, 202-211.

240. Safdar, M., Safdar, G. A., Hafeez, A., & Malik, M. A. (2019). Promoting Morality in Virtual Reality Learning Systems. http://oasis.col.org/bitstream/handle/11599/3394/PCF9_Papers_paper_195.pdf?sequence=1&isAllowed=y

241. Sampaio, A. Z., & Martins, O. (2017, March). VR model of bridge construction: a didactic application. In Proceedings of the Virtual Reality International Conference-Laval Virtual 2017 (pp. 1-3).

242. Sanchez-Sepulveda, M. V., Torres-Kompen, R., Fonseca, D., & Franquesa-Sanchez, J. (2019). Methodologies of learning served by virtual reality: A case study in urban interventions. *Applied Sciences*, *9*(23), 5161.

243. Sanchez-Sepulveda, Monica V., Nuria Marti-Audi, and David Fonseca-Escudero. "Visual technologies for urban design competences in architecture education." Proceedings of the Seventh International Conference on Technological Ecosystems for Enhancing Multiculturality. 2019.

244. Saraiva, Francisco, et al. ‘SHREWS: A Game with Augmented Reality for Training Computational Thinking (Short Paper).’ Second International Computer Programming Education Conference (ICPEC 2021). Schloss Dagstuhl-Leibniz-Zentrum für Informatik, 2021.

245. Saunders, Jonathan, et al. "Validating virtual reality as an effective training medium in the security domain." 2019 IEEE conference on virtual reality and 3D user interfaces (VR). IEEE, 2019.

246. Scaravetti, D., & François, R. (2021). Implementation of Augmented Reality in a Mechanical Engineering Training Context. *Computers*, *10*(12), 163.

247. Securing Your Reality: Addressing Security and Privacy in Virtual and Augmented Reality Applications. (2018). EDUCAUSE. https://er.educause.edu/articles/2018/5/securing-your-reality-addressing-security-and-privacy-in-virtual-and-augmented-reality-applications

248. Shaltout, Eman Hassan, Ahmed Afifi, and Khaled Mohammed Amin. "Augmented Reality Based Learning Environment for Children with Special Needs." 2020 15th International Conference on Computer Engineering and Systems (ICCES). IEEE, 2020.

249. Shema-Shiratzky, Shirley, et al. "Virtual reality training to enhance behavior and cognitive function among children with attention-deficit/hyperactivity disorder: brief report." Developmental neurorehabilitation 22.6 (2019): 431-436

250. Siegle, D. (2019). Seeing Is Believing: Using Virtual and Augmented Reality to Enhance Student Learning. Gifted Child Today, 42(1), 46–52. https://doi.org/10.1177/1076217518804854

251. Silić, A., Vukojević, J., Čulo, I., & Falak, H. (2019). Hikikomori silent epidemic: a case study. *Research in Psychotherapy: Psychopathology, Process, and Outcome*, *22*(2).

252. Sims, Robert, et al. "Logibot: Investigating Engagement and Development of Computational Thinking Through Virtual Reality." 2021 7th International Conference of the Immersive Learning Research Network (iLRN). IEEE, 2021.

253. Sirakaya, M., & Kilic Cakmak, E. (2018). Effects of augmented reality on student achievement and self-efficacy in vocational education and training. International journal for research in vocational education and training, 5(1), 1-18.

254. Skult, N., & Smed, J. (2020). Interactive storytelling in extended reality: concepts for the design. In Game User Experience And Player-Centered Design (pp. 449-467). Springer, Cham.

255. Slater, M. (2021). Beyond Speculation About the Ethics of Virtual Reality: The Need for Empirical Results. Frontiers in Virtual Reality, 0, 81. https://doi.org/10.3389/FRVIR.2021.687609

256. Slater, Mel, et al. "The ethics of realism in virtual and augmented reality." Frontiers in Virtual Reality 1 (2020): 1.

257. Soltani, P., & Andrade, R. (2021). The influence of virtual reality head-mounted displays on balance outcomes and training paradigms: a systematic review. *Frontiers in sports and active living*, 233.

258. Southgate, E., Smith, S. P., Cividino, C., Saxby, S., Kilham, J., Eather, G., ... & Bergin, C. (2019). Embedding immersive virtual reality in classrooms: Ethical, organisational and educational lessons in bridging research and practice. International Journal of Child-Computer Interaction, 19, 19-29.

259. Stavroulia, K. E., Christofi, M., Baka, E., Michael-Grigoriou, D., Magnenat-Thalmann, N., & Lanitis, A. (2019). Assessing the emotional impact of virtual reality-based teacher training. *The International Journal of Information and Learning Technology*.

260. Stylianidou, N., Sofianidis, A., Manoli, E., & Meletiou-Mavrotheris, M. (2020). "Helping Nemo!"—Using Augmented Reality and Alternate Reality Games in the Context of Universal Design for Learning. *Education Sciences*, *10*(4), 95.

261. Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. Computers in Human Behavior, 86, 77-90.

262. Syczewska, A. (2021). The Wirtualna rzeczywistość jako narzędzie dydaktyczne staje się normą: Virtual Reality jako część procesu projektowania ubioru w programie kształcenia Pracowni Projektowania Tkaniny i Ubioru Wydziału Architektury Wnętrz Akademii Sztuk Pięknych w Krakowie – case study. in*AW Journal - Multidisciplinary Academic Magazine*, *2*(1), 85-106. https://doi.org/10.52652/inaw.67

263. Sylaiou, S., Kasapakis, V., Gavalas, D., & Dzardanova, E. (2020). Avatars as storytellers: affective narratives in virtual museums. Personal and Ubiquitous Computing, 24(6), 829-841.

264. Sypsas, A., & Kalles, D. (2018, November). Virtual laboratories in biology, biotechnology and chemistry education: a literature review. In *Proceedings of the 22nd Pan-Hellenic Conference on Informatics* (pp. 70-75).

265. Tang, H. (2021). Applied research of VR technology in physical education. The International Journal of Electrical Engineering & Education. https://doi.org/10.1177/00207209211007774.

266. Tang, H. (2021). Applied research of VR technology in physical education. The International Journal of Electrical Engineering & Education, 00207209211007774.

267. Tang, Y.M.; Au, K.M.; Lau, H.C.W.; Ho, G.T.S.; Wu, C.H. Evaluating the effectiveness of learning design with mixed reality (MR) in higher education. Virtual Real. 2020, 24, 797–807

268. Tassinari, M., Aulbach, M. B., & Jasinskaja-Lahti, I. (2022). Investigating the Influence of Intergroup Contact in Virtual Reality on Empathy: An Exploratory Study Using AltspaceVR. Frontiers in psychology, 12, 815497.

269. Tassinari, M., Aulbach, M., & Jasinskaja-Lahti, I. (2021). The use of virtual reality in studying prejudice and its reduction: a systematic review.

270. Tassinari, Matilde, Matthias Aulbach, and Inga Jasinskaja-Lahti. "The use of virtual reality in studying prejudice and its reduction: a systematic review." (2021).

271. TeamViewer. (2022, April 27). Classroom. https://www.teamviewer.com/en/classroom/

272. Tegoan N, Wibowo S, Grandhi S. Application of the Extended Reality Technology for Teaching New Languages: A Systematic Review. Applied Sciences. 2021; 11(23):11360. https://doi.org/10.3390/app112311360.

273. Tegoan, N., Wibowo, S., & Grandhi, S. (2021). Application of the Extended Reality Technology for Teaching New Languages: A Systematic Review. Applied Sciences, 11(23), 11360.

274. The European Universities Initiative: a model for the future of higher education? garagErasmus Foundation. https://garagerasmus.org/the-european-universities-initiative-a-model-for-the-future-of-higher-education/

275. Theodorou, Paraskevi, et al. 'Augmented reality proves to be a breakthrough in Environmental Education.' Protection and Restoration of the Environment 7 (2018): 219-228.

276. Thisgaard, M., & Makransky, G. (2017). Virtual learning simulations in high school: Effects on cognitive and non-cognitive outcomes and implications on the development of STEM academic and career choice. Frontiers in psychology, 8, 805.

277. Thisgaard, Malene, and Guido Makransky. "Virtual learning simulations in high school: Effects on cognitive and non-cognitive outcomes and implications on the development of STEM academic and career choice." Frontiers in psychology 8 (2017): 805.

278. Torres C., (2018), Chemistry relationships with mathematics and language: Proposal of learning in a virtual environment, *Educ. Quim.*, 29(2), 51–61.

279. Torres-Ruiz, M., Mata, F., Zagal, R., Guzmán, G., Quintero, R., & Moreno-Ibarra, M. (2020). A recommender system to generate museum itineraries applying augmented reality and social-sensor mining techniques. Virtual Reality, 24(1), 175-189. ISO 690

280. Tosto, C., Hasegawa, T., Mangina, E., Chifari, A., Treacy, R., Merlo, G., & Chiazzese, G. (2021). Exploring the effect of an augmented reality literacy programme for reading and spelling difficulties for children diagnosed with ADHD. *Virtual Reality*, *25*(3), 879-894.

281. Triepels, C. P., Smeets, C. F., Notten, K. J., Kruitwagen, R. F., Futterer, J. J., Vergeldt, T. F., & Van Kuijk, S. M. (2020). Does three-dimensional anatomy improve student understanding?. Clinical Anatomy, 33(1), 25-33.

282. Trinon, Hélène. "Immersive technologies for virtual reality-case study: Flight simulator for pilot training." (2019).

283. Triviño-Tarradas, P., Mohedo-Gatón, A., Fernández, R. E. H., Mesas-Carrascosa, F. J., & Carranza-Cañadas, P. (2021). Preliminary results of the impact of 3D-visualization

resources in the area of graphic expression on the motivation of university students. Virtual Reality, 1-16.

284. Tromp, J., Le, C., Le, B., & Le, D.-N. (2018). Massively Multi-user Online Social Virtual Reality Systems: Ethical Issues and Risks for Long-Term Use. In Social Networks Science: Design, Implementation, Security, and Challenges. Springer International Publishing. https://doi.org/10.1007/978-3-319-90059-9_7

285. Trondsen, E., Member, B., & Vikings, S. (2019). Augmented / Virtual Reality in Nordic / Baltic Education, Learning and Training (April), 1–73.

286. Truchly, P., Medvecký, M., Podhradský, P., & Vančo, M. (2018). Virtual reality applications in STEM education. In 2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA) (pp. 597-602). IEEE.

287. Tsarava, K., Moeller, K., Pinkwart, N., Butz, M., Trautwein, U., & Ninaus, M. (2017, October). Training computational thinking: Game-based unplugged and plugged-in activities in primary school. In *European conference on games-based learning* (pp. 687-695). Academic Conferences International Limited.

288. Tsesmeli, S., & Tsirozi, T. (2015). Teaching compound words to a spelling-disabled child via Smart Notebook Technology: A case study approach. *Themes in Science and Technology Education*, *8*(1), 33-45.

289. Tsivitanidou, O. E., Georgiou, Y., & Ioannou, A. (2021). A Learning experience in inquiry-based physics with immersive virtual reality: Student perceptions and an interaction effect between conceptual gains and attitudinal profiles. Journal of Science Education and Technology, 30(6), 841-861.

290. Tzima, S., Styliaras, G., & Bassounas, A. (2019). Augmented reality applications in education: Teachers point of view. Education Sciences, 9(2), 99.

291. van Kessel, R., Wong, B. L. H., Rubinić, I., O'Nuallain, E., & Czabanowska, K. (2022). Is Europe prepared to go digital? Making the case for developing digital capacity: an exploratory analysis of Eurostat survey data. PLOS Digital Health, 1(2), e0000013.

292. Ulrich, F., Helms, N. H., Frandsen, U. P., & Rafn, A. V. (2021). Learning effectiveness of 360 video: experiences from a controlled experiment in healthcare education. *Interactive Learning Environments*, *29*(1), 98-111.

293. Vasconcelos, D. F. P., et al. "The protocol of a serious game based on Virtual Reality to aid in the literacy of children with Intellectual Disability." *Proceedings of SBGames, ISSN* (2017): 2179-2259.

294. Villena-Taranilla, R., Tirado-Olivares, S., Cózar-Gutiérrez, R., & González-Calero, J. A. (2022). Effects of virtual reality on learning outcomes in K-6 education: A meta-analysis. Educational Research Review, 100434.

295. Virtual Museum Transnational Network. Keys to Rome. http://keys2rome.eu/

296. Vistisen, P., Selvadurai, V., & Krishnasamy, R. K. (2020). Applied Gamification in Self-guided Exhibitions: Lessons learned from theory and praxis. In Gamescope Conference. Aalborg Universitetsforlag.

297. Wagener, Nadine & Schöning, Johannes & Rogers, Yvonne. (2020). Mitigating the Negative Impacts when Designing Educational VR Applications for Children.

298. Westra, Wybe. Virtual Reality Clothing Design. BS thesis. University of Twente, 2018.

299. Williams, Joseph Edward, Fatemeh Orooji, and Shahnaz J. Aly. 'Integration of Virtual Reality (VR) in Architectural Design Education: Exploring Student Experience.' 2019 ASEE Annual Conference & Exposition, 2019.

300. Wolf, M., Wehking, F., Montag, M., & Söbke, H. (2021). 360°-Based Virtual Field Trips to Waterworks in Higher Education. Computers, 10(9), 118.
301. Wolfartsberger, J. (2019). Analyzing the potential of Virtual Reality for engineering design review. Automation in Construction, 104, 27-37.
302. Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. British Journal of Educational Technology, 51(6), 1991-2005.
303. XR World Academy. (n.d.) Privacy & Compliance Guide for XR. https://xrworldacademy.com/privacy-compliance-guide-for-xr
304. Yang, F. C. O., Lo, F. Y. R., Hsieh, J. C., & Wu, W. C. V. (2020). Facilitating communicative ability of EFL learners via high-immersion virtual reality. Journal of Educational Technology & Society, 23(1), 30-49.
305. Young, G. W., Stehle, S., Walsh, B. Y., & Tiri, E. (2020). Exploring virtual reality in the higher education classroom: Using VR to build knowledge and understanding. Journal of Universal Computer Science, (8), 904-928.
306. Zhang, Lian, et al. 'Design and evaluation of a collaborative virtual environment (CoMove) for autism spectrum disorder intervention.' ACM Transactions on Accessible Computing (TACCESS) 11.2 (2018): 1-22.
307. Zhang, X., Shi, Y., & Bai, H. (2021). Immersive Virtual Reality Physical Education Instructional Patterns on the Foundation of Vision Sensor. Journal of Sensors, 2021.
308. Ziker, Cindy, Can XR improve Racial Equity in Higher Education?, 2021, https://media-and-learning.eu/type/featured-articles/can-xr-improve-racial-equity-in-higher-education/.
309. Zitter, Leah, How VR and AR Can Be Used to Support Students with Special Needs, 2020, https://www.techlearning.com/how-to/how-vr-and-ar-can-be-used-to-support-students-with-special-needs

List of studies examining European XR market used:

1. Capgemini Research Institute (2018). *Augmented and Virtual Reality in Operations*.
2. Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. *Https://Doi.Org/10.1080/10447318.2020.1778351*, 1658–1682.
3. Caserman, P., Garcia-Agundez, A., Gámez Zerban, A., & Göbel, S. (2021). Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality*, *25*(4), 1153–1170.
4. Hadwick, Alex (2019). *XR Industry Insight Report 2019-2020*.
5. Madary, M., & Metzinger, T. K. (2016). Real virtuality: A code of ethical conduct. Recommendations for good scientific practice and the consumers of VR-technology. *Frontiers Robotics AI*, *3*(FEB), 3. Tromp et al., 2018.
6. PwC (2019). *Seeing Is Believing How Virtual Reality and Augmented Reality Are Transforming Business and the Economy*.

The list of data sources for quantitative market data:

- Apple iPhone market share 2021 | Statista
- BusinessWire Global XR Forecast
- Counterpoint Research - device shipment forecast
- Deloitte (2022). A whole new world? Exploring the metaverse and what it could mean for you

- Ecorys (2021). XR and its potential for Europe
- Ecorys (2022). VR/AR Industrial Coalition: Final report
- IDC - AR & VR Headsets Market Share - device shipment forecast
- McKinsey&Company (2022). Value creation in the metaverse
- Mobile ad spend worldwide 2024 | Statista
- Mordor Intelligence Global XR Forecast
- Report Ocean: Europe Extended Reality Market Europe - Industry Dynamics, Market Size and Opportunity Forecast to 2030 (March 2022)
- Research And Markets European Forecast
- Research and Markets Global XR Forecast
- VR/AR market size 2024 | Statista

Annex 3. Success stories on the application of XR

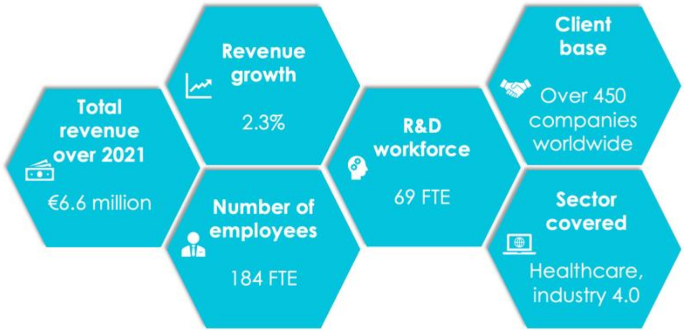
This annex presents four success stories of XR applications and their summaries. We present success stories in the healthcare, education, engineering, logistics and manufacturing sectors.

Success story in the healthcare sector: AMA

About AMA

AMA, a French company based in Rennes, is a publisher and integrator of software solutions to enhance collaborative work, as well as a supplier of advanced and highly secure remote assistance solutions for connected devices.[249] The company launched its business by using Google Glass in healthcare, successfully performing the first remote surgery using smart glasses in 2014. In 2016, *AMA* diversified from healthcare into industry and currently works with more than 450 customers in various sectors worldwide[250]. The company has 11 offices in eight territories: France (headquarters), Germany, Italy, Romania, Spain, Canada, Hong Kong, Japan, China, the United Kingdom, and the USA.

Figure 23. Background information about AMA



Notes: AMA's figures do not relate to the extended reality market in healthcare alone, but to the entire extended reality market for applications in industrial contexts.
Source: Visionary Analytics, 2022, based on AMA press release "2021 revenues", 31 January 2022, https://www.amaxperteye.com/wp-content/uploads/2022/01/AMA_CP_T4-22_20220131_EN.pdf; AMA website https://www.amaxperteye.com/about-us/

AMA sells subscriptions to its *XpertEye* software and resells hardware (mostly AR glasses)[251]. *AMA's XpertEye* solution has applications in the fields of assisted reality, dynamic workflow administration and online scheduling. *AMA's XpertEye* software can be used with smart glasses or can be adapted to use with any device that has an internet connection.

Based on the WebRTC[252] protocol, *XpertEye* is associated with smart glasses or another camera source (smartphone, endoscope, microscope, dermatoscope, etc.). These innovative solutions enable technicians and experts on site to share their field of vision, data and knowledge with a remote expert in real time via a secure software platform[253]. The remote expert, in turn, is connected to the user through audio and video.

[249] https://www.amaxperteye.com/category/news-press-xperteye/
[250] Interviews with representatives of AMA.
[251] Ibid.
[252] WebRTC (Web Real-Time Communication) is a technology that enables web applications and sites to capture and optionally stream audio and/or video media, as well as exchange data between browsers without requiring an intermediary. Interviews with representatives of AMA.
[253] https://www.amaxperteye.com/2020/09/21/how-ar-glasses-are-providing-instant-support-for-line-management-in-the-surface-treatment/

Figure 24. Key features of the AMA software

Feedback screen

- Remote expert can **project images and documents** into the user's field of vision

Photos or videos

- User can **capture photos or videos** that can be annotated by any of the participants in the call

Hands-free

- Possibility to operate the functions of the smart glasses **using only voice commands**

Encryption

- All **information under encryption** to protect data security and is not collected or retained by AMA

Security and resilience

- AMA software ensures **permanent connectivity** even in low-bandwidth areas. Security and resilience is ensured by implementing the **SecDevOps approach**, regular audits and intrusion testing.

Source: Visionary Analytics, 2022, based on https://www.amaxperteye.com/2020/09/21/how-ar-glasses-are-providing-instant-support-for-line-management-in-the-surface-treatment/ and the AMA web article "How Augmented Reality (AR) glasses are providing instant support for line management in the surface treatment" 2020. https://www.amaxperteye.com/2020/09/21/how-ar-glasses-are-providing-instant-support-for-line-management-in-the-surface-treatment/
Note: SecDevOps offers tools and practices that help developers and operations teams to perform their own security analysis, discover security issues and improve the way they code and operate software.

To ensure the high quality of its solutions, *AMA* provides technical support by assigning a project manager to each client [254]. The project manager manages client activities from pre-sale stage to deployment and further support, collecting feedback and requests for potential enhancements to the product.

Use cases in the healthcare sector

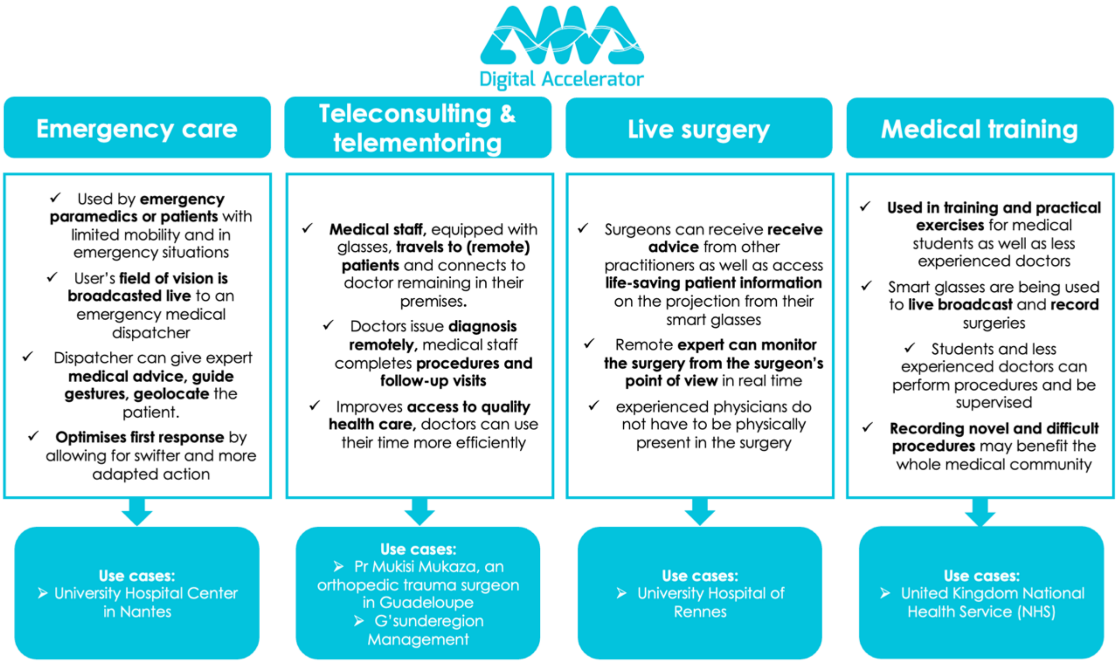
Within the realm of healthcare, *XpertEye* is applied in the following cases[255]:

- Emergency care;
- Teleconsulting and telementoring;
- Live surgery;
- Medical training.

These use cases are summarised in Figure 25 and presented in further detail in the sections that follow.

[254] Interviews with representatives of AMA.
[255] https://www.amaxperteye.com/

Figure 25. AMA use cases



Source: Visionary Analytics, 2022, based on AMA webpage: https://www.amaxperteye.com/

Challenges and future perspectives

AMA products meet the growing challenge of digitalisation for clients seeking to enhance productivity and competitiveness in a variety of fields ranging from teleconsulting and telementoring to quality control and training.[256] *AMA* expects to capitalise the expected growth in sales by expanding its client base and increasing the revenue generated from each client.

Figure 26. AMA's challenges

Source: Visionary Analytics, 2022, based on MIDCAP "Initiation of coverage Midcap Partners" 2021. https://www.amaxperteye.com/wp-content/uploads/2021/12/Etude_AMA_EN.pdf and interviews with representatives of AMA.

To address these challenges, *AMA* aims to constantly improve its product. One of the main directions for product improvements relates to increasing the level of integration[257] into clients' ecosystems (both digital and non-digital)[258]. Moreover, *AMA* foresees large investments in expanding its R&D team from 69 employees at the end of 2021 to 200 in 2023[259].

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[256] MIDCAP "Initiation of coverage Midcap Partners" 2021. https://www.amaxperteye.com/wp-content/uploads/2021/12/Etude_AMA_EN.pdf
[257] Interviews with representatives of AMA.
[258] Interviews with representatives of AMA.
[259] This target is likely to be postponed.

Success story in the education sector: Varjo

About Varjo

Varjo, a Finnish company based in Helsinki, is a manufacturer of VR, AR and MR headsets as well as software. It specialises in the development of high-resolution devices that offer a resolution comparable to that of the human eye. The company was founded in 2016, and today *Varjo's* products are specifically designed for demanding enterprise applications in various fields such as training and simulation, design and engineering, research and medicine. *Varjo* currently works with more than 1,500 enterprise customers in around 40 countries, and has expanded its sales activities and reseller network to include offices worldwide.

Figure 2727. Background information on Varjo

Source: Varjo, based on interviews with Varjo employees.

The company offers three high-quality hardware products. The ***Varjo XR-3*** and ***VR-3*** headsets are primarily intended for professional use in situations where high resolution is crucial (e.g. automotive design or critical mission training). These headsets offer the highest resolution available on the market (over 70 PPD[260]), with photorealistic visual fidelity and built-in Bionic Display[TM261] (90 Hz[262]) and integrated eye tracking (200 Hz), enabling the analysis of even the slightest eye movements. Incorporating a hand-tracking feature developed by *Ultraleap,*[263] *XR-3* and *VR-3* provide natural interactions and an engaging training experience.[264] ***Varjo Aero*** is primarily intended for commercial use by XR professionals and other individual users. Its lower hardware specifications make *Varjo Aero* suitable for larger training deployments, including classroom training.

Varjo works with several manufacturers across Europe and Asia to produce its hardware. However, most of the manufacturing is in China, and – as company representatives noted – production logistics are predominantly established there, making it more cost-effective to source some components closer to the production chain than in Europe.

Alongside its hardware, *Varjo* also offers several software solutions, which are presented below in Figure 28.[38]
Several other aspects distinguish *Varjo* from its competitors:

- **Adherence to high security requirements.** *Varjo* is one of the few XR providers to work with government customers in the aerospace and defence industries in the United States. The company adheres to strict information security procedures (e.g. no automatic downloads are performed, no personal data are collected or transferred to other

PPD refers to pixels per degree. A higher PPD means sharper, more compelling VR images.
[261] According to Varjo, Bionic Display combines two displays – one in the peripheral area and one focus display – using a semi-transparent mirror, to create an image that has both a wide field of view, but also offers highly precise detail.
[262] Measured in Hertz (Hz), the refresh rate counts the number the display fully refreshes every second. For example, a 60Hz display refreshes 60 times per second. The higher the refresh rate, the more accurately the image can be analysed and displayed in the headset.
[263] Ultraleap can be accessed at: https://www.ultraleap.com.
[264] https://Varjo.com/products/.

devices[265]) and requirements[266]. This allows *Varjo* products to be used by governmental customers if they are produced in Europe.[267] According to company staff, to meet the required security standards, *Varjo* assembles the final TAA-compliant product at its factory line in Helsinki, rather than in China.

- **Technical support and assistance provided to customers.** The company does not explicitly provide its customers with training on its hardware; however, as staff explained, the company takes a proactive approach to supporting software companies and *Varjo* technology resellers[268] to set up and implement their products in workplaces or training sites, if such a need is expressed. For example, *Varjo* can assign an on-site person to help with the process and provide support. Alternatively, customers can solve issues quickly by contacting the company's technical support team. Moreover, a representative of *Volvo Cars* explained that *Varjo* has a great support team, with whom they communicate via Slack. The representative stated that the response times from Varjo were excellent.

Use cases in the training and education sector

In the field of education and training, *Varjo*'s products are mainly applied in:

- Medical and surgical training
- Pilot training
- Astronaut training
- Critical safety and maintenance training.

These use cases are presented in further detail in Figure 28.

[265] https://Varjo.com/products/xr-3/
[266] For example, the Trade Agreements Act (TAA) and Buy American and Trade Agreements (BAA).
[267] Varjo web article "Varjo's Trade Agreements Act (TAA) Compliant Mixed Reality Products Now Available in the U.S. via ITI Systems" 2022 https://Varjo.com/company-news/Varjo-adds-trade-agreements-act-taa-compliant-mixed-reality-products-to-the-u-s-general-service-administration-gsa/
[268] A complete list of Varjo's technology resellers in Europe can be found here: https://varjo.com/resellers/

Figure 2828. Use cases in the training and education sector

VARJO

Medical and surgical training	Pilot training	Astronaut training	Safety and maintenance
✓ High quality medical data or human anatomy visualisation with Bionic display ✓ Integrated hand-tracking enables students to interact with tools and medical equipment in an immersive virtual environment ✓ Better collaboration and skill training in a simulation	✓ Simulation of real-flight conditions with real cockpits ✓ Effective training of dangerous scenarios in a safe immersive environment ✓ First EASA-approved VR simulator allows pilots to formally log time spent in a VR-based simulator ✓ Faster learning and cost-effective training solutions	✓ Varjo technology allows astronauts to train for safety-critical scenarios, including operating the spacecraft and docking with the International Space Station (ISS) ✓ VR solutions for improving astronauts' ability to react and make decisions in dangerous situations	✓ VR solutions for company-specific training and maintenance processes ✓ VR solutions to simulate scenarios, such as a nuclear accident or a chemical spill ✓ Resource saving and reducing the cost of training compared to traditional methods
Used by: Toltech, Laerdal, Osgenic, Loma Linda University	**Used by:** European Union Aviation Safety Agency, Finnish Air Force , US Air Force Navy	**Used by:** Boeing, NASA	**Used by:** Loviisa Nuclear Power Plant, Fortum

Source: Visionary Analytics, 2022, based on the Varjo e-book "A Beginner's Guide to VR and XR for Medical & Healthcare", https://varjo.com/e-book/e-book-a-beginners-guide-to-vr-and-xr-for-medical-and-healthcare/; Varjo Whitepaper "Virtual and Mixed Reality for Pilot Training and Simulation" https://Varjo.com/e-book/white-paper-virtual-and-mixed-reality-for-pilot-training-and-simulation/; Varjo web article "Varjo & Boeing: A New Era in Astronaut Training using Virtual Reality", https://Varjo.com/boeing-starliner/;Case Fortum: Virtual Reality (VR) for Nuclear Power Plant Operator Training, https://Varjo.com/blog/case-fortum-using-virtual-reality-to-train-nuclear-power-plant-operators/.

Challenges and future perspectives

Varjo maintains its position as a global leader in the XR market worldwide, providing professional, cutting-edge XR software and hardware technology to businesses. *Varjo* representatives claim that the company has a competitive advantage over other companies in the industry, because it has already established itself as a quality VR headset provider in such application areas as aerospace, the military and automotive design, which demand the highest possible resolution from headsets. *Varjo*'s products meet the needs of a growing customer base across industry, and have earned a reputation among avid VR users as the most advanced VR headsets in terms of quality, compared with other headsets available on the global market.[269]

However, despite its growing success, the company still faces a few challenges. For example, the pandemic posed a challenge to the company's growth, as *Varjo*'s products are mainly used in shared office spaces and dedicated VR facilities, which were largely closed during lockdowns.[270]

Although the company tripled its revenue in the first quarter of 2022 compared with the previous year and is growing fast, *Varjo* is still in the investment phase and does not yet expect to be profitable.

Other challenges and barriers to *Varjo*'s growth, as judged by company representatives, are not company-specific, but rather relate to ecosystem challenges faced by the XR market as a whole (Figure 29 below).

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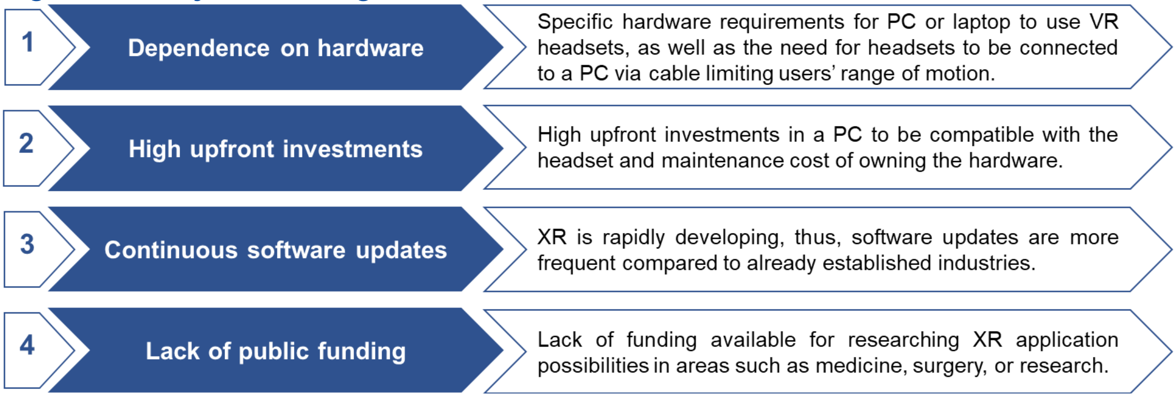
[269] https://www.xrtoday.com/mixed-reality/htc-vive-pro-vs-varjo-vr-3/

[270] As representatives of Varjo explained, companies are more inclined to invest in VR technology that is not for individual employee use but is shared among team members for cost efficiency. Although the pandemic has changed the working conditions for potential Varjo clients, it was not considered necessary and efficient by most companies to invest in VR headsets for each employee to use when working remotely.

Figure 29. Varjo's challenges

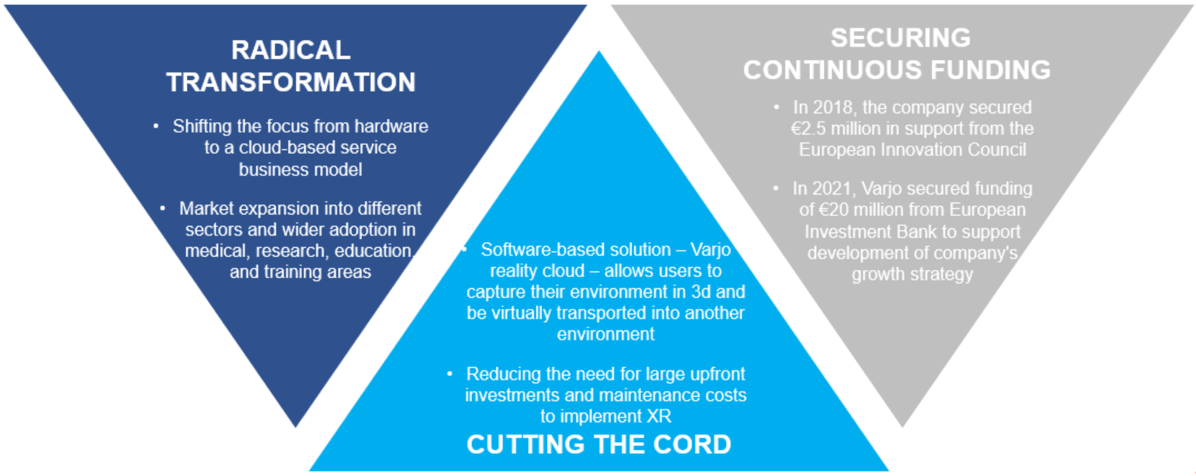


Source: *Varjo*, based on interviews with company representatives

In terms of barriers to using *Varjo's* products and services, the representative of *Volvo Cars*[271] interviewed commented on the company's revenue model, explaining that a lump-sum subscription fee might be less complex for subscribers than a monthly one.

Despite these challenges, company representatives stated that *Varjo* expects to grow its business in sales and industrial applications over the next two to three years. To drive its transformation, maintain its competitive advantage in the XR market and overcome the challenges listed above, *Varjo* is undergoing a 'radical transformation'[272], *and* has secured continuous funding from various sources (see Figure 30).

Figure 3029. Varjo's steps to drive its transformation



Source: Varjo, based on interviews with company representatives

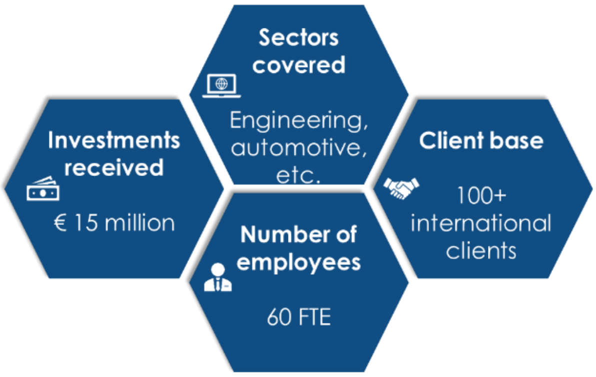
[271] A client/end user of Varjo's products and services which has been working with Varjo from the company's early prototyping stages. The use cases for Volvo include, among others, early design reviews, product validation and UX.
[272] https://Varjo.com/blog/Varjo-reality-cloud/

Success story in engineering and manufacturing[273]: Holo-Light

About Holo-Light

Founded in 2015, *Holo-Light* is an XR company based in Germany and Austria which aims to develop "the most powerful immersive streaming platform" to make AR/VR use cases more scalable[274]. Even though demand for XR technologies is growing rapidly, the performance and rendering capabilities of XR devices is sometimes still suboptimal. This opens up a market for solutions that allow the seamless streaming of XR apps and AR/VR content. With the announcement of the first AR glasses, HoloLens by Microsoft, *Holo-Light* saw potential in the industrial and everyday application of XR solutions. Its idea was to create a software solution that would bridge the gap between virtual planning and the real world[275]. Figure 31 presents some background information about *Holo-Light*.

Figure 31. Background information about Holo-Light



Source: Interview with *Holo-Light* employees.

Working primarily with XR technologies, *Holo-Light* focuses on creating and integrating a server-based system that optimises the use of XR applications by the user through eliminating performance issues, incompatibilities between different XR devices, and ensuring data security. The company's business model is subscription-based, with customers subscribe to AR3S and ISAR via yearly licenses.

Use cases

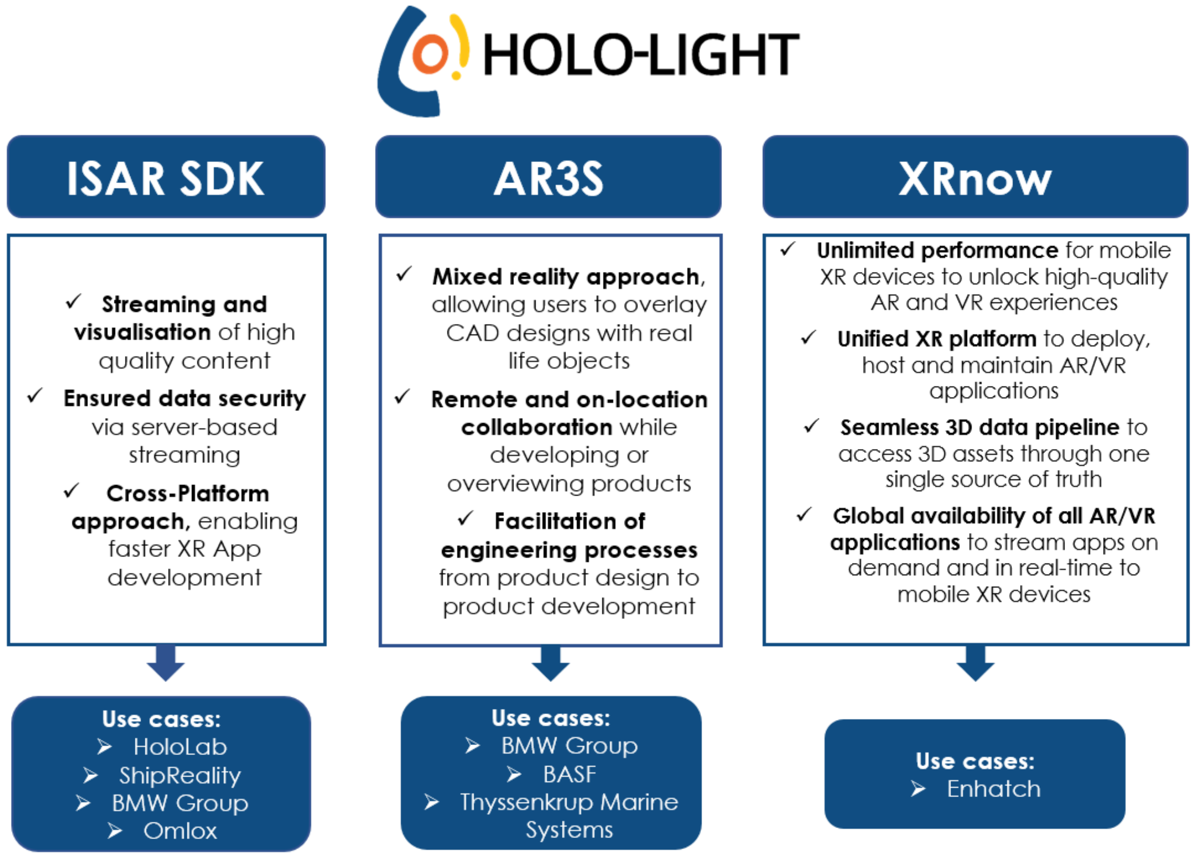
Holo-Light offers three main software and technology solutions:

- **ISAR SDK** – a server-based streaming system for XR apps;
- **AR3S** – an augmented reality engineering app;
- **XRnow** – an all-encompassing streaming metaverse.

[273] However, applications are also possible in the automotive, healthcare/medtech, construction and architecture, aerospace and defence, process industry, training and education sectors.
[274] https://holo-light.com/about/
[275] https://holo-light.com/5-years-of-holo-light-5-questions-for-our-5-founders/

While these software solutions are fully functional individually, the company says the best results can be obtained by integration them together[276]. These solutions and their use cases are presented in further detail in Figure 32.

Figure 3230. Holo-Light solutions and their use cases

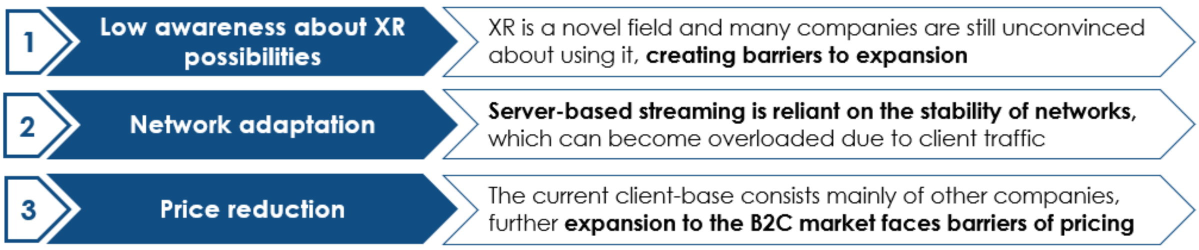


Source: Visionary Analytics, 2022, based on information from Holo-Light

Challenges and future perspectives

Despite Holo-Light's rapid growth and success, the company still faces **challenges to further expansion into different sectors and client bases (Figure 33)**[277].

Figure 3331. Holo-Light challenges



Source: Visionary Analytics, 2022, based on interviews with Holo-Light employees.

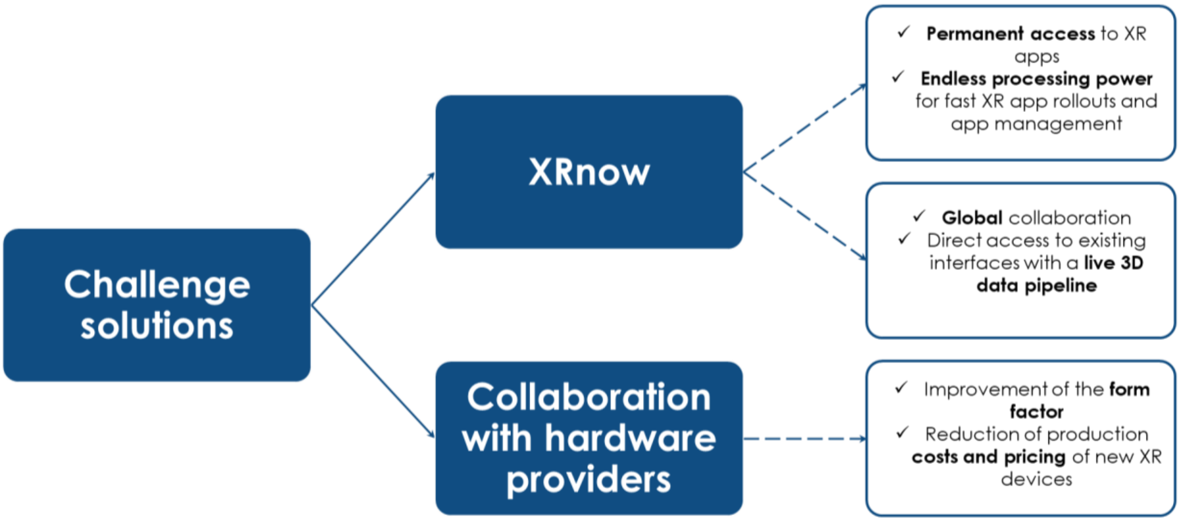
To address these challenges, *Holo-Light* is developing a new product: an all-encompassing XR metaverse, XRnow[278]. XRnow will allow companies to host AR/VR apps developed by

[276] Interview with Holo-Light employees.
[277] Interview with Holo-Light employees.
[278] Interview with Holo-Light employees.

them[279]. The platform will also encompass the current *Holo-Light* solutions ISAR SDK and AR3S. The ISAR SDK will be the technological basis for streaming XR content, while AR3S will be the first out-of-the-box XR application running in the industrial metaverse, demonstrating how XR apps can be stored, streamed and managed on the XRnow platform.

Holo-Light aims to address the market challenges it faces with the XRnow metaverse, as well as collaborating with hardware providers, as summarised in Figure 34 [280].

Figure 3432. Holo-Light's strategy for overcoming barriers



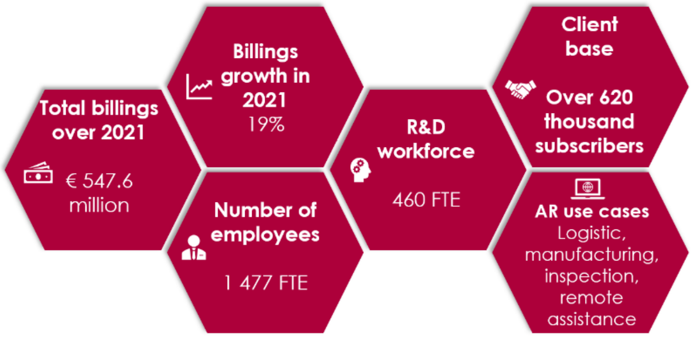
Source: Visionary Analytics, 2022, based on interviews with Holo-Light employees.

[279] https://holo-light.com/immersive-streaming-platform-xrnow/
[280] Interviews with Holo-Light employees.

Success story in logistics and manufacturing: TeamViewer

About TeamViewer

Figure 3533. Background information about



Source: TeamViewer AG, Annual Report 2021

***TeamViewer*, a leading global technology company,** was founded in Goppingen (Germany) in 2005. The company builds on its historical strengths in cloud technologies that enable remote support and online collaboration. The very first and the best-known product developed by the company, named after the company itself – *TeamViewer* – is a software package that allows users to remotely access and control computers and other devices.[281] Since its launch in 2005, this software has been installed on more than 2.5 billion devices.[282]

Following the success of its first product, the company continued to grow, acquiring other technology-oriented companies and thus expanding its capabilities into augmented reality (AR), among others.[283] The company's latest enterprise product, ***TeamViewer Frontline*** – developed to focus on needs of the deskless workforce – offers a consolidated AR-based platform that integrates various AR solutions.[284] *TeamViewer Frontline* enables companies to leverage the full spectrum of AR capabilities, from simple AR annotations to 2D or 3D overlays, as well as more sophisticated AR features.[285] These features allow companies to implement digital solutions for their mobile workers, even those who are not familiar with the application of AR technologies, as it requires zero AR expertise or coding knowledge.[286]

The *TeamViewer Frontline* software is device-agnostic, working on smart glasses and other wearable mobile devices, and is thus adaptable to every IT infrastructure and business environment.[287] With *TeamViewer Frontline*, employees can work hands-free while receiving real-time information and pre-defined workflows directly to their devices. The easy-to-use software can be used by employees in their day-to-day operations to add immediate value to processes.[288]

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[281] TeamViewer products, TeamViewer, Available at: https://www.teamviewer.com/en/products/teamviewer/
[282] Ibid.
[283] TeamViewer, A Brief History of TeamViewer. Available at: https://www.teamviewer.com/en/company/
[284] Interview with representatives of TeamViewer.
[285] TeamViewer Frontline. Available at: https://www.teamviewer.com/en/solutions/frontline/
[286] Cision News, TeamViewer's Augmented Reality Platform 'Frontline' Recognized as Number One European Enterprise AR Offering by Industry Analyst Firm ABI Research, 2022. Available at: https://www.prnewswire.com/news-releases/teamviewers-augmented-reality-platform-frontline-recognized-as-number-one-european-enterprise-ar-offering-by-industry-analyst-firm-abi-research-301462314.html
[287] Ibid.
[288] Ibid.

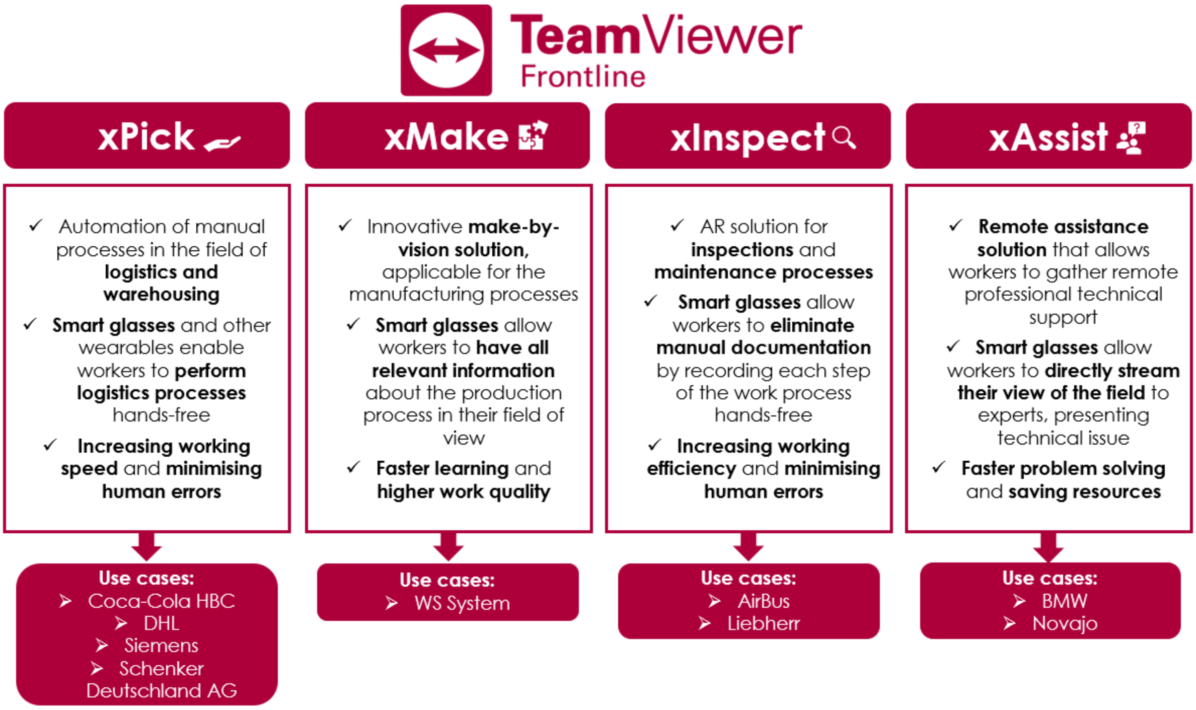
Use cases

The ***TeamViewer Frontline*** software offers four different solutions, which can be applied for different purposes by companies operating in different sectors [289]:

- **xPick** – logistics and warehousing;
- **xMake** – manufacturing and production;
- **xInspect**– inspection and maintenance;
- **xAssist** – remote assistance.

Companies can apply these solutions separately or in combination, based on their needs.[290] These solutions and use cases are presented in further detail below.

Figure36. TeamViewer Frontline solutions and use cases



Source: Visionary Analytics, 2022, based on the TeamViewer webpage: https://www.teamviewer.com/en/frontline/

[289] TeamViewer Frontline. Available at: https://www.teamviewer.com/en/solutions/frontline/
[290] Interview with representatives of TeamViewer.

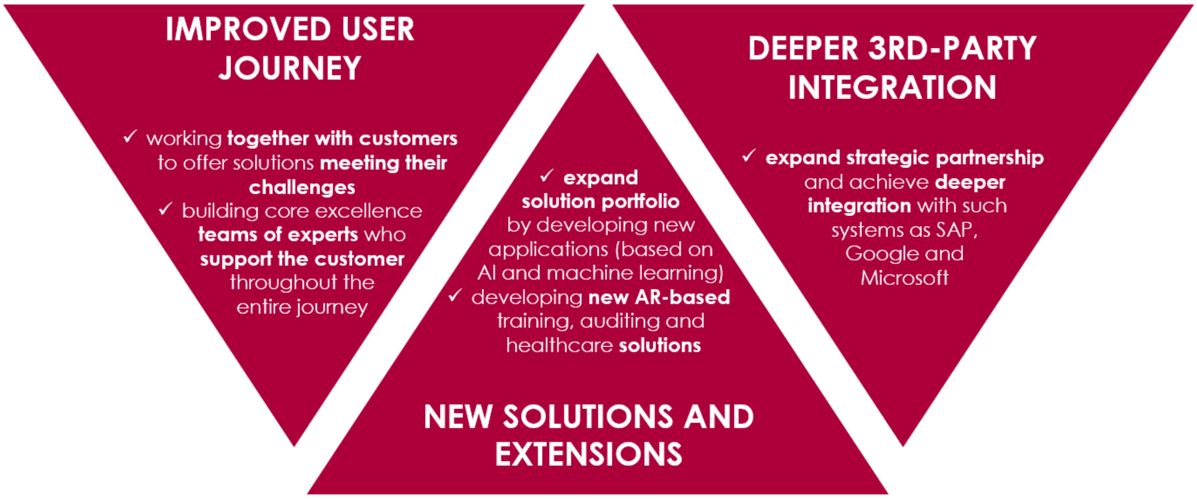
Challenges and future perspectives

Despite the significant progress that TeamViewer has made in recent years (company growth, acquisition of other technology-oriented companies, and expansion of its AR-based solution portfolio), the company faces challenges to its further growth, both in relation to its AR-based solution and across the portfolio of all TeamViewer services (see Figure below).[291]

Figure 37. TeamViewer's challenges

Source: Visionary Analytics, 2022, based on TeamViewers' Annual Report (2021) and interviews with representatives of TeamViewer.

Figure 38. Three key pillars of TeamViewer's growth strategy



Source: Visionary Analytics, 2022, based on TeamViewer, Capital Market Day, Presentation, 2021. Available at: https://ir.teamviewer.com/websites/teamviewer/English/2600/capital-markets-day.html

To address these challenges, *TeamViewer* is applying a risk management and control system that aims to ensure the early identification, assessment and addressing of risks.[292] Moreover, the company constantly seeks to optimise its internal working processes, and is investing in product innovation with the aim of improving and expanding its product portfolio.[293] The company's strategy for further growth focuses on three key pillars (see Figure 38).[294]

[291] TeamViewer AG, Annual Report 2021. Available at: https://annualreport.teamviewer.com/media/TeamViewer_Annual_Report_2021.pdf
[292] Interview with representatives of TeamViewer.
[293] Interview with representatives of TeamViewer.
[294] Interview with representatives of TeamViewer.

Annex 4. The policy context and initiatives in EU Member States

Initiative	Budget	Target groups	Description
Austria			
Tender, Digital and Social Transformation in Higher Education 2020-2024[295] Funded by the Federal Ministry of Education, Science and Research (Bundesministerium für Bildung, Wissenschaft und Forschung – BMBWF	The funding offered was high, with a total of EUR 50 million set until 2024	Austrian public universities and various other educational institutions	This recent call for tender explicitly focuses on new and creative digitisation projects that can achieve structural change in universities, with the goal of enabling universities to adapt to modern social structures. Its aim was to support projects that have the potential to increase the innovation, capabilities and efficacy of universities and the higher education system in the digital age. One of the projects funded relates to image digitalisation and immersive use in medical training. With this tender, the Ministry of Education acknowledges the need for digital tools in education, and mentions VR as one of those tools on its website.
Eight-Point Plan Funded by the Ministry of Education	USD 236 million	Schools, teachers, and students	The K12 Digital Education Expansion: eight-point plan for digital learning solutions in primary and secondary schools through 2022 focused on hardware, software, training and curriculum standardisation.
Digital realities[296] Funded by the Vienna Business Agency	EUR 1 million	Start-ups	The Vienna Business Agency's 'Digital Realities' funding competition addresses the possible applications of VR, AR and MR for creative work (including cultural education as well). Its aim is to help companies from all areas of the creative industries to implement their VR, AR and MR projects, and thus leverage existing potential in Vienna.
General comments: • Investment activity has been picking up recently; however, the majority of AR and VR companies are self-funded. • Many XR-related projects are funded by the Horizon 2020 or Erasmus+ programmes. • National policies focus on broader digitalisation; MR/VR/AR is not explicitly mentioned in strategic documents. • However, Austria initiates financing programmes for projects relating to digitalisation in education, under which projects concerning XR can be funded.			
Belgium			
Action plan for XR[297]	EUR 5.5 million	Vulnerable groups – vocational training	As explained by a policymaker during an interview, in Belgium, the Flemish initiative of the Ministry of Education has allocated EUR 5.5 million to XR technologies in general, and is working together with several educational institutions, including universities. It not only provides governmental guidance and recommendations on XR hardware and software, but also launches tenders for applied research on how to implement XR effectively in education. It also carries out programmes to train teachers to become proficient at using XR technologies in education. Lastly, the Ministry of Education also plans to launch

[295] https://pubshop.bmbwf.gv.at/index.php?article_id=9&sort=title&search%5Btext%5D=digitalisierungsvorhaben&pub=799
[296] https://wirtschaftsagentur.at/fileadmin/user_upload/Kreativwirtschaft/Publikationen/White_Paper_EN_Digital_Realities.pdf
[297] The Flemish Parliament, 2021, pp. 6-7. URL.

Initiative	Budget	Target groups	Description
			tenders for the creation of curriculum-aligned XR software for education, co-created with the field of educational itself.
Flemish Resilience Relay Plan	n/a	Vulnerable pupils	This is an initiative of the Flemish Ministry of Education with the purpose of strengthening the Flemish education system's resilience following the Covid-19 crisis, with particular focus on vulnerable pupils. It is based on two pillars: (1) getting ahead of the learning backlog created by the pandemic; and (2) promoting mental well-being among students. As part of pillar (1), the Ministry of Education is planning to implement digital innovations, including XR, into the secondary school system.
Bulgaria			
Digital Transformation of Bulgaria for the Period 2020-2030[298]	n/a	Students, teachers	Broader digital transformation: development, adaptation and implementation of digital educational content, as well as the identification and validation of valuable interactive multimedia e-learning resources, enabling blended distance learning (both synchronous and asynchronous) for learning purposes, improving the ICT skills of students and teachers, educational applications, and games. No explicit mention of AR/MR/VR in documents.
E-infrastructure (CLaDA BG) for resources and technologies for the Bulgarian language and cultural heritage, member of the pan-European research consortia CLARIN ERIC and DARIAH ERIC[299]	Co-funded by the Bulgarian government and the EU	n/a	The Bulgarian national research infrastructure for resources and technologies for language, cultural and historical heritage, integrated within CLARIN EU and DARIAH EU. CLaDA BG intends to establish a Knowledge Graph reflecting the Bulgarian language, culture and history (the so-called 'Bulgaria-centric Knowledge Graph'). This Knowledge Graph and the infrastructure of services implemented will form a basis for supporting research into digital humanities and social sciences in Bulgaria, applying modern technologies such as artificial intelligence, big data and virtual reality. The results and achievements of CLaDA BG are directly applicable to education, social and governmental policies, e-government, tourism, etc. (e.g. 3D museum exhibitions).
Creating a laboratory for virtual reality	USD 25 million	Students at the University of Burgas	The Municipality of Burgas, the Bulgarian Ministry of Education and Science and the US-based XR company EON Reality are contributing USD 25 million to establish an XR training centre at the University of Burgas. This centre will provide approximately 5,000 eligible students and 750 eligible faculty members with access to high-quality teaching materials, equipment and software. The centre is intended to boost the local IT and XR sectors.
General comments: • Focus on broader digitalisation, no national policies regarding XR. • Most XR initiatives are (co)-funded by the EU, e.g. Sofia Tech Park, under which the Virtual and Augmented Reality Lab300 was established.			
Croatia			

[298] https://www.mtc.government.bg/sites/default/files/digital_transformation_of_bulgaria_for_the_period_2020-2030_f.pdf
[299] https://mon.bg/upload/26650/RoadMapBulgaria_2020-2027_EN_11062021.pdf
[300] https://sofiatech.bg/en/activities/laboratories/laboratoriya-po-virtualna-i-razshirena-realnost/

Initiative	Budget	Target groups	Description
e-Schools: development of the system of digitally mature schools programme[301]	More than EUR 200 million, financed through the European Regional Development Fund, European Social Fund and Croatian government	Schools, teachers, students	e-Schools are envisaged as digitally mature schools connected to ultra-fast internet, well equipped with ICT, employing digitalised teaching, learning and administrative processes. During the second phase of the programme, by the end of 2022, all schools will be equipped with wired and wireless local area networks and the corresponding active network equipment. Also, to further facilitate and encourage the use of ICT, suitable digital educational content, e-content and e-services are being developed. Under this programme, some initiatives were carried out using interactive digital tools to create digital posters (possibly involving AR) and virtual tours.[302] Agencies included: the Croatian Academic and Research Network – CARNET, the Ministry of Science and Education.
Strategy For Education, Science and Technology[303]	n/a	Schools, teachers, students	Implementation of digital tools in schools and universities, e-learning platforms, ICT skills for students and teachers, more research opportunities, e-schools.
General comments: • Focus on broader digitalisation, digital tools and e-learning, no national policies explicitly mention XR. • Most XR-related initiatives are (co)-funded by the EU.			
Cyprus			
VRTEACHER (virtual reality-based training to improve digital competences of teachers)	The VRTEACHER project is funded under Key Action 2 of the Erasmus+ programme and will last two years until 31 May 2023, with a total budget of EUR 219,589	Pre-service student teachers (higher education students, PhD candidates, etc.), and in-service educators/teachers	The VRTEACHER project aims to provide effective educational responses in relation to educators' training using a novel VR-based pedagogical approach for virtual practicum, the university says. The project will address challenges related to class management in crisis situations, such as a pandemic, with the vision to equip teachers with key skills including empathy, perspective-taking, self-efficacy and adaptability through immersive and experiential training exercises that reflect the real-life scenarios and situations faced during a crisis.[304]
Digital Cyprus 2025[305]	n/a	n/a	The use of virtual experience technologies to deliver educational and cultural experiences using virtual/augmented/mixed reality that promote historical and cultural heritage, but also enable the delivery of safer, realistic immersive training to public servants whose jobs may require it (e.g. police officers, firefighters, search and rescue crews etc.) (*only expressed as one of the objectives of digital transformation, no clear KPIs mentioned*).
EON Icube, a traffic education study[306]	Approved for funding under the Call 2011 Package Programme for Research, Technological Development and Innovation 2009-2010 of	Fourth-grade students from the Second Primary School Ayios Athanasios in Limassol	Goals of the projects: to identify factors that affect/influence children with regard to traffic safety; to use virtual reality technology to prevent life-threatening risks. Aimed at traffic education, specifically to improve road-crossing skills among children. Enable children to learn in a virtual, immersive environment before they face a world in which there is a possibility of a fatalities.

301 https://pilot.e-skole.hr/en/e-schools/project-description/
302 https://en.unesco.org/news/how-innovative-project-croatia-developing-digitally-mature-schools
303 https://mzo.gov.hr/UserDocsImages//dokumenti/Obrazovanje//Strategy%20for%20Education,%20Science%20and%20Tehnology.pdf
304 https://cyprus-mail.com/2021/07/07/tepak-programme-enhances-educators-digital-training-skills/
305 https://www.dmrid.gov.cy/dmrid/research.nsf/all/927EA351714F99EDC22587CE0028C090/$file/Digital%20Strategy%202020-2025.pdf?openelement
306 https://eonreality.com/wp-content/uploads/2019/12/Cyprus-Case-Study-1.pdf

Initiative	Budget	Target groups	Description
	the Research Promotion Foundation and co-financed by the European Regional Development Fund and the Republic of Cyprus. No information is available about concrete funding.		
General comments: • No clear or concrete national policies are identified with regard to VR/AR/MR in education; however, Cyprus is now introducing various wider policies aimed at all-encompassing digital transformation. • Includes the adoption of national strategies such as the National Digital Strategy and E-Government Strategy, which focuses on leading technologies such as artificial intelligence (AI), distributed ledger technologies (DLT), big data and the Internet of Things (IoT), supporting infrastructures related to electronic communications and information technology. • The use of VR/MR/AR technologies for education and culture has been mentioned once in the National Digital Strategy 'Digital Cyprus 2025', but no further concrete actions were found in other policy documents. • Agencies involved: Deputy Ministry of Research, Innovation and Digital Policy; Research Promotion Foundation; Cyprus universities and research institutions that carry out projects relating to XR, funded by EU initiatives. • As of the time of writing, many educational initiatives involving XR are at an individual rather than governmental level, and are led by research institutions and universities.			
Czechia			
Strategy for the Education Policy of the Czech Republic up to 2030+	n/a	Schools, teachers, students	First, to ensure the promotion of digital literacy for all pupils; and second, To support the digital competencies of all teachers. The transformation of the content of education towards digital literacy and computational thinking or the use of digital technologies and resources in general, digital content creation.
General comments: • Focus on broader digitalisation, digital tools and e-learning, no national policies explicitly mention XR.			
Denmark			
Ministry of Higher Education and Science grant	DKK 20 million	Research institutions, universities	Roskilde University (RUC) will head up a new project to develop virtual learning technologies and map the best ways to use these new technologies for teaching in the future. This project is intended to act as a platform for establishing broader collaboration within virtual learning. RUC will invite other educational institutions, development environments and companies to participate in broad collaboration, RUC's rector explains.
Royal Danish Air Force Flying School	n/a	The Royal Danish Air Force	The Royal Danish Air Force Flying School (RDAF) and VRpilot are collaborating on the implementation of VR-based flight training to expand immersive learning modules. The new solution will seamlessly bridge the gap between real-world flying training and flight simulation. This example represents a commitment to funding and implementing XR in the public sector.
Filmby Aarhus opens laboratory for XR, film and game productions	DKK 2.9 million	Local business and VR creators	The Danish Business Promotion Board (Danmarks Erhvervsfremmebestyrelse) has extended a DKK 2.9 million grant to the media organisation Filmby Aarhus. The initiative aims to promote local business potential and improve conditions for VR creators. In addition to this funding, Filmby Aarhus has raised DKK 5.8 million, which has been used

Initiative	Budget	Target groups	Description
			to establish Denmark's first publicly accessible XR laboratory. The laboratory is run in partnership with a number of partner companies: KongOrange, WiredFly, AateVR, MANND, Crash, and the educational institution VIA. It will provide local XR game and film producers with previously inaccessible technological opportunities. Motion capture is the most important piece of technology made available.
The government's new digitalisation strategy	DKK 2 billion	Vocational training	The Danish government's latest digitalisation strategy recognises the importance of VR and AR for vocational education and training. The strategy highlights the fact that immersive technologies strengthen the link between theoretical in-school and practical in-company training. As a result, the government has set aside funds to enable schools to acquire relevant equipment up to 2023.
Dansk Lyd hackathon	n/a	VR enthusiasts	The innovation network Dansk Lyd and the Belgian cluster screen.brussels have initiated a collaboration that focuses on virtual reality. One of its key outputs was the first European VR Hackathon, which welcomed more than 100 VR enthusiasts to build new VR/AR projects. Dansk Lyd also continues to collaborate with other innovation clusters. Examples include the 'VR Sound' initiative with BSR Innovation Express, and a networking trip for Danish innovation clusters to the world's first VR industry convention.
Estonia			
Information Technology Foundation for Education (HITSA) Since 2020, all activities of the Information Technology Foundation for Education have been transferred to the Education and Youth Board. The new board is directly subordinate to the Ministry of Education and Research.)	Varying grant sizes	n/a	HITSA has recently begun a programme for educational innovators, to enhance the use of new technologies in K-12 education by developing meaningful use cases. One section of the programme involves XR. Teachers participating in the programme are given the necessary hardware, which they can use to test and create lesson plans that implement AR and VR.
Finland			
PLEAR (Planning Learning Environment with Augmented Reality)	n/a, funding from the Finnish National Board of Education	Teachers and students	Students and teachers can start to design their new school's learning environment in augmented reality, and then 3D print the best improvements. The project will be carried out in cooperation with 3DBear,[307] a Finnish company that brings AR to classrooms using an app and aims to help educators create an environment in which students can learn the life skills necessary to bring them success in the 21st century.
TEKES, the Finnish Funding Agency for Innovation	Varying grant sizes	Start-ups, research institutions	TEKES is the most important public funding organisation in Finland providing support to the VR/AR/MR industry. The Tekes campaign 'Team Finland Mixed Reality' provides funding for companies that develop solutions and utilise virtual, augmented and mixed

[307] https://www.3dbear.io/blog/2018/12/11/planning-learning-environment-with-augmented-reality-ar

Initiative	Budget	Target groups	Description
			reality in their business operations, and build expertise in Finland. One example of this is MIRACLE[308].
Finnish National Board of Education	Varying grant sizes	Start-ups, research institutions	Example of a project funded: FinEduVR[309], a collaborative project, one of whose main goals is to share information about the possibilities of virtual reality in education, and to test different VR/AR platforms in schools.
Helsinki XR Center	n/a	XR enthusiasts and professionals	The Helsinki XR Center is an incubator for talent in the field of virtual and augmented reality. It is run by the Metropolia University of Applied Sciences, supported by the City of Helsinki, and collaborates with the Finnish Virtual Reality Association (FIVR). Its operations are structured around four pillars. First, the centre provides shared workspaces, equipment and services, as well as co-learning and mentorship. In addition, the centre actively engages in a range of XR projects, applies for funding, and consults on projects. Lastly, the Helsinki XR Center organises various events (e.g. get-togethers, workshops, showcases).
France			
Digital Experiences Fund	EUR 10 million	Arts sector	The Digital Experiences Support Fund (XN Fund) was established by CNC (the National Centre for Cinema and the Moving Image) in October 2018. The fund focuses on artistic objectives, on enhancing the organisation and structuring of the sector, and, above all, on interactive and/or immersive projects. Three types of aid are provided: i) assisting companies in preparing project proposals; ii) offering development aid; and iii) providing support for project production work. The XN Fund is administered by the department of digital creation, which also administers grants for video games (Fonds d'Aide au Jeu Vidéo and Video Game Tax Credit) and digital arts (DICRéAM).
Commune Image	n/a	Businesses	Commune Image is the first virtual reality-focused business incubator in Europe. Its focus is on the production of film and virtual reality media. It hosts and supports creators and enables the realisation of the most ambitious ideas. It is supported by the French Ministry of Culture and the Île-de-France region. Benefits of joining the community include access to mentoring seminars, a VR Lab, Commune Image events, and a network of virtual reality professionals, mentors and partners.
Germany			
Connected Teacher Education (CoTeach)	Funded by the German Federal Ministry of Education and Research (BMBF): 'Funding for teacher training with a focus on digitalisation in teacher training'	Teachers and students	CoTeach[310] develops and evaluates innovative teaching and learning contexts for student teachers and scholars. One work package couples the potential of VR with principles of intercultural learning to create tangible experiences of pedagogically responsible value. CoTeach includes six work packages addressing different school subjects, forms of school and technologies (including VR). One CoTeach work package concentrates on learning

[308] https://tt.utu.fi/ar/research/miracle
[309] http://fineduvr.fi/
[310] www.uni- wuerzburg.de/pse/forschen/co-teach- connected-teacher-education

Initiative	Budget	Target groups	Description
			environments with full spatial immersion (VR) for intercultural encounters in foreign language learning.
FFF-Bayern: Extended Realities (XR)	EUR 30,000 per project	Film and game projects	FFF-Bayern is a funding provider for film and game projects in Bavaria, Germany. The organisation receives funding from Bavaria’s state government, the Bavarian Regulatory Authority for New Media (BLM), as well as public and private broadcasters. FFF-Bayern offers a dedicated funding stream for XR projects. This funding stream provides non-repayable subsidies of up to 80% of total project expenses, or a maximum of EUR 30,000, for initiatives advancing from development to prototyping.
Interactive systems in virtual and real spaces – innovative technologies for the digital society	Varying grant sizes	Start-ups and SMEs	The Federal Ministry of Education and Research (BMBF) aims to entice start-ups as well as small and medium-sized enterprises (SMEs) to collaborate and improve the innovative potential of German SMEs. This should enhance interpersonal connections and the development of skills. These solutions should provide interactive systems that are superior to current methods, and encourage research and development of interactive systems in virtual and real spaces.
Greece			
Innovation competition for AR and VR	n/a	Greek innovators and entrepreneurs	The inaugural Innovation Competition in Virtual and Augmented Reality Technologies was organised by the Hellenic World Foundation to promote Greek innovation and entrepreneurship. The competition recognises and rewards innovative concepts based on new technology. Ideas for new systems and applications are solicited from individuals as well as small business start-ups and established organisations. Participants are also invited to take part in roundtable discussions as well as collaborations with international forums and organisations.
Hungary			
n/a			
Ireland			
Virtual reality tourism in Ireland	EUR 150 million	Historical and cultural sites	Fáilte Ireland, the Irish tourism development agency, aims to raise the importance of immersive historical and cultural resources in the tourism industry. A total of EUR 150 million is made available for future projects aimed at attracting more visitors to the country. The Platforms for Growth plan will prioritise tourism attractions centred on Ireland's cultural heritage.
Nimbus Extended Reality Innovation Lab	n/a	Industry	The Nimbus Extended Reality Innovation Lab is equipped with the most advanced VR, AR and MR technologies to support and expand its innovation capability within the industry. Labs are used for simulation training, operational performance assessment, equipment and facility maintenance, and safety awareness. This effort was financed by Enterprise Ireland's Capital Call Equipment Fund, to help researchers collaborate closely with industry partners to study, design, develop and test the latest breakthroughs in AR/MR technology.
Italy			

Initiative	Budget	Target groups	Description
Giovani2030	Varying grant sizes	Innovative businesses/teams/academics/spin-offs	Virtual Reality Experience (VRE), in collaboration with other partners, announced a call for organisations to use XR to achieve the objectives of the National Recovery and Resilience Plan. The call is aimed at innovative businesses, teams and academic spin-offs. Winners will become members of a major entrepreneurial network and will be provided with financial resources to launch or advance their projects.
Florence, the first immersive education workshop in Italy	n/a	University students	The first-ever immersive didactic laboratory for 360-degree video creation for education has been established in Florence, Italy. It will be used to teach agricultural sciences and technology courses, providing a testing ground for new ideas.
Latvia			
Ministry of Defence grants to six Latvian companies for the development of innovative products	A total of EUR 350,000 in grants. This grant money covers 50% of the costs for each project, which could be increased to 75% if the project progresses sufficiently.	n/a	Projects applicable to the defence sector (e.g. procedural training). One of the six companies awarded grants is Exonicus[311], for the development of an emergency medical care virtual reality training simulator.
Skola 2030 https://www.skola2030.lv/lv/macibu-saturs/macibu-jomas/tehnologijas	n/a	Students and teachers, schools	The aim of the project 'Competence Approach to Curriculum' (School2030) implemented by the State Education Content Centre (VISC) is to develop, test and subsequently introduce general educational content and an approach to teaching from pre-school to secondary school that will result in students acquiring the knowledge necessary for life today. Aimed at digital literacy, the use of ICT in teaching and learning, and updating the curriculum by including subjects such as digital design. XR tools are not explicitly mentioned.
General comments: • The majority of the projects relating to XR in education in Latvia are funded using EU funds. • National policies and initiatives are aimed at wider digital education and training in digital skills, but XR tools are not mentioned in these documents.			
Lithuania			
EdTech Digital Education Transformation	n/a	n/a	Plans under the EdTech Digital Education Transformation project 2021–2024 include the testing of new technological solutions in 150 educational institutions, a programme to develop the digital competencies of teachers and lecturers, and a database of digital teaching/learning resources being developed. 2,021 contracts have been drawn up with innovators and educational institutions to develop educational technologies and innovations and to test the platform. Funding for MR/AR/VR is not mentioned, however.
"The New Generation Lithuania"	EUR2.225 billion	XR-related business, initiatives	Lithuania has established the 'New Generation Lithuania' plan, which focuses on the country's economic recovery and resilience as well as green and digital development. Parts of the strategy concentrate on the development and use of XR technologies. For example, investments are anticipated in modern technologies such as high-performance computing, virtual and augmented reality solutions. The 'Green and Digital VET

311 https://eng.lsm.lv/article/society/defense/latvian-defense-ministry-to-fund-virtual-reality-training-tech.a342167/

<table>
<tr><th>Initiative</th><th>Budget</th><th>Target groups</th><th>Description</th></tr>
<tr><td></td><td></td><td></td><td>Competencies' programme will focus on growing the use of virtual and augmented reality for distance learning, increasing the flexibility and accessibility of vocational training.</td></tr>
<tr><td colspan="4">General comments:
No concrete policies exist with regard to AR/MR/VR in the education sector; these technologies are not mentioned in strategic policy documents.
The focus is on wider digital transformation in education (EdTech), ensuring the hardware and software capabilities of schools, internet connection and digital tools for teaching and learning.
Projects which apply XR tools in educational settings are usually funded under EU frameworks.</td></tr>
<tr><td colspan="4">Luxembourg</td></tr>
<tr><td colspan="4">n/a</td></tr>
<tr><td colspan="4">Malta</td></tr>
<tr><td colspan="4">n/a</td></tr>
<tr><td colspan="4">Netherlands</td></tr>
<tr><td colspan="4">n/a</td></tr>
<tr><td colspan="4">Poland</td></tr>
<tr><td colspan="4">n/a</td></tr>
<tr><td colspan="4">Portugal</td></tr>
<tr><td colspan="4">n/a</td></tr>
<tr><td colspan="4">Romania</td></tr>
<tr><td>National Strategy on the Digital Agenda for Romania 2014-2020 https://www.trusted.ro/wp-content/uploads/2014/09/Digital-Agenda-Strategy-for-Romania-8-september-2014.pdf</td><td>n/a</td><td>Students, teachers</td><td>Main objectives: to provide schools with ICT equipment and systems; implementation of ICT infrastructure complemented by the installation of educational software; providing ICT specific training courses; including Web 2.0 platforms in the learning processes, including Interactive visual materials and additional sources of information provided by the Internet. XR tools are not mentioned explicitly.
Ministries involved: the Ministry of Education, with support from Ministry for the Information Society.</td></tr>
<tr><td>Start-up Nation, Romania's small business start-up programme, was launched by the Ministry of Business, Trade and Entrepreneurship</td><td>The programme offers 100% non-refundable financing for up to 200,000 lei per project for a maximum number of 10,000 beneficiaries each year. This means a 0% personal contribution from the entrepreneur is required in terms of eligible expenditure.</td><td>Entrepreneurs</td><td>Various VR start-ups and initiatives are financed through this program. For example, Universe is a start-up that organizes events in a virtual reality space, based in Bucharest. The business was founded 2 years ago by entrepreneur Mircea Matei and received funding from the program. The start-up organizes various educational VR activities (https://www.univrse.ro/up-grade/).</td></tr>
<tr><td colspan="4">General comments:
No concrete policies with regard to AR/MR/VR were found in national policy documents.
The focus is on wider digital education transformation, ICT and digital skills in schools.</td></tr>
</table>

Initiative	Budget	Target groups	Description
• Projects that apply XR tools in educational settings are usually funded under EU frameworks or through collaborations between private enterprises and universities/organisations, e.g. EON Reality and Babeș-Bolyai University (UBB)[312]; EON Reality and National Union of Romanian Employers (UNPR)[313].			
Slovakia			
Action plan for the digital transformation of Slovakia for 2019–2022	n/a	Students, teachers	Objectives: to improve ICT infrastructure from central to regional level; to improve electronic services and information system of the ministry, digital technologies to enable innovation and improve the quality of education; the development of competencies and skills for digital transformation; transformation of schools into digital schools; improving management using data and ICT. No mention is made of AR/MR/VR.
Slovenia			
n/a			
Spain			
Educa en Digital	EUR 190 million through Red.es (EUR 184 million from FEDER funds) and EUR 70 million from the Autonomous Communities	K-12 schools, vocational training, higher education	The programme will provide half a million devices with connectivity to publicly owned centres that will make them available to students with the aim of promoting digital education. The programme will establish assistance platforms for teachers, students and educational authorities through the application of artificial intelligence (AI), as well as implementing the Digital Plan for Educational Centres by providing equipment, transforming spaces, providing training and applying AI methods to facilitate the teaching-learning process, and creating Open Educational Resources (OER) in digital format.
Sweden			
Vinnova – the Swedish research funding agency grants	Varying grant sizes	Universities, research institutions	Examples of projects funded: VR-based Competence Development in Process Industries 2017; Trollsag – a unique VR game that enhances players' empathy skills 2018-2019.

[312]https://www.virtualrealitypulse.com/romania/?open-article-id=15326505&article-title=eon-reality-and-babe--bolyai-university-announce-partnership-for-educational-xr-center&blog-domain=eonreality.com&blog-title=eonreality-

[313]https://www.virtualrealitypulse.com/romania/?open-article-id=14535316&article-title=eon-reality-and-the-national-union-of-romanian-employers-announce-xr-classroom-partnership&blog-domain=eonreality.com&blog-title=eonreality-

Annex 5. Public procurement analysis

This annex provides an overview of information about public procurements relating to XR[314] extracted from the Tenders Electronic Daily (TED). Information is presented on number of procurements, broken down according to the following criteria:

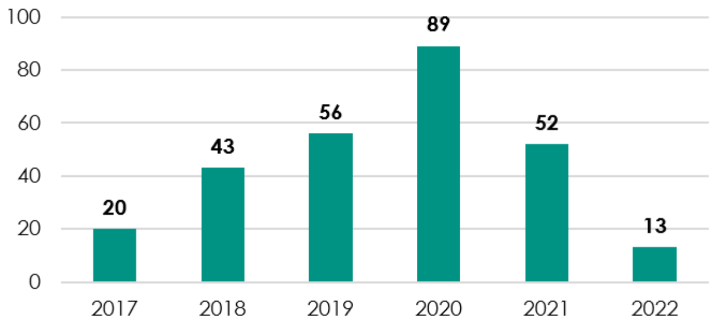
- Year
- Country
- Contracting authority
- Main activity of the contracting authority
- Use cases of procurements

Procurements published between 6 January 2017 to 03 March 2022 were analysed. Information was collected about 273 procurements. In most instances (152 procurements), it was unclear how much of the budget was dedicated specifically to XR-related purchases. In 31 procurements, the exact value dedicated to XR was specified; 90 procurements did not indicate any value at all. The value of procurements ranged from EUR 278.94 to EUR 1 billion, with the median being EUR 387,000 and the mean amount being EUR 12.7 million. As the exact value of XR component of the procurements was not clear in most cases, the value of procurements was not analysed according to different breakdowns.

Breakdown by year

The number of procurements was largest in 2020 (see Figure 39). The number of procurements in 2020 was more than four times higher than in 2017; however, the number of procurements decreased after 2020. There were 13 procurements during the first two months of 2022, indicating a rising trend.[315]

Figure 39. Number of procurements per year, N=273



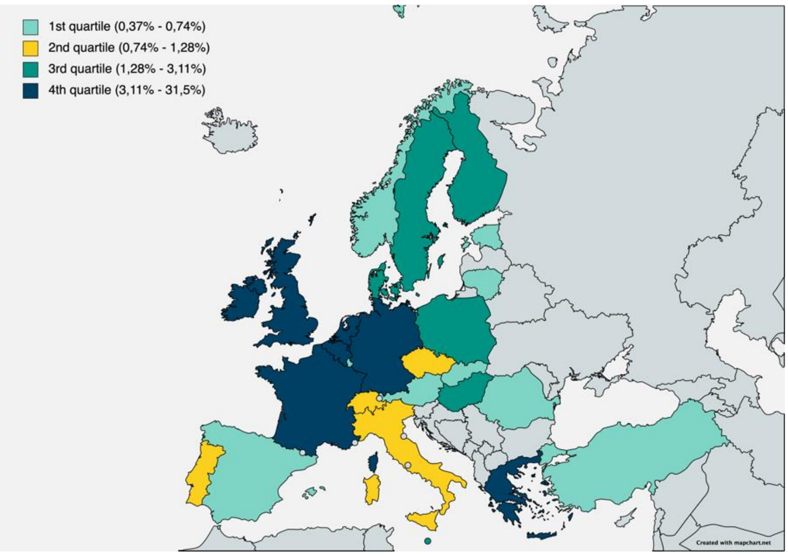
Source: Visionary Analytics, 2022, based on TED data.

Breakdown by country

The countries that accounted for the greatest numbers of purchases were Germany (86 procurements; 31.5%) and the United Kingdom (69 procurements; 25.27%). Greece, Belgium, the Netherlands and Ireland each accounted for around 4-5% of total procurements (see Figure 40 for more details).

[314] The search for procurements was carried out using several search terms, including ‘extended reality’, ‘virtual reality’, ‘augmented reality’, and ‘immersive’.
[315] The date of the most recent procurement recorded in this report was 3 March 2022.

Figure40. Number of procurements by country, N=273

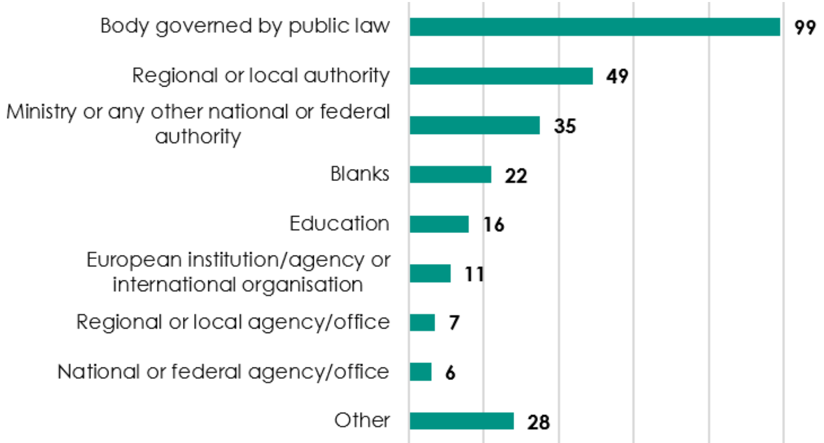


Source: Visionary Analytics, 2022, based on TED data

Breakdown by contracting authority

The contracting authorities with the largest number of procurements were entities regulated by public law (N=99), regional or local authorities (N=49), and ministries or other national or federal authorities, including their regional or local divisions (N=35). More details are provided in Figure 41 below.

Figure 41. Number of procurements by type of contracting authority, N=273

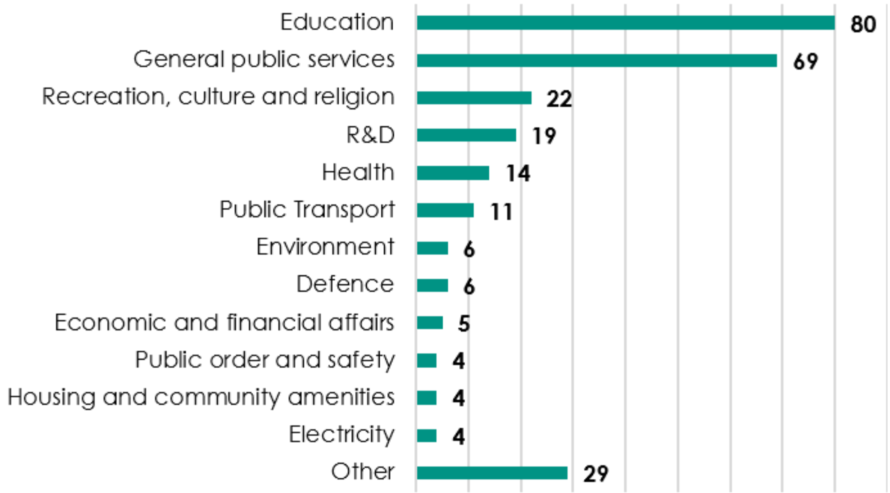


Note: 'Other' includes: budgetary authority; European Economic Interest Grouping (EEIG); grantee; independent public healthcare establishment; joint venture between the Department of Health and Sopra Steria; limited liability company subject to German private law, publicly funded mainly by the Federal Republic of Germany; museum; non-profit research institution under private law; other legal person; private institution; private organisation subject to public orders; research association; sector commissioning body; state organisational unit without legal personality; supported organisation.
Source: Visionary Analytics, 2022, based on TED data

Main activity of contracting authority by occurrence and value

Most procurements were launched by authorities working in the education (N=80) and general public services (N=69) sectors. Recreation, culture and religion accounted for 22 procurements (see Figure 42).

Figure 42. Number of procurements by main activity of contracting authority, N=273

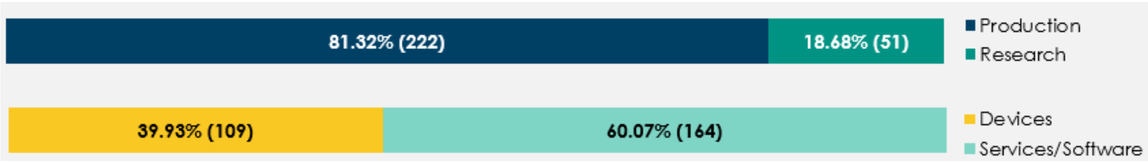


Notes: 'Other' includes: agriculture and fisheries; controller; employment; forestry; Leisure time, culture and religion; general public services and health; higher education, research and innovation; ICT (IT industry); interior, digitalisation and migration; job placement and vocational training; leisure, culture, education, natural science and technology Museum; media; port-related activities; production, transport and distribution of gas and heat; self-administration; social protection; statutory activities; support for public service broadcasting; support to local businesses via public funded projects; television channel; tourism promotion; traffic; water.
Source: Visionary Analytics, 2022, based on TED data

Breakdown of procurements by use case

This section examines the applications and categories of the items procured. If no references were available to research in the procurement description (laboratory, research project, etc.), the procurement was categorised as production (procurements including the purchase of materials, creation of activities within different organisations). Examples of production procurements include the provision of virtual reality equipment to educational institutions, the acquisition of military ammunition with virtual reality capabilities, and the establishment of XR education labs in universities. The procurements were also classified as either services (including software development) or devices. Figure 43 demonstrates that the quantity of production exceeds that of research. Moreover, we can see that the quantity of services procurements exceeds procurements of devices.

Figure 43. Number of procurements by use case, N=273



Source: Visionary Analytics, 2022, based on TED data

The following items occurred most often among all the devices and services acquired (we extracted all of the procured items that were mentioned more than once, and then calculated their occurrence):

- Devices: computer equipment and supplies (N=9); software packages and information systems (N = 8); and audio-visual equipment (N=7).
- Services: IT services such as consulting, software development, internet and support (N=28); advertising and marketing services (N=9); education and training services (N=7); office and computing machinery, equipment and supplies, excluding furniture and software packages (N=7); research and experimental development services (N=1).

Figure 44 below provides some more detailed examples of procurements.

Figure 44. Specific examples of procurement use cases

Source: Visionary Analytics, 2022, based on TED data.

Procurements on national portals

In addition to reviewing information regarding XR-related public procurements collected from Tenders Electronic Daily (TED), the national public procurement websites of Finland[316], Germany[317], Spain[318] and France[319] were analysed, as these countries are considered advanced in terms XR, and it was expected that they would be active in procurements relating to XR. The same search criteria were used as before[320]. A search was also made for public procurements in Denmark, but all the procurements identified were already accounted for in the TED database.

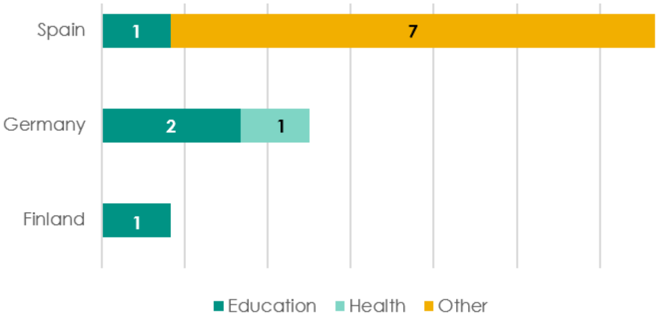
A total of 12 XR-related procurements found: three in Germany, one in Finland[321], and eight in Spain. None of the procurements discovered on the French national procurement portal related to XR. The small number of XR-related procurements discovered via national public

316 https://www.hankintailmoitukset.fi/fi/
317 https://www.dtvp.de/
318 https://contrataciondelestado.es/wps/portal/plataforma
319 https://www.marches-publics.gouv.fr/?page=Entreprise.AccueilEntreprise
320 The search for procurements was carried out using several search terms, including ‘extended reality’, ‘virtual reality’, ‘augmented reality’, and ‘immersive’, and the procurements analysed were published from 2017 to 3 March 2022.
321 In addition to the procurements listed above, three additional procurements were found in Finland that were posted on the national procurement website and TED; however, these were not included into this calculation, as they were already covered above by analysing TED data.

procurement websites indicates that most XR-related procurements are announced through TED.

Four out of the total of 12 procurements identified related to education, one to the health sector, and the remaining seven to other sectors such as tourism, advertising and the navy (for more details, see Figure 45).

Figure 45. XR related procurements identified on national portals, N=12



Source: Visionary Analytics, 2022, based on data from national procurement portals.

In terms of the items procured, seven of the procurements focused on services, three on purchasing devices, and the remaining two did not specify what was being procured. None of the procurements focused on research. All use cases were production-related.

Annex 6. Statistics about the Apple ecosystem

Table 14. Statistics about Apple ecosystem

Apple iPhone revenue 2021	USD 191,973 million
Apple services revenue	USD 68,425 million
Worldwide gross Apple app store revenue (in-app purchases, subscriptions, premium apps)	USD 81,500 million
Estimated advertising revenue on iPhone	USD 67,392 million
Estimated ecosystem revenue (non-Apple)	USD 148,892 million
Estimated ecosystem revenue incl. Apple	USD 409,290 million

Source: Visionary Analytics, 2022, based on Apple annual report for 2021, Statista Apple App Store revenue, Statista mobile ad spend worldwide.

Annex 7. List of European XR device manufacturers

Table 15. List of European XR device manufacturers

Name	Country of company headquarters	Short description
ActiveLook	France	ActiveLook is an innovative smart glasses technology platform that offers the eyewear industry and application developers the capability for incredibly small head-up displays. The ActiveLook module is designed to be integrated into regular glasses ("ActiveLook inside"), and can be controlled by any Bluetooth Low Energy-equipped device through the ActiveLook free and open API, including smartphones, Garmin watches and bicycle computers. ActiveLook technology is offered on a variety of glasses, including the Julbo EVAD 1, Engo-1 and Cosmo VIsion.
.lumen (Dotlumen)	Romania	.lumen is a Romanian start-up that creates glasses to assist the blind. The .lumen glasses imitate the major characteristics of a guide dog in a scalable product and are capable of understanding their surroundings, calculating interaction pathways to desired items, and providing information to the blind through haptic and aural impulses. The .lumen headset includes a collection of five cameras with varying characteristics that comprehend and map the world. They identify the user's location and perceive contextual information. The feedback system then transmits information to its user through audio and haptic feedback.
Eyesynth	Spain	Eyesynth is an audiovisual system for the blind developed by a Spanish business. It is made up of a pair of glasses that are linked to a microcomputer. The system captures the surroundings in three dimensions. The acquired data is then transformed into understandable audio for the blind. The glasses record the whole scene and relay sounds in stereo. The consumer receives a complete stereo audio panorama.
Iristick	Belgium	Iristick manufactures and supports smart safety glasses for industrial applications. Along with its software partners, the company delivers high-quality solutions for remote assistance, step-by-step workflow guidance, pick-by-vision and video conferencing. Iristick is designed for the deskless workforce to reduce errors and increase productivity. It enables frontline workers and field technicians to connect in real time with remote experts to get work done efficiently. In addition, Iristick glasses are fully compliant with eyewear safety requirements and are made to be reliable even in harsh industrial environments. Iristick's solution is currently used in the manufacturing, healthcare, field services, oil and gas, and agro-biotech sectors.
Lightspace	Latvia (also in the US and UK)	Lightspace is a deep-tech company whose R&D labs, industrialisation facilities and fabrication facilities create crucial technologies for the next generation of augmented reality. A pioneer in volumetric, multi-focal and light field technology, Lightspace created Optical Reality, the world's first multi-focal technology that combines multiple displays for eye accommodation that the company claims is as close as possible to natural sight. Lightspace Optical Reality offers realistic, high-resolution 3D overlays. Its glasses are used in the manufacturing and healthcare

Name	Country of company headquarters	Short description
		industries, particularly for surgical assistance, training and collaboration.
Lynx	France	Lynx, based in France, develops mixed reality solutions for professionals and consumers. The company claims its Lynx-R1 headset is the most cost-effective and adaptable gadget for experiencing mixed reality. Due to the fact that the headset is not integrated with social network accounts, the firm assures data privacy by design. It is also an open platform device, with raw sensor data being accessible through the SDK. The corporation collaborates with surgeons, industrial firms and defence actors.
Magos Gloves	Greece	Magos from Greece incorporates novel technology into gloves to provide state-of-the-art human-computer interaction in XR. More details about the company are provided in Table 10 of the main report.
SenseGlove	The Netherlands	SenseGlove is a Dutch business that enables touch interaction in VR. More details about the company are provided in Table 10 of the main report.
Stylus XR	Austria	Holo-Light is company based in Germany and Austria that works in the augmented and virtual reality enterprise market. Its product, Stylus XR, is an augmented reality input device with AI tracking. It combines a head-mounted display with a device that offers the accuracy of a surgical tool and the ease of use of a pen. STYLUS XR reduces accuracy flaws and opens up new areas of use, such as surgical intervention training situations. The gadget is compatible with smart glasses such as the HoloLens 2 and provides several advantages: precision, enhanced by AI-based tracking technology; intuitive interaction (accuracy of 1-3 mm); the ability to sketch and construct fully interactive 3D holograms; and a cross-platform approach.
Varjo Aero	Finland	Varjo is a Finnish company that makes cutting-edge virtual reality, augmented reality and mixed reality headgear for professionals. Varjo develops cutting-edge VR/XR hardware and software for industrial applications, paving the way for a true-to-life metaverse. Varjo claims its Aero is the lightest and brightest professional-grade headset ever created, with a future-proofed optical design and twin mini-LED screens. It boasts crystal-clear, variable resolution aspheric lenses that provide a significant improvement in visual quality. It also boasts automated IPD adjustment and built-in, ultra-fast eye-tracking. Varjo Aero provides high levels of realism for virtual simulations while eliminating screen-door effects and so-called 'god rays'.
VRgineers	Czech Republic	VRgineers provides professional and military customers with next-generation virtual and mixed reality pilot training solutions. VRgineers has developed the XTAL, a virtual and mixed reality headset with the highest definition and biggest field of vision currently on the market. The technology is useful for pilot training in flight schools, as well as tactical mission training.

Source: Visionary Analytics, 2022, based on information provided by company representatives during interviews, https://www.activelook.net/, https://www.dotlumen.com/, https://eyesynth.com/?lang=en, https://iristick.com/, https://lightspace3d.com/about/, https://www.lynx-r.com/, https://www.linkedin.com/company/lynx-r/, https://www.themagos.com/, https://www.senseglove.com/, https://holo-light.com/products/stylus-xr/, https://varjo.com/, https://vrgineers.com/xtal-3-mixed-reality/.

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