WORKER EXPOSURE TO VIRTUAL AND AUGMENTED REALITY AND METAVERSE TECHNOLOGIES: HOW MUCH DO WE KNOW?

1 Introduction

In the dynamic landscape of workplace technology, the EU is witnessing a shift with the advent and progressive integration of new visualisation technologies, virtual reality (VR), augmented reality (AR), extended reality (XR) and the metaverse. These technologies are increasingly used in a multitude of occupational sectors. Originally confined to specialised applications such as flight simulation, these technologies now play a significant role in a variety of sectors like manufacturing, construction, education and healthcare. In these diverse fields, AR, VR, XR and metaverse technologies are set to modify work environments and work organisation. These technologies are currently used for different purposes across workplaces, including training, data visualisation and remote work. Recent rapid advancements in mobile internet, sophisticated artificial intelligence (AI), increased computational power and high-resolution displays have been instrumental in the rapid development of these technologies (Angelov et al., 2020; Hamad & Jia, 2022; Hoyer et al., 2020; Rauschnabel et al., 2022).

The practical use of AR and VR in training and maintenance, for instance, highlights their benefits. AR's role in complex machinery training offers realistic, virtual experiences that improve learning with real-time feedback. In maintenance, AR provides precise guidance, improving efficiency and safety.

Research Gap on the use of AR, VR and metaverse

However, there is a significant research gap regarding the risks of adopting AR and VR in the workplace, like cybersickness and ergonomic concerns. As AR, VR, XR and metaverse technologies become increasingly integrated into day-to-day workplace practices, the associated challenges and opportunities for OSH are introduced. This evolving landscape requires a proactive approach from all relevant stakeholders: policymakers, researchers, industry leaders, technology designers and OSH professionals. They must not only keep pace with technological advancements but also anticipate and mitigate the related OSH risks. It is vital to comprehensively understand the occupational safety and health (OSH) implications associated with the use of these technologies.

The European Agency for Safety and Health at Work (EU-OSHA) has already spotlighted OSH risks associated with VR and AR (EU-OSHA, 2018, 2023a, 2023b). Such risks have been found to be potentially associated with a variety of negative outcomes for users (in this case, workers using the technology) (Lavoie et al., 2020; Somrak et al., 2019). In practical terms, this means workers using VR and AR technologies may experience adverse side-effects (e.g. cybersickness, eye strain, feelings of confusion, etc.), which could impact their health and wellbeing as well as hinder their work performance (Oh & Son, 2022; Souchet et al., 2023a; Souchet et al., 2023b). Researchers have argued that it is important to acknowledge and address the side effects of modern visual technologies in the workplace (Souchet et al., 2023a). This is essential for the development of standards and guidelines. Ensuring the OSH of workers using AR, VR, XR and metaverse technologies is paramount; all stakeholders should be fully aware of the potential benefits and risks associated with the use of these technologies.

Scope of Article

This article presents a comprehensive literature review and integrates it with semi-structured interviews with seven selected experts who have worked or have knowledge in the field of VR, AR, XR and the metaverse, including OSH specialists in the sector, industry operators and supervisors with first-hand experience, national and international safety experts, interest group representatives and industrial stakeholders. More information about the method applied in this study and the interviewees is available in the annex.

This first section of this article introduces the foundation for the ensuing discussion. The second section explores terminologies and concepts, providing thorough explanations to ensure clarity and comprehension. The third section examines the present applications and opportunities of AR, VR, XR and metaverse technologies within OSH. The fourth section addresses the OSH risks and impacts on worker safety and health that are associated with these technologies, drawing on findings from literature reviews and interviews conducted as part of this study. The fifth and final section discusses the principal findings, presenting recommendations for the adoption of metaverse technologies in workplace environments and identifying gaps and needs for future research and policies.

2 Concepts and terminology

A review of the concepts and terminologies related to VR, AR, XR and the metaverse reveals the heterogeneous and inconsistent use of several terms to describe the same types of hardware and applications (Laato et al., 2024). This is confusing for scholars and experts navigating the published literature, as it is not immediately evident what type of technology is being referred to in a given context.

There have been recent efforts to standardise the terminology. In this article, **VR is defined as an immersive experience in a visually isolated three-dimensional space**, without meaningful interaction of the user with the physical world outside the simulation (Rauschnabel et al., 2022).

On the other hand, **AR is defined as an experience that integrates virtual elements into the user's physical space**, with varying degrees of integration of the virtual elements into the physical space (Rauschnabel et al., 2022).

This article borrows terms and definitions that have been proposed by the recent development of the xReality[1] (XR) framework (Rauschnabel et al., 2022). This framework conceives of XR as a comprehensive concept that includes both VR and AR, and also including all other terminologies in the literature used to refer generally to VR and AR technologies, like immersive visual technologies (IVTs) (Grassini & Laumann, 2021), digital reality (DR) (Haleem et al., 2022), virtual environments (Ellis, 1994), cross reality (Ziker et al., 2021), virtual worlds (Hew & Cheung, 2010) and media-generated reality (Laato et al., 2024).[2] In the present article, the term XR generally includes technologies that use head-mounted displays (HMDs); under the XR framework, **XR is used as an umbrella term to indicate both VR and AR technologies**.[3]

Figure 1: Example of VR head-mounted display

[1] Some authors use the same acronym for the term 'extended' or 'expanded' reality, referring to a similar concept. See Dwivedi et al. (2020) and Chuah (2018).

[2] In the scientific literature, all these terminologies are also used to refer to technologies that do not use head-mounted displays (HMDs): examples are the Cave Automatic Virtual Environment (CAVE) (Manjrekar et al., 2014) and large displays (Tan et al., 2003).

[3] It is worth mentioning that scholars often also use the term mixed reality (MR). This term describes the integration of virtual and physical elements (Farshid et al., 2018, Flavián et al. 2019); it is also an umbrella term including all the previously discussed technologies (Skarbez et al., 2021). To avoid ambiguity, the term MR will not be used in the current article.

Figure 2: Example of AR head-mounted display

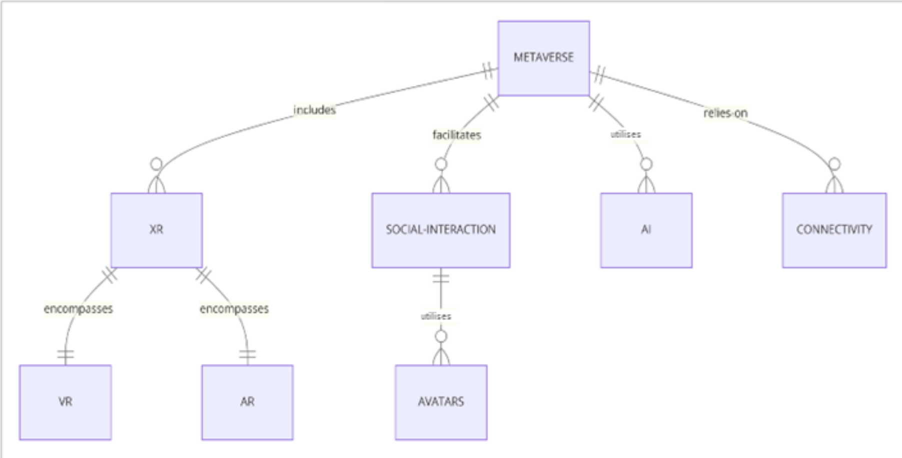
Originating from Neal Stephenson's 1992 novel 'Snow Crash' (Stephenson, 1992), the term metaverse has evolved to describe a future iteration of the internet and virtual experiences. Today the metaverse is seen, in some theoretical debate, as the potential evolution of the current internet and XR technologies (R. Cheng et al., 2022).

It is hypothesised that it may surpass XR frameworks by the strong incorporation of other technologies, blending elements of connectivity, AI and other innovations to create immersive, interactive environments such as blockchain (a secure, decentralised digital ledger for recording transactions). It thus forges an intricate virtual universe where people can perform all activities that today are generally performed in person (Bale et al., 2022). This is particularly pertinent when the connectivity, the future integration with AI, the possibility of interacting with digital twins (a virtual replica of a physical object, process or system, used for simulation, analysis and control), or the use of avatars is a focal point of the XR use (De Felice et al., 2023).

It stands out for its service-oriented architecture that emphasises social interaction and user-generated content, diverging from what has often claimed to be the technology-centric essence of the XR technologies (Dwivedi et al., 2023; Hussain et al., 2023; Zhu et al., 2023). However, defining the metaverse comprehensively is challenging. As a rapidly evolving digital landscape, it eludes static definitions. Some researchers (Dolata & Schwabe, 2023) have described the metaverse as a 'moving target' and a buzzword, emphasising its elusive nature and high interpretative flexibility.

For clarity, the present paper **will refer to the metaverse as the integration of XR technologies with connectivity and AI, and with a focus on social interaction between users**; it will use **XR as a general term encompassing AR and VR**. An explanatory diagram is presented in Figure 3. Since the metaverse is generally described as a space constituted of XR technologies, all content relating to the potential risks and impacts of XR on worker safety and health applies is also applicable to the larger concept of the metaverse.

Figure 3: The relationship between the various technologies discussed in this paper



Source: Author's elaboration.

The use of HMDs (head-mounted displays)

Users of XR technologies (and, by extension, of the metaverse) predominantly wear HMDs. This equipment resembles large eyeglasses which users wear to receive images near their eyes. During the past decade, HMDs have undergone a process of miniaturisation and increase in power. While first-generation HMDs were bulky and needed a physical connection to a computer with a cable to deliver images on the goggles, newer technologies are stand-alone (i.e. they do not necessarily need a physical cable connection to a computer), and they are generally less bulky, lighter (or with a better weight balance), and more ergonomic compared to their predecessors (Fang et al., 2023; Greenwald, 2023; Lang, 2017; Truly, 2023). In some cases, HMDs have become heavier with newer technological iterations, as in the case of some of the Meta/Oculus products (see Bérastégui (2024). However, it is worth noting that these newer HMDs feature also improved ergonomics and better weight balance (as well as higher technical specifications) that may compensate for the increase in weight.

Ergonomic improvements in recent HMDs include adjustable straps and contoured padding, which ensure a more comfortable fit for a wide range of head sizes and shapes. Additionally, advancements in weight distribution help reduce strain on the neck and shoulders, enhancing user comfort during extended use. Furthermore, the screen resolution and refresh rate have increased, making the experience more immersive and pleasant overall. HMDs commonly include a computational unit able to process information, and a battery or cables for power.

Modern VR employs HMDs almost universally. Similarly, widely used AR devices also fall under the HMD category. However, AR can be experienced through alternative methods: smartphone cameras can interact with real environments to augment them digitally, and transparent screens can overlay digital information onto the physical surroundings, offering another avenue for engagement with AR.

3 OSH opportunities in XR and metaverse technologies: an overview

VR technology – training and health and safety

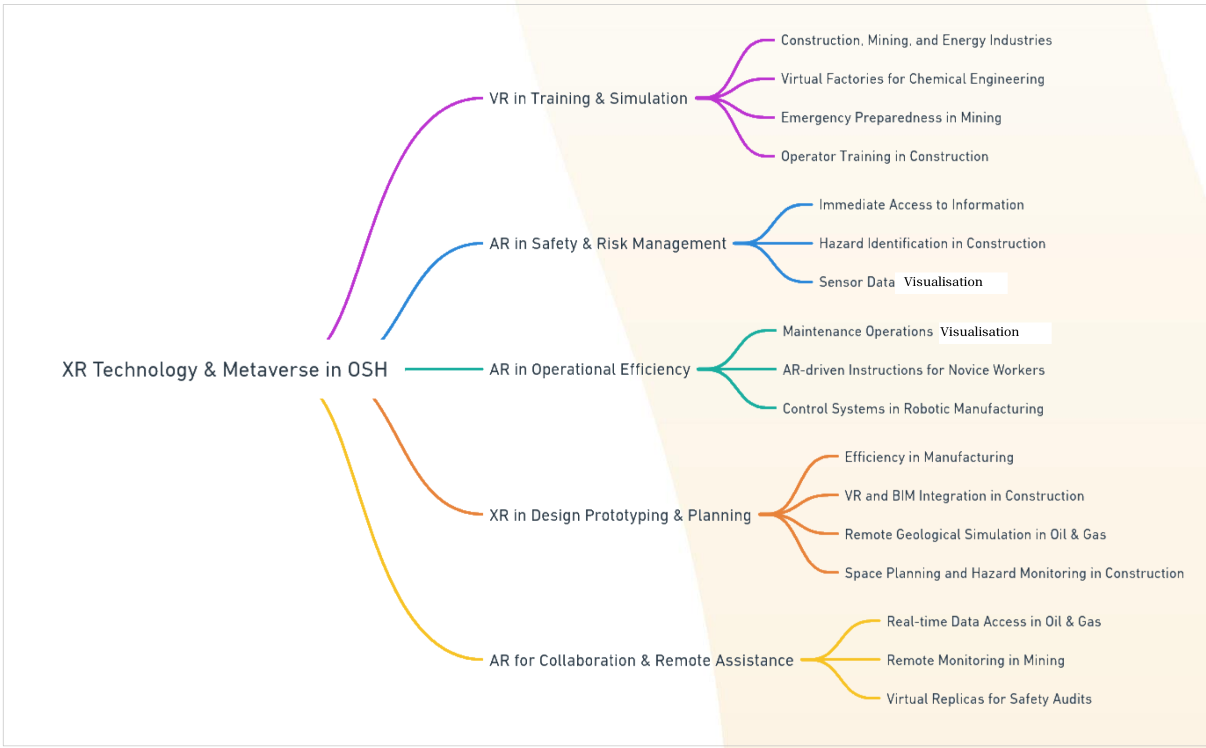
Over the years, VR technology has emerged as an important tool in training programmes across numerous industries, particularly in fields such as construction, mining and energy. These sectors, often characterised by the need to conduct training in potentially dangerous environments, adopted VR technology early on to improve both the safety and efficiency of their training methodologies (Grassini & Laumann, 2020b). Current literature on the topic reveals that VR technology is crucial for facilitating hands-on training and simulations across a broad range of industries.

For example, some studies have highlighted VR's critical role in creating virtual factories in the chemical and biochemical engineering domains, enabling the safe simulation of complex industrial processes (see for example, Luo et al. (2015)). Other studies have demonstrated VR's effectiveness in the mining industry, particularly in improving emergency preparedness and operational versatility among underground coal miners (Grabowski & Jankowski, 2015). Moreover, the construction industry benefits from VR in improving its operator training (Babalola et al., 2023). These lines of evidence underscore VR's integral role in advancing training models, offering a safe and efficient alternative to traditional training methods.

AR and metaverse – beyond training and the use for health and safety

The application of AR and the metaverse in general has now extended beyond training; it includes other uses like the design of workplaces and remote operations (e.g. remote operator assistance). These technologies offer also potential for OSH practices: for example, facilitating access of workers to real-time, immersive, virtual information necessary to work safely; and improving the way they assess and address OSH risks with the support of an AI-generated information overlay. They can also provide a platform where workers interact within a fully immersive, 3D virtual environment, replicating real-world scenarios (digital twins),[4] but without the OSH risks associated with the real-world working environments. Thanks to digital twins, workers can practice and hone their skills, make decisions and learn from mistakes — without the fear of real-world consequences such as accidents and OSH risks.

Figure 4: Main OSH-related uses and current opportunities offered by XR and metaverse technologies



Source: Author's elaboration.

AR technology has proven to be crucial in enhancing safety and risk management, thanks to its provision of immediate access to vital information during emergencies, which promotes rapid decision-making and accident prevention. In the chemical industry, the integration of AR with digital twin platforms is key to creating simulated environments for training and testing safety procedures (Büchner et al., 2022). It has highlighted how the application of XR technologies in the construction industry can help in hazard identification in building sites, risk assessment and safety management, affirming XR's role in improving safety performance and worker safety awareness (Babalola et al., 2023). XR technologies have also been used to elaborate and visualise sensor information, thereby increasing safety, and this has proved important in industrial sectors like the construction industry (Salinas et al., 2022).

[4] Virtual replicas of physical entities, systems or processes, designed to simulate, monitor and analyse their real-world counterparts in real time, enabling optimisation, prediction and improved decision-making.

AR technology - use for increase of operational efficiency and aid maintenance operations

AR technology has been used to increase operational efficiency and aid maintenance operations in various industries (Palmarini et al., 2018). AR technology has been identified as an asset particularly in maintaining industrial equipment, significantly reducing the time needed to search for and process diverse information during maintenance activities, and thereby impacting operators' safety (Koteleva et al., 2020, 2021). Van Lopik et al. (2020) acknowledge AR's beneficial impact not only for industries, but also for small businesses, by improving maintenance operations and providing economic advantages while ensuring safety. Innovations like the Mobile Augmented Reality Maintenance Assistant (MARMA)[5] are pivotal in enhancing OSH (Konstantinidis et al., 2020), for example by guiding novice workers through complex maintenance operations with AR-driven instructions and camera-based asset identification, thereby significantly reducing the risk of accidents and improving safety protocols. In managing robotic manufacturing, AR is essential for creating efficient and user-friendly control systems (Caiza et al., 2020), reducing potential risks for the users. Moreover, AR's use in presenting computer-aided manufacturing (CAM)[6] instructions[7] is crucial for ensuring worker safety and operational efficiency, thanks to its provision of clear operational guidelines (Mourtzis et al., 2018).

XR technology - to aid design prototyping

The use of XR technologies has been proposed to aid in design prototyping in the manufacturing industry (Bottani & Vignali, 2019), increasing efficiency and reducing risks for operators. The combination of VR with building information modelling (BIM)[8] in the construction sector highlights its utility in contexts like design and planning (Johansson & Roupé, 2024). Chen et al. (2022) detail how VR, when integrated with BIM, leads to improved decision-making, improved work quality and increased productivity, while also facilitating early hazard identification during the design phase.

Box 1: Example of XR technologies used for OSH management in the construction sector

A recent study (Babalola et al., 2023) on the construction industry found that XR technologies have successfully been used in this sector for OSH risk prevention and management, including training, hazard identification and visualisation, risk assessment and design for safety. XR technologies have been found to be important for several key factors influencing safety on construction sites (Rivera et al., 2024), including general factors (e.g. rules and regulations, safety, organisation, culture and climate), material and equipment factors, site factors, and human factors (e.g. motivation, competency, work pressure, worker behaviour and communication).

VR-based safety training in the construction industry suggests that VR can effectively improve safety performance, potentially reducing accidents and improving worker safety awareness (Chellappa et al., 2022). When combined with BIM, a digital process for generating and handling information about a building development across its life cycle, VR improves decision-making, leading to superior work quality, increased productivity and substantial cost reductions, and preventing OSH risks by supporting informed decisions (Chen et al., 2022). VR's potential in visualising building design and transitioning from traditional computer-aided design to immersive models significantly aids in hazard identification and planning for safer construction processes (Whyte et al., 2000). From an OSH perspective, the metaverse may offer safer and more efficient planning tools, reducing the risk of mistakes in planning and miscommunications, and improving safety protocols in construction environments.

The use of VR and AR in different sectors

In the oil and gas industry, VR's capability to simulate geological areas for remote exploration minimises the need for on-site drilling, thereby reducing worker exposure to hazardous environments (Jampeisov,

[5] A tool that uses augmented reality to provide real-time, visual guidance and information to assist in maintenance tasks, improving efficiency and accuracy.

[6] It refers to the use of software and computer-controlled machinery to automate manufacturing processes, including planning, managing and executing production tasks.

[7] For example, in CNC bending (a manufacturing process where computer-controlled machines are used to bend sheets of metal or other materials into specific shapes and angles with high precision and efficiency).

[8] A digital representation process that integrates physical and functional characteristics of building structures, enabling stakeholders to efficiently manage information throughout a building's life cycle.

2019). Furthermore, XR technologies have been used in the construction sector for aiding safe and effective construction managements, including space planning, monitoring of the site environment, and prediction of possible hazards to minimise risks before and during construction processes (Zhao et al., 2023).

AR technology can be used to improve collaboration and facilitate remote assistance of operators (Lukosch et al., 2015). In some industrial sectors, as in the oil and gas sector, AR wearables have been used to provide real-time data access to operation in the work sites, thus improving safety in challenging conditions (H. Cheng et al., 2022). In mining, AR enables remote monitoring through command-control systems, merging with real-time environmental sensor data to provide safety solutions, particularly during emergencies (Buddhan et al., 2019). XR has been used for remote monitoring and incident response in real time, providing OSH professionals and managers with tools to manage OSH proactively. For instance, virtual replicas of physical workspaces in the metaverse can allow for remote inspections and safety audits, reducing the need for a physical presence in hazardous environments (Al-Gnbri, 2022; Wang et al., 2022).

Box 2: How XR technology benefits OSH in the mining and extraction industry: example

VR's role in improving worker safety awareness is crucial in mining, a sector prone to OSH hazards, although the full potential of the technology in worker safety management is not yet fully realised (Duarte et al., 2019). VR is used in the comprehensive training of underground coal miners, enhancing their readiness for various mining scenarios and emergencies (Grabowski & Jankowski, 2015). Furthermore, VR is used to visualise complex information to address mining location safety, environmental effects and machinery upkeep (Duarte et al., 2021).

The introduction of VR-based training systems has outperformed traditional methods, offering a more effective and immersive learning experience. Mining operation trainees find VR-based training more immersive, intuitive, interactive and easy to use compared to a traditional screen-based system (Zhang, 2017). VR also plays a key role in simulating dynamic, three-dimensional mining environments for purposes like virtual design (Strzałkowski et al., 2024), in a process that can improve the safety of mining work environments. The use of VR in modelling ergonomic challenges related to mining equipment could aid in the design of safer machinery (Foster & Burton, 2004).

AR can also improve worker safety in mining, thanks to remote-monitoring command-control systems that combine AR with real-time environmental sensor data, offering worker safety solutions, particularly in emergencies (Buddhan et al., 2019). AR has been integrated with technologies like radio-frequency identification (RFID) for effective management of mining production processes, including the identification and localisation of moving objects (Vladimir et al., 2014), which is significant in preventing collisions with workers. Wearable AR interfaces aid in inspecting belt conveyors in mining by assisting drone pilots in enhancing worker safety and efficiency (Keller et al., 2018). AR, along with other sensing technologies, is helping mining operations by using 3D visualisation and energy autonomous sensor nodes for localisation, mapping, maintenance and safety (Kiziroglou et al., 2017).

AR's role in Ergonomics 4.0 within Industry 4.0 includes integrating human factors and ergonomics in mining operations for increased worker safety and operational efficiency (Paul & Briceno, 2021).

Finally, the integration of AR and VR in mining education is exemplified by projects like the Mixed Reality Handbooks for Mining Education (MiReBooks), which is developing AR- and VR-based interactive mining manuals for immersive educational tools, by simulating otherwise inaccessible or hazardous environments (Daling et al., 2020).

4 XR and metaverse in the workplace: OSH risks and worker safety and health outcomes

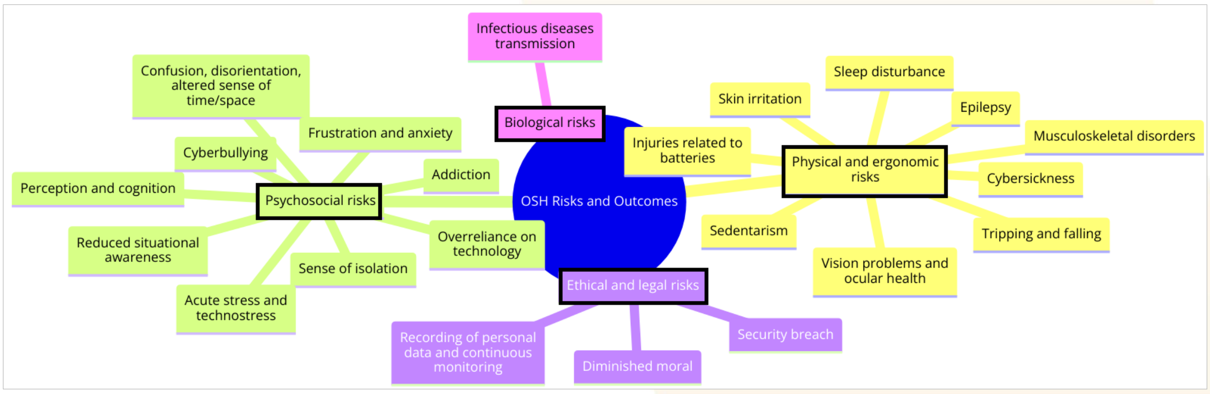
In the context of XR and metaverse technologies, VR stands out as the most extensively researched. VR has been used in professional settings more extensively than AR and the metaverse, which is why the OSH implications of its use have been more comprehensively considered. Most of the literature on

OSH implications of the use of VR at work focuses on ergonomic issues associated with the hardware that facilitates the VR experiences. As previously mentioned (see Chapter 2), this consists of an HMD worn by workers close to their eyes and commonly bound to the head and/or neck using straps. Recent research has highlighted various OSH risks associated with the use of VR in the workplace (Souchet et al., 2023a). Despite the fact that the short-term adverse effects of VR have been documented in the scientific literature, there remains a stark lack of in-depth scientific studies on the medium- and long-term side effects of prolonged VR technology usage.

Other OSH risks, especially those related to the psychosocial aspects associated with VR technology use and related to workers' mental health and wellbeing, generally less represented in the scientific literature, are presented in this section. These risks were identified in the relevant literature and their description was complemented by information gathered through the expert interviews.

The OSH risk categories discussed below are interconnected and should not be analysed in isolation (e.g. physical and ergonomic factors as well as privacy concerns can affect also psychosocial risks). Figure 5 maps the OSH risks and health outcomes related to the use of XR and metaverse technologies in the workplace.

Figure 5: OSH risks and health outcomes related to the use of XR and metaverse technologies in the workplace



Source: Author's elaboration.

The risks in Figure 5 span four areas:

- **Physical and ergonomic risks** relate to the HMD's ergonomics (weight, form factor, wearability), blue light emission close to the eyes, the reduced need for physical movement during XR operations and potentially malfunctioning technology. Furthermore, cybersickness can be experienced due a combination of physical and ergonomic factors of HMDs.
- **Psychosocial risks** relate to the potential of these technologies to cause stress due to the need to learn new skills and interact with new equipment, reduced physical interactions and interaction with peers, and isolation and risks related to the interaction with and between avatars. These also include sensory or cognitive overload, difficulty distinguishing between virtual and real environments leading to disorientation, and impacts on cognitive functions (attention, memory, spatial awareness).
- **Ethical-legal risks** relate to the new and unregulated nature of the technology, the ethical implication of digital interactions, and the technical features of the technology that make them prone to privacy breaches.
- **Biological risks** relate to potential pathogen contamination of the equipment worn by the user.

4.1 Physical and ergonomic-related OSH risks and health outcomes

XR and metaverse technologies introduce several OSH physical risks stemming from the design and usage of the hardware needed to enable the XR experience. These risks are analysed in this chapter. Key concerns include the ergonomic challenges posed by the form, fit and weight of HMDs, which can lead to discomfort, neck strain and musculoskeletal issues. Additionally, the proximity of screens to users' eyes raises the risk of visual strain due to the requirement for the eyes to constantly adjust to varying perceived distances within the virtual environment.

Cybersickness

Cybersickness[9] has a notable negative impact on the health of workers using VR technology in both personal and professional settings, and it has been extensively studied since the early 1990s (Kennedy et al., 1993). This phenomenon is among the most studied in the context of side effects of HMD use and has often been a significant factor hindering widespread adoption of these technologies (Garrido et al., 2021). This phenomenon, said to resemble motion sickness,[10] is believed to arise due to a sensory conflict experienced by users, where the information received by the vestibular system is at odds with the visual perception, with symptoms akin to the motion sickness and simulator sickness identified in earlier research: eye strain, headaches, nausea and disorientation (Reason & Brand 1975). Other theoretical approaches posit that the users' postural instability causes cybersickness (Stoffregen & Smart, 1998).

Despite initial optimism for overcoming this issue with the advent of HMDs (Biocca, 1992), discomfort during VR sessions remains a significant concern. Some findings show that about one-third of general users of VR of experience discomfort, with 5% reporting severe symptoms, and in some contexts, between 80% and 95% of users are affected (Kim et al., 2005; Stanney et al., 2020; Stanney et al., 2021). According to Bérastégui (2024), symptoms such as a feeling of unsteadiness or drunkenness worsening with head movement (similar to symptoms of postural ataxia) may last for several days after exposure. Although modern HMDs have improved, reducing some risk factors, cybersickness has not been eradicated (Caserman et al., 2021; Gallagher & Ferrè, 2018).

The side-effect of cybersickness was highlighted in all the interviews carried out as part of this study. One of the interviewees (Interview 1) reported that cybersickness is one of the factors for which companies and organisations seek advice and which potentially chiefly hinders the adoption of VR technologies. There is evidence that the negative impacts of XR technologies build up with use over the week, particularly in the case of nausea; this raises concerns about their sustained use in work settings (Bérastégui, 2024). In VR settings that simulate office environments and where user movement is minimal, cybersickness is less prevalent than in other settings (Filho et al., 2018; Filho et al., 2019a). However, our understanding of cybersickness is incomplete, and further scrutiny is required (Tian et al., 2022). The research primarily examines conflicts between proprioceptive (including i.e. the perception of self-movement and the body position in space), visual, and vestibular inputs, with some studies investigating visual issues such as vergence-accommodation conflict experienced during 3D image processing in VR (Chang et al., 2020; Descheneaux et al., 2020; Fuchs, 2017; Koohestani et al., 2019).

In fact, current theories on cybersickness remain a topic of scientific debate. Studies have revealed gender differences in cybersickness, with women experiencing symptoms more frequently, a disparity that might be related to the ergonomic design of HMDs or inherent motion sickness susceptibility, though this finding is contentious (Grassini & Laumann 2020a). The influence of the type of VR simulation, the exposure time (Thorp et al., 2022) and the hardware features like screen latency are acknowledged but not fully agreed upon, due to experimental variability (Grassini et al., 2021; Stauffert et al., 2020). Using HMDs with larger fields of view and greater visual realism of the virtual environment may increase the likelihood of suffering cybersickness (Bérastégui, 2024). VR exposure duration is a known factor in cybersickness severity (Dużmańska et al., 2018), and individual traits as well as health conditions also contribute to varied experiences of symptoms (Grassini et al., 2020; Kim et al., 2021; Widyanti & Hafizhah, 2021).

While AR may induce cybersickness like VR (Kaufeld et al., 2022), it has been shown that such adverse symptomatology is relatively small in AR: a study reported only negligible symptoms of cybersickness across participants, with most experiencing no discomfort and only a few facing minimal symptoms (Vovk et al., 2018). A relatively low frequency of cybersickness in AR was also noted in Interview 6. However, the interviewee noted that symptoms like cybersickness could affect operators in control rooms. Operators monitoring live streams from AR systems on 2D screens have been reported to experience cybersickness, particularly during certain camera movements from the HMDs streamed to their monitors.

---

[9] Sometimes the phenomenon is referred to as simulator sickness, VR sickness, cyberkinetosis or visually induced motion sickness.

[10] The sense of discomfort that may be experienced e.g., while travelling as a passenger on a vehicle.

Vision problems and ocular health

HMDs use stereoscopic images to create depth perception, which can induce visual strain (Grassini & Laumann, 2021; Hodges & Davis, 1993; Parker, 2016; Urey et al., 2011). Although significant visual strain is associated with HMD use, current research does not conclusively link it to myopia after short exposures (Turnbull & Phillips, 2017). Still, prolonged use of HMDs may encourage behaviours conducive to myopia and affect long-term visual functions (Németh et al., 2021). Stereoscopy in HMDs aims to mimic real-world depth perception through binocular and proprioceptive cues, depending on the inter-pupillary distance (IPD), which varies widely across individuals (Lambooij et al., 2009; Stanney et al., 2020). Misaligned IPD settings can be accountable for visual fatigue (Hibbard et al., 2020) and can as well be responsible for eye strain when the brain cannot merge images at certain positions and distances, causing double vision (Patterson, 2015).

Individuals with compromised binocular depth perception or age-related stereo acuity decline face increased risks (Bosten et al., 2015; Hess et al., 2015; Lambooij et al., 2009; Ramadan & Alhaag, 2018; Schubert et al., 2016). Additionally, blue light from organic light-emitting diode (OLED) and liquid-crystal display (LCD) screens may contribute to this fatigue, affecting retinal health and eye focus (Ahmed et al., 2018; Heo et al., 2017; Lawrenson et al., 2017), with display brightness and colour dynamics also playing a part (Erickson et al., 2020; Kim et al., 2016; Kweon et al., 2018). Finally, the unavoidable viewing of extreme angles inside VR headsets is linked to a heightened chance of developing heterophoria, a disorder characterised by the misalignment of the eyes when not focusing (GOV.UK, 2020).

Recent research indicates that to prevent adverse eye symptoms, usage sessions should be limited to between 55 and 70 minutes (Kourtesis et al., 2019). However, it has been shown that this guideline is often exceeded in professional contexts (Bérastégui, 2024).

The specific wavelengths and intensities of blue light are also known to pose risks of both temporary and permanent damage to ocular structures, with the retina being particularly vulnerable (Cougnard-Gregoire et al., 2023). Although there is no conclusive evidence to suggest that ordinary screen exposure negatively impacts retinal health, the implications of blue light exposure through advanced XR technologies on ocular health have not been thoroughly investigated.

Form factor issues that interact with user vision were also reported in Interview 7. Some AR devices obscure a significant portion of the user's field of vision, particularly in low-light or confined spaces. This limitation can impair situational awareness and operational efficiency, increasing the risk of accidents. In addition, the psychological impact of reduced field of vision can lead to heightened anxiety and reduced task efficiency.

Sleep disturbance

Research also demonstrates that being exposed to certain types of lighting common in screens, such as blue light, suppresses melatonin secretion, a hormone pivotal in regulating sleep cycles (Tähkämö et al., 2019). However, the implications of blue light exposure through advanced XR technologies on sleep disturbances have not been thoroughly investigated.

Epilepsy

VR headset manufacturers include safety warnings about epilepsy risks, noting that a small fraction of users (approximately one in 4,000) may experience severe dizziness, epileptic seizures or blackouts due to exposure to light flashes or patterns (Tychsen & Thio, 2020). It has recently been noted that the fluctuating brightness levels in VR HMDs may pose a risk especially for those prone to photosensitive epilepsy (Bérastégui, 2024), and such occupational risk has been previously reported by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES, 2021, as cited in Bérastégui, 2024). However, there is currently limited research on the topic, and the incidence of epilepsy in VR users seems to be small (Tychsen & Thio, 2022).

Musculoskeletal disorders

Historically recognised since the 1990s (Nichols, 1999) in the context of early VR systems, VR muscle fatigue has been compared to fatigue caused by traditional computer tasks. VR users show higher physical stress due to factors like the HMD weight on the head, neck and shoulders (Kim & Shin, 2018).

In VR, user interactions with computer-generated environments mainly depend on handling HMDs and hand, head, eye and body movements (Kim et al., 2020; Monteiro et al., 2021). These interactions can result in muscle fatigue due to non-habitual, repetitive gestures and hardware use.

It has been hypothesised that other potential factors may be somehow related to musculoskeletal fatigue and discomfort (Souchet et al., 2023a; Souchet et al., 2023b); however, they are not fully explored in the context of VR technologies. These include cognitive exertion (Brown et al., 2020), illumination of the environment and brightness of the screen (Merbah et al., 2020), and stress (Dehdashti et al., 2017).

HMD weight impacts neck joint torque and perceived exertion (Chihara & Seo, 2018; Yan et al., 2018), influencing muscle fatigue. Different interaction gestures, including micro gestures, can also be responsible for musculoskeletal discomfort (Li et al., 2020). Bourdin et al. (2019) have indicated higher physical fatigue in VR and unconscious motor adjustments in VR environments.

While VR may offer task variation that could alleviate musculoskeletal discomfort and therefore mitigate existing OSH risks in the workplace (Luger et al., 2014), there is a risk of injuries due to repetitive movements (van Tulder et al., 2007). The literature suggests the need to consider muscle fatigue in VR use and user comfort in OSH, though the full extent of this issue in VR is not yet clear. As AR equipment is lighter compared with VR equipment, the issue of muscle strain is likely to be less prominent for AR-like technologies; however, little evidence is available in the current scientific literature (Marklin et al., 2020).

The current knowledge on the potential for HMDs to induce musculoskeletal problems underscores the need for advancements in HMD design, specifically their ergonomics and weight, to mitigate ergonomic risks and improve user comfort (Ito et al., 2021; Vi et al., 2019). Inadequate or poorly designed XR systems may contribute to work-related musculoskeletal disorders in the workplace, as well as and other ergonomic issues (Souchet et al., 2023b).

Sedentarism at work

Two interviewees (Interviews 3 and 4) shed light on a growing concern related to XR technologies in the context of OSH: their capacity to increase prolonged sedentary behaviour. XR technologies, designed to immerse users in virtual environments often through (generally) seated interactions, inadvertently promote extended periods of physical inactivity in the users. This shift towards increased sedentary time raises significant OSH concerns, given the well-documented health risks linked to prolonged sitting such as musculoskeletal disorders, cardiovascular issues and mental health challenges.

Skin irritation

Interviews revealed that extended use of **HMDs** can lead to dermatological concerns, including skin irritation, in regions where the HMD rests against the skin (Bérastégui, 2024). This issue tends to become worse the longer the device is used and is further exacerbated by an increase in the user's body temperature (generally observed when the user wears the headset in front of his or her eyes for an extended period), which leads to sweating. The current ergonomic design of HMD equipment plays a significant role in this problem. The existing scientific and medical literature has not sufficiently tackled this issue yet, making it challenging to assess the problem's scope or the number of individuals impacted.

Body damages or injuries related to batteries

Significant issues such as thermal injuries from overheating batteries have been identified from an interview (Interview 6). Batteries that overheat or malfunction can lead to skin damage and burns, especially if they are located near the user's body.[11] Furthermore, overheated or damaged lithium batteries have the potential to ignite or explode, posing immediate harm to the user and escalating further risks in safety-critical environments. This is especially relevant for AR systems designed to, for

[11] Please note that the risk of overheating and explosion from lithium batteries of XR systems is the same as in equipment like cell phones and laptops. However, as wearable technologies are generally in close contact with the user's body, the potential for physical harm is high (see OSHA.gov, 2019).

example, assist workers during in high-risk environments, where sparks and ignition may cause explosions.

Slips, trips and falls

Workers using HMDs for VR can only see the virtual environment, not the real surroundings, which increases the risk of injuries due to collisions with objects in the real environment or trips over the VR system cables (Bérastégui, 2024). The use of HMDs with no cables and with virtual boundaries, allowing the user to stay within a safe area in the real world, can help reduce these risks (Bérastégui, 2024). According to a 2020 report (GOV.UK, 2020), VR also has a detrimental impact on users' balance and coordination when wearing the HMD over prolonged sessions. In addition, post-VR use, individuals often exhibit diminished depth perception, delayed reaction times and concentration difficulties. These cognitive and perceptual deficits heighten the risk of injuries from mishaps like slips, trips and falls.

The fact that the use of VR may lead to falls has only been marginally discussed in the scientific literature. Notably, Warner and Teo (2021) documented a case where a minor fall during VR usage led to severe outcomes, including spinal cord and hypoglossal nerve damage, vertebral artery dissection and traumatic brain injury. The adverse effects of the use of VR technology may be especially relevant for older adults, as age and other comorbidities could lead to significant damage, even from minor falls. A possible increase in physical accidents, such as tripping or falling due to being distracted by AR content, was also mentioned in some of the interviews (Interviews 2 and 6).

4.2 Work-related psychosocial OSH risks and health outcomes

The XR implications for OSH are increasingly critical due to the potential mental health risks (Spiegel, 2017); however, these risks have been often neglected in VR use in occupational settings, and only recently has the literature started to systematically assess them (Biener et al., 2022). These risks are related to the immersive nature of the XR that tends to isolate the user in confined virtual work environments. Furthermore, these technologies are often a novelty, used by relatively inexperienced users typically lacking adequate training. This is a factor further heightening the psychosocial risks associated with XR and leading to an increase in stress. In addition, the interaction between avatars in the metaverse opens up the potential for psychologically damaging social interactions.

Perception and cognition

OSH risks related to perception and cognition are commonly reported in the context of XR technologies. These risks are related to the quantity of information shown by the displays and can interfere with the normal perceptive function of the users. For example, the technologies can distract users from the real environment or cover with digital overlays important parts of the users' work environment, leading to risks to workers' safety (e.g. accidents) and health, in particular mental health.

Indeed, one of the main consequences of increased cognitive load is increased distraction, which implies a higher probability of workplace accidents and injuries. Cognitive load and mental workload (terms often used synonymously) refer to the utilisation of cognitive resources during a task, with their application varying across learning and ergonomic contexts (Leppink, 2017; Orru & Longo, 2019; van Acker et al., 2018). Office-like tasks (i.e. tasks like those workers generally perform at an office desk) performed in VR show varied impacts on mental workload (Broucke & Deligiannis, 2019; Filho et al., 2018; Filho et al., 2018; Filho et al., 2019a; Filho et al., 2019b; Makransky et al., 2019; Shen et al., 2019; Tian et al., 2021; Zhang et al., 2017). It was found that VR can either reduce or increase mental workload, depending on task characteristics and interface design (Biener et al., 2020; Geiger et al., 2018; Speicher et al., 2018; Zielasko et al., 2019).

Factors like task spatialisation (the way a particular task is distributed in the virtual space) and user expertise in VR also may be responsible for cognitive overload (Armougum et al., 2019; Baceviciute et al., 2021; Bernard et al., 2019; Wismer et al., 2018). This highlights the importance on the one hand of good user interface designs that do not excessively increase the cognitive overload of users, despite being information-rich, and on the other hand of worker training in better handling the type of information displayed in VR.

Confusion, disorientation, and altered sense of time and space

One of the interviews revealed that a significant impact was noted on workers' perception and cognition, leading to confusion and disorientation (Interview 7). This effect may be greater for novice users or those without proper training in the use of XR technologies.

It has been proposed that excessive VR use may also be linked to a distorted sense of time (Mullen & Davidenko, 2021). While such evidence may be related to settings outside work, it is nonetheless potentially relevant for OSH in the context of situation awareness of users that may expose them to work-related risks and potential injuries. The use of AR has been found to be associated with users' misinterpretation of time and space in real-world situations, for example, the underestimation of the speed of oncoming vehicles or overestimating reaction time, leading to increased risk of hazards (Sabelman & Lam, 2015).

Reduced situational awareness

AR technologies can increase human errors in critical human-machine interaction settings, as is the case in manufacturing workplaces (Bahaei, 2020). Implementing AR in safety systems presents risks due to device design and possible work distractions, potentially critical especially in high-risk workplaces (Tatic & Tesic, 2015). Vehicle head-up display (HUD)[12] illustrates a specific type of AR that has been linked to an increase in driving errors. Such systems, while aiming to improve safety, might obscure real traffic scenarios, raising the risk of accidents (Kim & Hwang, 2017). Wang et al. (2021) found that AR HUDs could cause inattentional blindness[13] in high workload driving but might mitigate it when pedestrians are highlighted. Additionally, some AR devices reduce the user's field of vision, especially in dim or tight spaces (Interview 7), compromising situational awareness and leading to accidents, anxiety and lower task efficiency. The safety effect of HUD is particularly important in the context of OSH, as heavy work vehicles are often integrated with such types of technologies.

Overreliance on technology

Interview 7 highlighted concerns about how data inaccuracies impact user situational awareness, especially when machine learning algorithms are employed to analyse environmental data (e.g. sensors). These inaccuracies pose substantial OSH risks. Specifically, the misalignment of XR content — where virtual information does not correctly overlay or correspond with the real world — was pinpointed as a source of potential operational errors. This misalignment could lead to human errors in machinery operation or incorrect responses because of overreliance on the (possibly faulty) technology.

Interview 7 also highlighted the possibility that users may become generally too over-reliant on XR technologies, especially in the context of AR. The excessive dependence of operators on digital guidance could lead to severe errors or misjudgements in scenarios when they cannot use the technology and can no longer gather environmental data using analogue sensors, for example. This dependence also raises questions about skill loss and the ability of workers.

Sense of isolation

Although it has been suggested that VR promotes social isolation in specific and non-work settings (Schober, 2017), the evidence is not conclusive; a broader link between computer technology and social isolation has been discussed over the past few decades (Hampton, 2009). The long-term effect of the feeling of isolation in VR has not been explicitly studied in work settings, but due to the potential impact on workers' mental health, this deserves to be investigated in work environments requiring workers to use VR for an extended amount of time. The interviews data revealed that the sense of isolation may not be hypothetical. One of the people interviewed (Interview 4), an instructor in the context of VR training, specifically mentioned that some workers preferred traditional classroom training to VR training because of the feeling of loneliness in VR simulated environments. However, this may have been attributable to the specific training setting and not generalisable to XR and metaverse technologies.

[12] Systems projecting data, like vehicle speed, onto windshields.

[13] Inattentional blindness is a psychological phenomenon where an individual fails to notice a fully visible but unexpected object because their attention is engaged in something else.

Frustration and anxiety

In the context of OSH, the anxiety-inducing aspects of VR are particularly concerning. VR's immersive nature can be distressing. Recent findings indicate that the challenging usability of current XR technologies (e.g. challenges in operating HMDs) negatively affects mental health. A comparison between participants' experiences working a 40-hour week in VR versus a conventional office setting (Biener et al., 2022) revealed that users experienced higher levels of frustration (42%) and anxiety (19%) when using HMDs.

Cyberbullying

The advancement towards more realistic virtual environments introduces risks of unwanted interactions. Cyberbullying, as identified by researchers (Upadhyay et al., 2023), becomes a significant issue in immersive spaces, allowing for new forms of user interaction (Bérastégui, 2024; Dwivedi et al., 2023). This form of bullying includes harassment and simulation of physical assaults, potentially affecting victims emotionally and psychologically (Porta et al., 2024). Ongoing developments in haptic technology that allow users to feel virtual contact like real physical sensations, when used together with XR or metaverse technologies, could also transform virtual violence, for example between two avatars, into a real physical form of violence, due to the improvement in sensing technologies (Bérastégui, 2024).

In addition, the selection of an avatar significantly affects user behaviour in digital interactions (Bérastégui, 2024). Research shows that individuals adapt their actions to align with their avatar's appearance (Peña et al., 2022), displaying more confidence and extroversion with avatars perceived as tall and attractive. This phenomenon, known as the Proteus effect, has been recently identified in the literature on the risk of metaverse technologies (Bérastégui, 2024). This effect could exacerbate cyberbullying in VR, where avatars mediate all interactions. XR technologies have been shown to amplify the Proteus effect more than traditional 2D displays (Beyea et al., 2022).

Furthermore, engaging with a confrontational virtual character can provoke significantly higher anxiety levels in VR than on a flat screen, largely due to the increased sense of physical presence (Dickinson et al., 2021). The incidence of avatar-based harassment and virtual sex crimes (Brandon, 2024; Clement, 2022; Wiederhold, 2022) raises serious concerns for worker safety, demanding the implementation of stricter legal and regulatory measures alongside technological safeguards like two-factor authentication and biometric verification to combat impersonation and trace malicious activities. These measures are crucial for ensuring a secure, safe and respectful virtual workplace. The challenge for providers is balancing protective measures while maintaining the immersive quality of the experience.

Addiction

Personal neglect associated with addiction has been observed with excessive media use (Andreassen et al., 2012; Dam et al., 2023), and it is anticipated that prolonged VR exposure could intensify this concern. It has been found that between 2% and 20% of users of VR technology show compulsive VR use (Barreda-Ángeles & Hartmann, 2022), underscoring the potentially addictive nature of such immersive technologies. Other studies have also highlighted the potential addictive problem connected to the metaverse (Bojić, 2022). Although these concerns have not been experimentally tested in work settings, the evidence from other domains suggests that further investigation of the potential OSH implications is needed.

Acute stress and technostress

XR technologies in workplaces can trigger both acute stress and technostress due to issues including technological complexity, digital skill gaps and information overload. Acute stress is characterised by sudden or short-term stress responses that can impair cognitive functions such as executive function, selective attention, working memory, memory consolidation and recall (Klier & Buratto, 2020; LeBlanc, 2009; Shields et al., 2016). Technostress, meanwhile, arises specifically from the use of digital technologies in the workplace (Bondanini et al., 2020; Khan, 2023; Mahapatra & Pillai, 2018). Managing multiple information streams can also increase work pace and volume, contributing to technostress (Atanasoff & Venable, 2017; Tarafdar et al., 2019). Additionally, VR meetings can provoke public-speaking anxiety, a known stressor (Owens & Beidel, 2015; Takac et al., 2019).

4.3 OSH risks and outcomes related to ethical and legal aspects

Due to the immersive nature of XR and the interconnected digital landscapes of the metaverse, there are ethical and legal considerations for user privacy, data security, content moderation and the potential for misuse of the technology. These represent areas of OSH risks that could cause an increase in worker stress and anxiety (Canbay et al., 2022; EU-OSHA, 2023b).

As workers navigate these digital spaces, the blurring lines between reality and virtuality pose distinctive challenges in ensuring ethical interactions and safeguarding against the infringement of rights. The creation of digital avatars, the collection of biometric and behavioural data, and the potential for surveillance and monitoring within these technologies are all examples of OSH risks stemming from the use of the XR and metaverse technologies in the workplace. Privacy concerns and the possibility of personal data breaches are examples of risks that, if not properly prevented and/or managed, can cause stress for workers using XR technologies. All the interviews pointed to the potential continuous monitoring of workers as one of the most critical points for adoption of the technologies.

Recording of personal data, continuous monitoring and worker management

XR technology's integration into workplaces poses serious worker data privacy and data security issues, which both represent OSH risks (EU-OSHA, 2022a, 2022b, 2023b) due to the ability of the technology to collect personal data in various ways (Hine et al., 2023), including personal 'kinematic fingerprints'[14] (Spiegel, 2017). This concern extends to AR devices, which can record surroundings and bystanders. It raises issues for both consensual (the existence of recorded data is critical for the user, even in consensual recordings, as data can be stolen or misused)[15] and non-consensual recording and privacy invasion, as well as concern for the inappropriate or uninformed use of such recordings.

As sensor-embedded HMDs enable the monitoring of workers and their performance, the use of such devices may exacerbate the OSH risks associated with remote working when used in this form of work, such as increased work intensity, performance pressure and micromanagement (Bérastégui, 2024; EU-OSHA, 2023c). More generally, there are concerns that the metaverse can lead to strengthened managerial control (Bérastégui, 2024).

Surveys and studies highlight discomfort with AR's potential for unpermitted recording and a preference for technologies that prevent it (Denning et al., 2014; Rauschnabel et al., 2018). The omnipresence of cameras in XR technologies necessitates strict data protection and privacy policies to safeguard workers, underlining the importance for employers and OSH managers of prioritising these concerns, especially in the metaverse context. All the interviews touched on the privacy issue of recording personal data, with some specifically referring to the fear of continuous monitoring as a common concern (Interviews 5 and 7).

Diminished moral responsibility

From an OSH perspective, the notion of 'abandonment of external constraints' in VR (Cranford, 1996) highlights the risk of diminished moral responsibility due to a perceived lack of real-world risks and consequences. This phenomenon is akin to the documented negative impacts of anonymity online, sparking concerns over VR's influence on societal ethics. Gooskens (2010) stresses the emotional immersion in VR s compared to traditional stage plays, warning of the moral hazards should virtual actions begin to affect real-world behaviour. This issue is particularly acute in multi-user and connected settings (Ford, 2001), where the distinction between virtual and real identities becomes obscured, leading to increased behaviour against the common moral standard or the law, which could impact on worker safety and health, including mental health.

Security breaches

The metaverse brings significant OSH challenges, given its foundational property of interconnectedness (Sharma & Zamfiroiu, 2023). This feature permits malign entities, potentially external to the work environment, to gather sensitive data from workers, including worker behaviours and biometrics. So, the issues of cybersecurity and personal data protection within the metaverse are crucial from an OSH

[14] Specific patterns of movements that may be used to identify a person, for example, eye movement and reflexes.

[15] In this context also see O'Brolcháin et al. (2015) for a discussion on digital footprints and potential cases of personal data misuse in the context of XR.

perspective, requiring solutions to prevent risks and their impacts in terms of stress and mental health issues (EU-OSHA, 2023b). This susceptibility of the metaverse augments the potential for fraud (Cheong, 2022; Smaili & de Rancourt-Raymond, 2022) and identity theft (Dwivedi et al., 2023), posing significant OSH concerns when these systems are integrated into workplaces.

4.4 Biological risks: transmission of infectious diseases

HMD equipment can become a vehicle for pathogens that users can pass to each other. The potential for user cross-contamination with bacteria is relatively high in the context of HMD use, as several different users commonly use the same equipment in work settings. Research by Creel et al. (2020) identified strains of *Staphylococcus aureus* with high antibiotic resistance on VR HMDs' nosepieces and foreheads, used in a software development course. These bacteria, commonly found on the skin and in the airway, can lead to severe health conditions like bloodstream infections, pneumonia, and infections in bones and joints in healthy individuals. Other bacteria, part of human normal flora but potentially harmful to those with weakened immune systems or other health risks, were also found in the study. Virus contamination has been less studied in the context of HMDs; however, it is known that some viruses can survive a relatively long time on surfaces (Marzoli et al., 2021) and this is especially hazardous due to the proximity of HMDs to a wearer's eyes and mouth.

The issue of transmission between workers is especially critical when the equipment is not properly cleaned between users. Some guidance on how to handle risks of contamination of HMDs has been proposed recently (Roberts et al., 2022). Isopropyl alcohol or alcohol-free quaternary ammonium cleaning wipes have been found effective in reducing VR headset contamination and infection risks. Given the challenges some users face in cleaning HMDs properly (Easa, 2021), innovations like replaceable face masks and protective foam for headsets are emerging as effective strategies to mitigate biological risks. At the peaks of the COVID-19 pandemic, several companies proposed UV light-based sanitation products specifically designed for HMDs (Moore et al., 2021).

4.5 Other important OSH-related issues

The interviews highlighted a range of additional issues related to the use of XR and metaverse technologies with OSH implications that are worth analysing.

Problematic integration with personal protective equipment

A notable issue is the challenge of integrating XR hardware into existing personal protective equipment (PPE), particularly head-mounted equipment and protective goggles (Interview 2) and helmets. Misalignment can compromise the effectiveness of both the XR system and the protective gear, leading to safety hazards. Psychological implications include decreased confidence in personal safety and increased cognitive load due to concerns about equipment reliability.

User discomfort due to hardware ergonomics

Most of the interviews pointed to the fact that wearing HMDs is somehow uncomfortable. This is a serious problem to address when introducing XR technologies in the work environment. Not only could it negatively impact workers' technology acceptance and overall job performance, but more importantly, it may also impair worker concentration and exacerbate existing OSH risks, increasing stress levels and the risk of accidents.

Lack of empirical data for different industrial contexts

A general empirical data gap on OSH risks in the use of XR in the workplace, and specifically, a lack of empirical data on risks by type of industry and use, was reported in the interviews. The lack of empirical data on the risks associated with AR hampers comprehensive understanding and mitigation strategies (Interview 6). This gap in research makes it difficult to create informed OSH policies and guidelines, potentially leading to unaddressed OSH risks. Furthermore, non-tested use of XR equipment was reported, where industries use the equipment for purposes not tested by the producer (Interview 6). This use of XR technology in untested scenarios poses additional risks, as the safety and effectiveness of the devices are not empirically established, leading to potential safety oversights and unaddressed hazards in the workplace.

Limited knowledge of long-term uses and risks

XR technologies are primarily used for specific tasks or short training sessions. This limits our understanding of their full potential and associated risks in the long term, in cases where these technologies are implemented for longer in some occupational settings. This affects how OSH risks are perceived and managed: employers perceive the risks to be limited (since OSH knowledge is limited to the short time that the technologies are in use in the workplaces) and therefore do not effectively communicate these risks and potential criticalities to operators. This, in turn, may impact workers' perception of the technology's reliability and safety. This criticality was highlighted in some of the interviews (Interviews 2, 3 and 4). A potential lack of reporting of criticalities and risks (Interview 5) and a concerning lack of empirical evidence on the risks of XR use (Interview 2) were also evidenced.

Limited workplace risk assessment communication of OSH risks to workers

The interviews showed that companies frequently overlook XR technologies in the workplace risk assessment, which is the employer's legal obligation as per the OSH Framework Directive. This oversight appears to stem from two different reasons. First, in many sectors, there is a lack of awareness regarding the potential risks associated with XR usage. Second, management often perceives these risks as minimal, rationalising that the use of XR technologies is typically brief and confined in scope. The data consistently pointed to a widespread shortcoming of both awareness and communication of these risks across various industries. However, it was observed that industries with a longstanding history of XR device use have developed a more robust approach towards risk assessment, communication and the establishment of clear guidelines (Interview 7).

The digital divide and inequality

Differences in the understanding and adoption of XR technology, particularly among different age groups and levels of digital literacy, can influence how XR is integrated and managed in the workplace, potentially leading to disparities in technological proficiency in and acceptance of the technology (Interview 1). Many HMD-based XR devices are not designed for diverse users (Derby et al., 2023; Grassini & Laumann, 2020a), potentially excluding certain demographics and limiting the technology's inclusivity and effectiveness. This exclusion can have significant mental health implications, contributing to feelings of marginalisation and inequality in the workplace.

5 Discussion and conclusions

From an OSH perspective, the integration of XR technologies and the metaverse in the workplace presents both potential benefits and inherent risks. This necessitates ensuring a balanced approach between the use of technological advancements and OSH risks prevention and management.

The application of XR technologies in the workplace offers **significant opportunities** in various OSH-related domains: OSH-related training, remote working and guidance, complex and fast interpretation of environmental or sensor data, and design of a more rational and safe work environment. However, these opportunities should be considered in the context of several identified OSH risks, particularly in environments with inherent hazards. The literature review and expert interviews indicate the use of these technologies is generally endorsed, underlining their potential to **improve work performance, efficiency and overall workplace safety and health**, and stressing that most reported risks today can be mitigated with technological advances in software and hardware.

The use of XR and metaverse technologies marks a step forward in **enhancing OSH through risk-free training environments**, allowing for the simulation of hazardous scenarios without real-world risks. For example, construction workers can safely experience high-altitude work, while manufacturing workers can operate heavy machinery at a distance in a virtual setting. Immersive training sessions in VR not only aid in skill development but could also promote a culture of safety and OSH awareness, as well as help identify work-related risks.

The adoption of metaverse-like technologies for **remote collaboration significantly reduces OSH risks** by removing workers from hazardous environments, eliminating the need for physical travel to the worksite (with the OSH opportunities and risks that this entails),[16] proving crucial during global health crises, and maintaining effective communication and teamwork. Furthermore, these technologies help **prioritise safety and ergonomic considerations in the design and prototyping phases**, addressing potential OSH risks at an early stage, and promoting a safer environment for workers. They also ensure **workplace accessibility**, potentially offering customised interfaces for workers with disabilities, vital for inclusivity and compliance with legal safety standards. In real estate and space planning, XR and metaverse tools facilitate the **assessment of safety and emergency protocols**, aiding in the development of safer commercial and residential spaces. In healthcare, these technologies increase patient and practitioner safety by offering platforms to improve patient education and for practice without the risk of real-life errors.

Lastly, integrating sensor data and analytics into XR and metaverse environments **improves OSH management** by allowing for intuitive visualisation of potential hazards, compliance monitoring and maintenance planning, ensuring a safer working environment.

However, exploring XR and metaverse technologies requires a thorough analysis of the **multifaceted risks and implications** these technologies bring to OSH. Their incorporation in professional settings introduces a complex blend of OSH risks and impacts on worker safety and health that this article attempts to categorise as physical or ergonomic, psychosocial, ethical or legal, and biological, expanding previous attempts to categorise OSH risks in the use of XR in the workplace (The AREA, 2024a).

The use of XR technologies at work is primarily affected by **significant physical and ergonomic risks** due to the ergonomics of the HMD equipment. The discomfort, neck strain and visual fatigue stemming from the **design and use of HMDs** should stimulate ergonomic improvements in future iterations of the technologies, if these are to be effectively implemented in work environments. Moreover, the occurrence of **cybersickness**, which mirrors symptoms of motion sickness, highlights the critical need for a collaborative effort from hardware and software developers to design experiences that are both user friendly and not harmful to worker safety, health and wellbeing. OSH issues frequently reported by the interviewees also include the **risk of seizures** triggered by specific visual patterns and thermal risks associated with **XR device batteries**.

Alongside physical risks, **psychosocial risks** associated with XR technologies raise serious concerns for workers' mental health. Examples of such psychosocial risks include **social isolation, anxiety** and the potential for negative interactions in virtual environments, such as **avatar-based harassment and cyberbullying**. Creating XR environments that foster positive social engagement and provide adequate support mechanisms is essential for maintaining a healthy balance between technology use and mental health. Importantly, the interviews carried out under this study revealed that these risks are among **the least assessed**, and the scientific literature provides very limited evidence about such risks relevant for the workplace use of XR technologies. Further assessments are therefore urgently needed.

Furthermore, XR and metaverse technologies can potentially overwhelm workers, leading to **cognitive overload**, impaired decision-making and an increase in errors, putting workers' safety and health at risk. The increased risks of accidents such as **trips and falls** due to high cognitive workload or distraction by XR content were highlighted by the interviewees, reflecting concerns about loss of **awareness of one's surroundings**. Such important negative effects highlight the importance of creating XR interfaces that are cognitively ergonomic and tailoring XR experiences to support workers' cognitive processes without causing undue stress and accidents. The goal is to ensure that XR technologies contribute positively both to workplace productivity and OSH. To mitigate such risks, user experience or interface (UX/UI) experts and engineers should work together, attempting to create cognitive-friendly interfaces and software, and to create guidelines for effectively displaying information in VR simulations or in the AR overlays to the real environment.

Ethical and legal concerns also play a crucial role in the OSH implications of XR and metaverse technologies. **Privacy issues**, data security challenges, and the risk of **data breach and misuse** necessitate the establishment of stringent ethical standards, robust privacy protections and clear legal frameworks. It is critical to ensure that XR platforms not only respect workers' rights but also promote ethical interactions. This involves protecting workers' personal data, preventing avatar-based

[16] See EU-OSHA publications on the OSH implications of remote work at https://osha.europa.eu/en/publications-priority-area/remote-and-hybrid-work

harassment, and upholding a clear distinction between virtual behaviours and real-world ethical standards. With the advent of the metaverse (and the possibility for it to include AI-generated content), risks related to data uses are prominently emerging. These ethical and legal issues may generate stress and anxiety in workers and have negative consequences for workers' mental health.

The literature review also identified **biological risks** related to the use of HMDs. These relate to the possibility for the equipment to be contaminated with pathogens, and therefore to potentially contribute to bacterial and viral transmission and infections among users.

Inclusivity and accessibility are critical considerations in the deployment of XR technologies in the workplace, and these emerged in both the scientific literature and the interviews. Many XR HMDs are not designed for a diverse range of users, and may exclude certain demographics (e.g. women are commonly more susceptible to side effects like simulator sickness). The interviews highlighted concerns about the suitability of XR devices for different body types, ages and abilities. These issues limit the technology's effectiveness and inclusivity and can have significant mental health implications, contributing to feelings of marginalisation and inequality in the workplace. This emphasises the need for inclusive design practices that accommodate the diversity of the workforce.

Finally, the interviews also revealed that current XR has limited standardisation procedures or obligation to comply with certification requirements (Interview 6). The **current lack of standardisation** obstructs the adoption of these technologies, especially in risk-prone work environments that may be more reluctant to introduce technologies with uncertified specifications that may not be trusted as inherently safe. Furthermore, some industries face the challenge of **integrating HMDs with existing safety equipment** (e.g. protective goggles, safety helmets), due to the issues of poor HMD ergonomics.

In conclusion, addressing these risks and challenges is important for ensuring workers' OSH in environments employing XR and metaverse technologies, especially if **HMDs are worn for long periods of time**. As the **negative impacts on users of such technologies seem cumulative** with frequency of use, there are **concerns about their sustained use in work contexts**.

While the present paper acknowledges the positive potential for XR and metaverse technologies to be integrated in the workplace, it also emphasises the need for a **comprehensive understanding of their OSH implications**. In particular, there is a need to investigate the effects on workers of **combined exposures to the full range of potential OSH risks**, and not only those associated with the XR or metaverse technologies themselves, but with the occupational environment as well, rather than to each risk separately. This understanding is crucial for the development of **effective strategies and frameworks that prevent and mitigate OSH risks**, ensuring the safe and ethical integration of these technologies in occupational settings and in the society at large.

6 Considerations and policy pointers

Incorporating XR technologies into work settings requires tailored guidance taking into consideration the OSH perspective. The following guidance focus on ensuring the security and privacy of XR systems as well as the safety, health and wellbeing of the workers using them. Recommendations for the introduction of XR in workplaces have been made in other literature; the guidance presented here take into account previous discussions, policies and practices (see, for example, Abraham et al. (2022), Adhyaru and Kemp (2022), and The AREA (2024b)) as well as the new insights emerging from this study, in particular from the interviews and the OSH perspective from which the literature reviewed was analysed.

6.1 Guidance and policy pointers for implementing XR and metaverse technologies in the workplace

- **Ergonomic design of XR devices.** XR devices used in the workplace should be ergonomically designed to prevent strain or injury. This includes adjustable straps, lightweight materials and considerations for prolonged usage. OSH guidelines on ergonomic practices must be integrated into the design and deployment of these devices.
- **Regular training and awareness programmes**. Hold regular training sessions to familiarise workers with the safe and efficient use of XR technologies. These programmes should also cover

privacy practices, data security protocols and awareness of potential OSH risks impacts, aligning with OSH standards.

- **Monitoring and mitigating impacts on workers' mental health.** Put in place monitoring mechanisms to assess the impact of (prolonged) XR usage on workers' mental health, such as XR-related cognitive overload, fatigue or disorientation. Providing mental health support and setting usage limits can help to prevent or mitigate the risks.
- **Emergency response protocols in XR environments.** Develop and integrate emergency response protocols into XR systems. In a real-world emergency, users should be able to quickly disengage from the XR environment. These protocols would include easy-to-access exit procedures and alerts that can disrupt the immersive experience.
- **Compliance audits for XR usage.** Schedule regular compliance audits by specialised audit firms or internal compliance teams, to ensure the XR technology's use meets legal, ethical and OSH standards. These audits can help identify areas for improvement and ensure that XR technologies are being used responsibly and safely.
- **Transparency in personal data collection and usage.** In a workplace setting, it is crucial to transparently communicate to workers what data the XR systems are collecting and when. Additionally, clarity on where and how data are processed (internally or externally) is essential for workers. This transparency not only aligns with privacy standards but also promotes a trustful work environment.
- **Development of workplace-specific XR standards and guidelines**. The interviews carried out for this research have emphasised the current lack of — and need for — workplace-specific standards and guidelines for the use of XR and metaverse technologies. These standards and guidelines should encompass data collection, privacy and security issues, but also the prevention of the risks to worker's safety and health associated with XR use highlighted in this paper. This will contribute to the creation of safe and healthy XR environments and safeguard worker safety, health and wellbeing.
- **Involvement of workers in the design and implementation of XR and metaverse technologies.** Worker consultation is the employer's obligation as per the OSH Framework Directive. This is critical as workers´ involvement ensures that the technology is aligned with their needs and OSH requirements. It encourages a sense of ownership and commitment to safe and healthy practices.
- **Consideration of XR and the metaverse in workplace risk assessments.** The use of XR and metaverse technologies should be incorporated into workplace risk assessments, as per the OSH Framework Directive. This consideration will ensure that potential risks associated with the use of these technologies at work are identified and managed effectively, promoting a safe and healthy work environment.

6.2 Recommendations for future research

- **Evaluate workers' long-term health impacts, including mental health.** Carry out longitudinal studies to assess the long-term health impacts of prolonged and/or repetitive XR usage in occupational settings, focusing on physical aspects like vision and posture as well as psychosocial aspects such as cognitive load and mental wellbeing. These studies should aim to draw from robust experimental designs such as randomised controlled trials. Additionally, future research endeavours should study the impact of XR tools on worker productivity, job satisfaction and overall workplace morale. Understanding these aspects can help optimise the use of XR for worker wellbeing and efficiency.
- **Quantitatively evaluate the effectiveness of XR training programmes.** Investigate the effectiveness of XR-based training and educational programmes in improving workplace OSH. Compare traditional training methods with XR-based methods to determine efficacy in terms of retention, engagement and practical application, and assess when and how XR technologies should

best be used for training purposes. It is important to strike the right balance between maximising the benefits of using XR technologies and mitigating the associated OSH risks.

- **Carry out real-time OSH monitoring.** Study how to best use psychophysiological sensors, AI and algorithms within XR devices to monitor real-time indicators of workers' OSH such as stress levels, eye strain and posture, while avoiding the pitfalls of data privacy and worker surveillance issues, which, in turn, negatively impact workers' (mental) health. For example, real-time alerts may be integrated to prompt workers to adjust their posture, take breaks or stop working with XR technologies for a certain time, in line with OSH best practices.
- **Research possibilities for standardisation of XR equipment and protocols.** Investigate the needs to support the development of standardisation in XR equipment and safety protocols across various industries. This research should aim to establish common standards and best practices for the safe and healthy use of XR technologies.
- **Integrate OSH considerations into XR development.** Conduct research on the impacts on workers and their OSH and integrate findings into the XR design and development stage to provide human-centred technologies. For this, OSH experts should collaborate with XR technology developers to integrate OSH considerations into the early stages of XR system design. This should also be done in consultation with end users, meaning the workers using these technologies.

6.3 Policy pointers

- **Establish comprehensive OSH policies.** Develop and put in place comprehensive OSH policies specifically tailored for XR and metaverse applications in the workplace. These policies should address potential risks to OSH, including physical, ergonomic and psychosocial, as well as ethical and data privacy concerns, and ensure the safe, healthy and ethical use of such technologies.
- **Support research and development.** Allocate resources and funding to support research on XR safety and usability and its implications for worker health and productivity. Policymakers should encourage partnerships between governmental bodies, academic institutions and industry experts.
- **Create guidelines for virtual workplace interactions.** Draw up guidelines to govern interactions within virtual workplaces in the metaverse. These should cover aspects like virtual harassment, ethical behaviour and avatar impersonation. Guidelines should be flexible and adaptable, to keep pace with a fast-developing technology and diverse modes of use.
- **Run training and certification programmes.** Promote the introduction of training and certification programmes for XR technology use, focusing on OSH and best practices. This ensures that workers are adequately prepared to use these technologies in a safe, healthy and effective way.
- **Ensure inclusive policymaking.** Involve a diverse group of stakeholders in the policymaking process, with multidisciplinary expertise and various backgrounds, including XR users or workers and employers, developers, OSH experts and legal professionals. This ensures that diverse perspectives and experiences are considered.
- **Assess workplace impact.** Regularly monitor and evaluate the impact of XR technologies on worker safety and health to support evidence-based policymaking and prevention. This is particularly important for the development and applications of XR technologies and the metaverse, as the shifting sands in this area have the potential to constantly reveal new and emerging OSH risks and challenges.

References

Abdalla, S., Apramian, S. S., Cantley, L. F., Cullen, M. R., Mock, C. N., Nugent, R. ... & Smith, K. R. (2017). Occupation and risk for injuries. In C. N. Mock, R. Nugent, O. Kobusingye, & K. R. Smith (Eds), *Disease control priorities, third edition (Volume 7): Injury prevention and environmental health* (pp. 97-132). World Bank Group.

Abraham, M., Saeghe, P., Mcgill, M., & Khamis, M. (2022, October). Implications of XR on privacy, security and behaviour: Insights from experts. In *Nordic Human-Computer Interaction Conference* (Article 30). Association for Computing Machinery.

Adebowale, O. J., & Agumba, J. N. (2022). Applications of augmented reality for construction productivity improvement: A systematic review. *Smart and Sustainable Built Environment, 13*(3), 479-495. Available at: https://doi.org/10.1108/SASBE-06-2022-0128

Adhyaru, J. S., & Kemp, C. R. (2022). Virtual reality as a tool to promote wellbeing in the workplace. *Digital Health, 8*.

Ahmed, S. F., McDermott, K. C., Burge, W. K., Ahmed, I. I., Varma, D. K., Liao, Y. J., Crandall, A. S., & Khaderi, S. K. (2018). Visual function, digital behavior and the vision performance index. *Clinical Ophthalmology, 12*, 2553-2561.

Akçayır, M., & Akçayır., G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review, 20,* 1-11.

Alam, F., Iqbal, K., Sattar, M. Z., & Nazir, S. (2020). Using augmented reality for teaching chemistry. *International Journal of Experiential Learning & Case Studies, 5*(2) 226-235. https://www.academia.edu/91241588/Using_Augmented_Reality_for_Teaching_Chemistry?f_ri=3419

Al-Gnbri, M. K. (2022). Accounting and auditing in the metaverse world from a virtual reality perspective: A future research. *Journal of Metaverse, 2*(1), 29-41.

Andreassen, C.S (2012). Development of a facebook addiction scale. Psychological Reports, 2012,110, 2, 501-517.

Angelov, V., Petkov, E., Shipkovenski, G., & Kalushkov, T. (2020, June). Modern virtual reality headsets. In *2020 International congress on human-computer interaction, optimization and robotic applications (HORA)* (pp. 1-5). IEEE.

ANSES. (2021). *Expositions aux technologies de réalité virtuelle et/ou augmentée. Avis de l'Anses: Rapport d'expertise collective*. Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail. Available at: https://www.anses.fr/fr/system/files/AP2017SA0076Ra.pdf

Armougum, A., Orriols, E., Gaston-Bellegarde, A., Marle, C. J. L., & Piolino, P. (2019). Virtual reality: A new method to investigate cognitive load during navigation. *Journal of Environmental Psychology, 65,* Article 101338*.* https://doi.org/10.1016/j.jenvp.2019.101338

Atanasoff, L.M., & Venable, M.A. (2017). Technostress: Implications for Adults in the Workforce. *Career Development Quarterly, 65*, 326-338.

Babalola, A., Manu, P., Cheung, C., Yunusa-Kaltungo, A., & Bartolo, P. (2023). A systematic review of the application of immersive technologies for safety and health management in the construction sector. *Journal of Safety Research, 85*, 66-85.

Baceviciute, S., Terkildsen, T., & Makransky, G. (2021). Remediating learning from non-immersive to immersive media: Using EEG to investigate the effects of environmental embeddedness on reading in virtual reality. *Computers & Education, 164*, Article 104122. https://doi.org/10.1016/j.compedu.2020.104122

Bahaei, S. S. (2020). A framework for risk assessment in augmented reality-equipped socio-technical systems. In *2020 50th Annual IEEE-IFIP International Conference on Dependable Systems and Networks-Supplemental Volume (DSN-S)* (pp. 77-78). IEEE.

Bale, A. S., Ghorpade, N., Hashim, M. F., Vaishnav, J., & Almaspoor, Z. (2022). A comprehensive study on metaverse and its impacts on humans. *Advances in Human-Computer Interaction, 2022*, Article 3247060*.*

Barreda-Ángeles, M., & Hartmann, T. (2022). Hooked on the metaverse? Exploring the prevalence of addiction to virtual reality applications. *Frontiers in Virtual Reality, 3*, Article 1031697

Beyea, D., Ratan, R.A., Lei, Y.(., Liu, H., Hales, G.E., & Lim, C. (2022). A New Meta-Analysis of the Proteus Effect: Studies in VR Find Stronger Effect Sizes. *PRESENCE: Virtual and Augmented Reality, 31*, 189-202.

Bérastégui, P. (2024, February 8). *Working in the metaverse: What are the risks?* ETUI, The European Trade Union Institute. https://www.etui.org/publications/working-metaverse-what-are-risks

Bernard, F., Zare, M., Sagot, J.-C., & Paquin, R. (2019). Virtual reality simulation and ergonomics assessment in aviation maintainability. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, & Y. Fujita (Eds), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (Vol. 822, pp. 141-154). Springer International Publishing. https://doi.org/10.1007/978-3-319-96077-7_15

Biener, V., Kalamkar, S., Nouri, N., Ofek, E., Pahud, M., Dudley, J. J. et al. (2022). Quantifying the effects of working in VR for one week. *arXiv*. https://doi.org/10.48550/arXiv.2206.03189

Biocca, F. (1992). Will simulation sickness slow down the diffusion of virtual environment technology? *Presence: Teleoperators & Virtual Environments, 1*(3), 334-343.

Bojić, L. (2022). Metaverse through the prism of power and addiction: What will happen when the virtual world becomes more attractive than reality? *European Journal of Futures Research, 10*(1), 1-24.

Bondanini, G., Giorgi, G., Ariza-Montes, A., Vega-Muñoz, A., & Andreucci-Annunziata, P. (2020). Technostress dark side of technology in the workplace: A scientometric analysis. *International Journal of Environmental Research and Public Health, 17*(21), Article 8013.

Bosten, J. M., Bosten, J. M., Goodbourn, P. T., Lawrance-Owen, A. J., Bargary, G., Hogg, R. E., & Mollon, J. D. (2015). A population study of binocular function. *Vision Research, 110*, 34-50.

Bottani, E., & Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade. *IISE Transactions, 51*(3), 284-310.

Bourdin, P., Martini, M., & Sanchez-Vives, M. V. (2019). Altered visual feedback from an embodied avatar unconsciously influences movement amplitude and muscle activity. *Scientific Reports, 9*(1).

Brandon, M. (2024). The dark reality of sexual assault in the metaverse. Retrieved the 20.5.2024 from https://www.psychologytoday.com/intl/blog/the-future-of-intimacy/202403/sexual-assault-in-the-metaverse

Broucke, S. V., & Deligiannis, N. (2019). Visualization of real-time heterogeneous smart city data using virtual reality. In *2019 IEEE International Smart Cities Conference (ISC2)* (pp. 685-690). IEEE.

Brown, D. M., Graham, J. D., Innes, K. I., Harris, S., Flemington, A., & Bray, S. R. (2020). Effects of prior cognitive exertion on physical performance: A systematic review and meta-analysis. *Sports Medicine, 50*(3), 497-529.

Büchner, A., Micheli, G., Gottwald, J., Rudolph, L., Pantförder, D., Klinker, G., & Vogel-Heuser, B. (2022, October). Human-centered augmented reality guidance for industrial maintenance with digital twins: A use-case driven pilot study. In *2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 74-76). IEEE.

Buddhan, A. R., Eswaran, S. P., Buddhan, D. M., & Sripurushottama, S. (2019). Even driven multimodal augmented reality based command and control systems for mining industry. *Procedia Computer Science, 151*, 965-970.

Caiza, G., Bonilla-Vasconez, P., Garcia, C. A., & Garcia, M. V. (2020). Augmented reality for robot control in low-cost automation context and IoT. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (Vol. 1, pp. 1461-1464). IEEE.

Canbay, Y., Utku, A., & Canbay, P. (2022). Privacy concerns and measures in metaverse: A review. In *2022 15th International Conference on Information Security and Cryptography (ISCTURKEY)* (pp. 80-85). IEEE.

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.

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.

Chellappa, V., Mésároš, P., Špak, M., Spišáková, M., & Kaleja, P. (2022). VR-based safety training research in construction. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1252, Article 012058). IOP Publishing.

Chen, Y., Huang, D., Liu, Z., Osmani, M., & Demian, P. (2022). Construction 4.0, Industry 4.0, and building information modeling (BIM) for sustainable building development within the smart city. *Sustainability, 14*(16), Article 10028.

Cheng, H., Liu, Z., Cai, F., Zhang, L., Ma, X., Sun, X., Hu, J., & Wang, P. (2022). AR technology in the design of oil and gas field surface engineering: Applications and prospects. *Wearable Technology, 3*(2), 23-31. https://doi.org/10.54517/wt.v3i2.1641

Cheng, R., Wu, N., Varvello, M., Chen, S., & Han, B. (2022). Are we ready for metaverse?: A measurement study of social virtual reality platforms. In *Proceedings of the 22nd ACM Internet Measurement Conference* (pp. 504-518). Association for Computing Machinery.

Cheong, B. C. (2022). Avatars in the metaverse: Potential legal issues and remedies. *International Cybersecurity Law Review, 3(2),* 467-494.

Chihara, T., & Seo, A. (2018). Evaluation of physical workload affected by mass and center of mass of head-mounted display. *Applied Ergonomics, 68*, 204-212.

Chuah, S. H.-W. (2018, December 13). Why and who will adopt extended reality technology? Literature review, synthesis, and future research agenda. Available at SSRN: https://doi.org/10.2139/ssrn.3300469

Clement, D. (2022, June 2). Sex in the metaverse: virtual body, real sexual assault. The Law Association Inc. Retrieved the 20.5.2024, from https://thelawassociation.nz/sex-in-the-metaverse-virtual-body-real-sexual-assault/

Cougnard-Gregoire, A., Merle, B. M., Aslam, T., Seddon, J. M., Aknin, I., Klaver, C. C., ... & Delcourt, C. (2023). Blue light exposure: ocular hazards and prevention—a narrative review. *Ophthalmology and therapy*, *12*(2), 755-788.

Cranford, M. (1996). The social trajectory of virtual reality: Substantive ethics in a world without constraints. *Technology in Society, 18*(1), 79-92.

Creel, B., Rinz-Jones, C.J., Jones, A., & Jackson, C.R. (2020). *Bacterial Load of Virtual Reality Headsets.* Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology.

Daling, L. M., Kommetter, C., Abdelrazeq, A., Ebner, M., & Ebner, M. (2020). Mixed reality books: Applying augmented and virtual reality in mining engineering education. In V. Geroimenko (Ed.), *Augmented reality in education: A new technology for teaching and learning* (pp. 185-195). Springer.

Dam, V. A. T., Dao, N. G., Nguyen, D. C., Vu, T. M. T., Boyer, L., Auquier, P., Fond, G., Ho, R. C. M., Ho, C. S. H., & Zhang, M. W. B. (2023). Quality of life and mental health of adolescents: Relationships with social media addiction, Fear of Missing out, and stress associated with neglect and negative reactions by online peers. *PloS one, 18(6),* e0286766. https://doi.org/10.1371/journal.pone.0286766

De Felice, F., Rehman, M., Petrillo, A., & Baffo, I. (2023). A metaworld: Implications, opportunities and risks of the metaverse. *IET Collaborative Intelligent Manufacturing, 5*(3), Article e12079.

Dehdashti, A., Mehralizadeh, S., & Mahjoubi, Z. (2017). Workplace stresses and musculoskeletal disorders among nurses: A cross-sectional study. *Middle East Journal of Rehabilitation and Health Studies, 4*(3).

Denning, T., Dehlawi, Z., & Kohno, T. (2014). In situ with bystanders of augmented reality glasses: Perspectives on recording and privacy-mediating technologies. In *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems—CHI'14* (pp. 2377-2386). Association for Computing Machinery.

Derby, J. L., Mello, S. M., Horn, N. R., StClair, A. N., & Chaparro, B. S. (2023). Examining the inclusivity of extended reality (XR) in current products. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 67*(1), 2198-2204.

Descheneaux, C. R., Reinerman-Jones, L., Moss, J. D., Krum, D. M., & Hudson, I. L. (2020). Negative effects associated with HMDs in augmented and virtual reality. In *Virtual, Augmented and Mixed Reality. Design and Interaction: 12th International Conference, VAMR 2020, Proceedings, Part I 22* (pp. 410-428). Springer International Publishing.

Dick, E. (2021, June 1). *Current and potential uses of AR/VR for equity and inclusion*. Information Technology and Innovation Foundation. https://itif.org/publications/2021/06/01/current-and-potential-uses-arvr-equity-and-inclusion/

Dickinson, P., Jones, A., Christian, W., Westerside, A., Mulloy, F., Gerling, K. M., Hicks, K., Wilson, L., & Parke, A. (2021). Experiencing simulated confrontations in virtual reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Article 255). Association for Computing Machinery.

Ding, X., Sun, M., Bai, W., & Li, X. (2022). Exploration of architectural design in the co-construction mode of user and designer in the metaverse environment. In *Proceedings of the 2022 7th International Conference on Systems, Control and Communications* (pp. 55-60). Association for Computing Machinery.

Dolata, M., & Schwabe, G. (2023). What is the metaverse and who seeks to define it? Mapping the site of social construction. *Journal of Information Technology, 38*(3), 239-266.

Duarte, J., Dinis, M. D., & Baptista, J.S. (2019). Virtual reality applications in the extractive industry—A short review. In *Studies in Systems, Decision and Control* (pp. 53-60). Springer International Publishing.

Duarte, J., Torres Marques, A., & Santos Baptista, J. (2021). Occupational accidents related to heavy machinery: A systematic review. *Safety, 7*(1), Article 21. https://doi.org/10.3390/safety7010021

Duncan, R. (2015). The potential contribution of augmented and virtual reality to the oil and gas industry. *International Journal of Management, 2*(3), 112-120. https://doi.org/10.18646/2056.23.15-011

Dużmańska, N., Strojny, P., & Strojny, A. (2018). Can simulator sickness be avoided? A review on temporal aspects of simulator sickness. *Frontiers in Psychology, 9*, Article 410742.

Dwivedi, Y. K., Ismagilova, E., Hughes, D. L., Carlson, J., Filieri, R., Jacobson, J., Jain, V., Karjaluoto, H., Kefi, H., Krishen, A. S., Kumar, V., Rahman, M. M., Raman, R., Rauschnabel, P. A., Rowley, J. E., Salo, J. T., Tran, G. A., & Wang, Y. (2021). Setting the future of digital and social media marketing research: Perspectives and research propositions. *International Journal of Information Management, 59*, Article 102168.

Dwivedi, Y. K., Kshetri, N., Hughes, L., Rana, N. P., Baabdullah, A. M., Kar, A. K., Koohang, A., Ribeiro-Navarrete, S., Belei, N., Balakrishnan, J., Basu, S., Behl, A., Davies, G. H., Dutot, V., Dwivedi, R., Evans, L., Felix, R., Foster-Fletcher, R., Giannakis, M. … Yan, M. (2023). Exploring the darkverse: A multi-perspective analysis of the negative societal impacts of the metaverse. *Information Systems Frontiers, 25*(5), 2071-2114.

Easa, S. (2021). Human factor considerations in virtual reality: Adequate or inadequate? *Ergonomics International Journal, 5*(2), 1-11.

Ellis, S. R. (1994). What are virtual environments? *IEEE Computer Graphics and Applications, 14*(1), 17-22.

Erickson, A., Kim, K., Bruder, G., & Welch, G. (2020). Effects of dark mode graphics on visual acuity and fatigue with virtual reality head-mounted displays. In *2020 IEEE Conference on virtual reality and 3D user interfaces (VR)* (pp. 434-442). IEEE.

EU-OSHA – European Agency for Safety and Health at Work, *Foresight on new and emerging occupational safety and health risks associated with digitalisation by 2025*, 2018. Available at: https://osha.europa.eu/en/publications/foresight-new-and-emerging-occupational-safety-and-health-risks-associated

EU-OSHA – European Agency for Safety and Health at Work, *Artificial intelligence for worker management: implications for occupational safety and health*, 2022a. Available at: https://osha.europa.eu/en/publications/artificial-intelligence-worker-management-implications-occupational-safety-and-health

EU-OSHA – European Agency for Safety and Health at Work, *Incorporating occupational safety and health in the assessment of cybersecurity risks*, 2022b. Available at: https://osha.europa.eu/en/publications/incorporating-occupational-safety-and-health-assessment-cybersecurity-risks

EU-OSHA – European Agency for Safety and Health at Work, *Smart digital monitoring systems for occupational safety and health: opportunities and challenges*. 2023a. Available at: https://osha.europa.eu/en/publications/smart-digital-monitoring-systems-occupational-safety-and-health-opportunities-and-challenges

EU-OSHA – European Agency for Safety and Health at Work, *Smart digital monitoring systems for occupational safety and health: uses and challenges*, 2023b. Available at: https://osha.europa.eu/en/publications/smart-digital-monitoring-systems-occupational-safety-and-health-uses-and-challenges

EU-OSHA – European Agency for Safety and Health at Work, *Surveillance and monitoring of remote workers: implications for occupational safety and health*, 2023c. https://healthy-workplaces.osha.europa.eu/en/publications/surveillance-and-monitoring-remote-workers-implications-occupational-safety-and-health-0

Fang, W., Chen, L., Zhang, T., Chen, C., Teng, Z., & Wang, L. (2023). Head-mounted display augmented reality in manufacturing: A systematic review. *Robotics and Computer-Integrated Manufacturing, 83*, Article 102567.

Farshid, M., Paschen, J., Eriksson, T., & Kietzmann, J. (2018). Go boldly!: Explore augmented reality (AR), virtual reality (VR), and mixed reality (MR) for business. *Business Horizons, 61*(5), 657-663.

Filho, J., Freitas, C. M., & Nedel, L. P. (2018). VirtualDesk: A comfortable and efficient immersive information visualization approach. *Computer Graphics Forum, 37*(3), 415-426.

Filho, J., Freitas, C. M., & Nedel, L. (2019a). Comfortable immersive analytics with the virtualdesk metaphor. *IEEE computer graphics and applications*, *39*(3), 41-53.

Filho, J., Stuerzlinger, W., & Nedel, L. P. (2019b). Evaluating an immersive space-time cube geovisualization for intuitive trajectory data exploration. *IEEE Transactions on Visualization and Computer Graphics, 26*(1), 514-524.

Flavián, C., Ibáñez-Sánchez, S., & Orús, C. (2019). The impact of virtual, augmented and mixed reality technologies on the customer experience. *Journal of Business Research, 100*, 547-560. https://doi.org/10.1016/j.jbusres.2018.10.050

Ford, P. J. (2001). A further analysis of the ethics of representation in virtual reality: Multi-user environments. *Ethics and Information Technology, 3*(2), 113-121.

Foster, P., & Burton, A. (2004). Virtual reality in improving mining ergonomics. *Journal of The South African Institute of Mining and Metallurgy, 104*(2), 129-133.

Fuchs, P. (2017). *Virtual reality headsets – A theoretical and pragmatic approach.* CRC Press.

Gallagher, M., & Ferrè, E. R. (2018). Cybersickness: A multisensory integration perspective. *Multisensory Research, 31*(7), 645-674.

Garrido, L. E., Frías-Hiciano, M., Moreno-Jiménez, M. D., Cruz, G. N., García-Batista, Z. E., Guerra-Peña, K., & Medrano, L. A. (2021). Focusing on cybersickness: Pervasiveness, latent trajectories, susceptibility, and effects on the virtual reality experience. *Virtual Reality, 26*(4), 1347-1371.

Geiger, A., Bewersdorf, I., Brandenburg, E., & Stark, R. (2018). Visual feedback for grasping in virtual reality environments for an interface to instruct digital human models. In T. Ahram, & C. Falcão (Eds), *Advances in usability and user experience*: *Proceedings of the AHFE 2017 International Conference on Usability and User Experience* (pp. 228-239). Springer International Publishing. https://doi.org/10.1007/978-3-319-60492-3_22

Gooskens, G. (2010). The ethical status of virtual actions. *Ethical Perspectives, 17*(1), 59-78.

GOV.UK. (2020) *The safety of domestic virtual reality systems: A literature review*. BEIS Research Paper 2020/038, Department for Business, Energy & Industrial Strategy. https://assets.publishing.service.gov.uk/media/5f763502d3bf7f7c2bcf9eb9/safety-domestic-vr-systems.pdf

Grassini, A., & Jankowski, J. (2015). Virtual reality-based pilot training for underground coal miners. *Safety Science, 72*, 310-314.

Grassini, S., & Laumann, K. (2020a). Are modern head-mounted displays sexist? A systematic review on gender differences in HMD-mediated virtual reality. *Frontiers in Psychology, 11*, 545946.

Grassini, S., & Laumann, K. (2020b). Evaluating the use of virtual reality in work safety: A literature review. In P. Baraldi, F. Di Maio, & E. Zio (Eds), *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference* (pp. 4964-4971). Research Publishing, Singapore.

Grassini, S., & Laumann, K. (2021). Immersive visual technologies and human health. In *Proceedings of the 32nd European Conference on Cognitive Ergonomics* (Article 6). Association for Computing Machinery.

Grassini, S., Laumann, K., & Luzi, A.K. (2020). Association of individual factors with simulator sickness and sense of presence in virtual reality mediated by head-mounted displays (HMDs). *Multimodal Technologies and Interaction, 5*(3), Article 7.

Grassini, S., Laumann, K., de Martin Topranin, V., & Thorp, S. (2021). Evaluating the effect of multi-sensory stimulations on simulator sickness and sense of presence during HMD-mediated VR experience. *Ergonomics, 64*(12), 1532-1542.

Greenwald, W. (2023, October 30). *Meta Quest 3 vs. Meta Quest 2: What's different and which VR headset is better?* PCMag. https://uk.pcmag.com/comparison/149395/meta-quest-3-vs-meta-quest-2-whats-different-and-which-vr-headset-is-better

Guo, Z., Zhou, D., Zhou, Q., Zhang, X., Geng, J., Zeng, S., Lv, C., & Hao, A. (2020). Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review. *Journal of Manufacturing Systems*, 56, 525-538.

Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers, 3*, 275-285.

Hamad, A., & Jia, B. (2022). How virtual reality technology has changed our lives: An overview of the current and potential applications and limitations. *International Journal of Environmental Research and Public Health, 19*(18), Article 11278.

Hampton, K.N., Sessions, L.F., Her, E.J., & Rainie, L. (2009). Social isolation and new technology. Retrieved the 20.5.2024 from: https://www.site.uottawa.ca/~stan/csi2911/Pew.pdf

Heo, J., Kim, K., Fava, M., Mischoulon, D., Papakostas, G. I., Kim, M., Kim, D. J., Chang, K. J., Oh, Y., Yu, B. H., & Jeon, H. J. (2017). Effects of smartphone use with and without blue light at night in healthy adults: A randomized, double-blind, cross-over, placebo-controlled comparison. *Journal of Psychiatric Research, 87*, 61-70.

Hess, R. F., To, L., Zhou, J., Wang, G., & Cooperstock, J. R. (2015). Stereo vision: the haves and have-nots. *i-Perception*, *6*(3), 2041669515593028.

Hew, K. F., & Cheung, W. S. (2010). Use of three-dimensional (3-D) immersive virtual worlds in K-12 and higher education settings: A review of the research. *British Journal of Educational Technology, 41*(1)*, 33-55.*

Hibbard, P. B., van Dam, L. C., & Scarfe, P. (2020). The implications of interpupillary distance variability for virtual reality. In *2020 International Conference on 3D Immersion (IC3D)* (pp. 1-7). IEEE.

Hine, E., Neroni Rezende, I., Roberts, H., Wong, D., Taddeo, M., & Floridi, L. (2023). Safety and privacy in immersive extended reality: An analysis and policy recommendations. *SSRN Electronic Journal, 1*(1), 1-44. http://dx.doi.org/10.2139/ssrn.4585963

Hodges, L. F., & Davis, E. T. (1993). Geometric considerations for stereoscopic virtual environments. *Presence: Teleoperators & Virtual Environments, 2*(1), 34-43.

Hoyer, W. D., Kroschke, M., Schmitt, B. H., Kraume, K., & Shankar, V. (2020). Transforming the customer experience through new technologies. *Journal of Interactive Marketing, 51*(1), 57-71.

Hussain, Z., Khan, A., & Ali, A. (2023). The impact of user-generated content, social interactions and virtual economies on metaverse environments. *Journal of Sustainable Economics, 1*(2), 34-44.

Ito, K., Tada, M., Ujike, H., & Hyodo, K. (2021). Effects of the weight and balance of head-mounted displays on physical load. *Applied Sciences, 11*(15), Article 6802.

Jampeisov, Z. (2019). Using virtual reality technology in oil and gas industry. *International Journal of Engineering and Management Research, 9*(2), 124-127.

Johansson, M., & Roupé, M. (2024). Real-world applications of BIM and immersive VR in construction. *Automation in Construction, 158*, Article 105233.

Kaufeld, M., Mundt, M., Forst, S., & Hecht, H. (2022). Optical see-through augmented reality can induce severe motion sickness. *Displays, 74*, Article 102283.

Keller, B. N., Lonczynski, J. P., D'Angelo, T., & Delabrida, S. E. (2018). Evaluation of wearable devices for belt conveyor inspection using augmented reality. In *Proceedings of the 17th Brazilian Symposium on Human Factors in Computing Systems* (Article 23). Association for Computing Machinery.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology, 3*(3), 203-220.

Khan, B. (2023). *Emergence of technostress in multi-user VR environments for work-related purposes* [Master's thesis, Faculty of Management and Business, Tampere University]. Trepo. https://trepo.tuni.fi/handle/10024/151182

Kim, E., & Shin, G. (2018). Head rotation and muscle activity when conducting document editing tasks with a head-mounted display. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 62*(1), 952-955.

Kim, H., Kim, D. J., Chung, W., Park, K., Kim, J. D., Kim, D., Kim, K., & Jeon, H. J. (2021). Clinical predictors of cybersickness in virtual reality (VR) among highly stressed people. *Scientific Reports, 11*(1), Article 12139.

Kim, J., & Irizarry, J. (2020). Evaluating the use of augmented reality technology to improve construction management student's spatial skills. *International Journal of Construction Education and Research,* 17(2), 99-116.

Kim, J., & Renfroe, J. (2022). Construction workforce training assisted with augmented reality. In *2022 8th International Conference of the Immersive Learning Research Network (iLRN)* (pp. 1-6). IEEE.

Kim, J., Kim, S., & So, G. (2016). The modeling of color fatigue in 3-dimensional stereoscopic video. *International Journal of Computer Theory and Engineering, 8*(3), 229-234.

Kim, K., & Hwang, Y. (2017). The usefulness of augmenting reality on vehicle head-up display. In N. Stanton, S. Landry, G. Di Bucchianico, & A. Vallicelli (Eds), *Advances in human aspects of transportation: Proceedings of the AHFE 2016 International Conference on Human Factors in Transportation* (pp. 655-662). *Advances in Intelligent Systems and Computing*, 484. Springer.

Kim, Y. M., Rhiu, I., & Yun, M. H. (2020). A systematic review of a virtual reality system from the perspective of user experience. *International Journal of Human–Computer Interaction, 36*(10), 893-910.

Kim, Y. Y., Kim, H. J., Kim, E. N., Ko, H. D., & Kim, H. T. (2005). Characteristic changes in the physiological components of cybersickness. *Psychophysiology, 42*(5), 616-625.

Kiziroglou, M. E., Boyle, D. E., Yeatman, E. M., & Cilliers, J. J. (2017). Opportunities for sensing systems in mining. *IEEE Transactions on Industrial Informatics, 13*(1), 278-286.

Klier, C., & Buratto, L. G. (2020). Stress and long-term memory retrieval: A systematic review. *Trends in Psychiatry and Psychotherapy, 42*(3), 284-291.

Konstantinidis, F. K., Kansizoglou, I., Santavas, N., Mouroutsos, S. G., & Gasteratos, A. (2020). MARMA: A Mobile Augmented Reality Maintenance Assistant for fast-track repair procedures in the context of Industry 4.0. *Machines, 8*(4), Article 88.

Koohestani, A., Nahavandi, D., Asadi, H., Kebria, P. M., Khosravi, A., Alizadehsani, R., & Nahavandi, S. (2019). A knowledge discovery in motion sickness: A comprehensive literature review. *IEEE Access, 7*, 85755-85770.

Koteleva, N., Buslaev, G., Valnev, V., & Kunshin, A. (2020). Augmented reality system and maintenance of oil pumps. *International Journal of Engineering, 33*(8), 1620-1628.

Koteleva, N., Valnev, V., & Frenkel, I. (2021). Investigation of the effectiveness of an augmented reality and a dynamic simulation system collaboration in oil pump maintenance. *Applied Sciences, 12*(1), Article 350.

Kourtesis, P., Collina, S., Doumas, L. A., & MacPherson, S. E. (2019). Validation of the virtual reality neuroscience questionnaire: Maximum duration of immersive virtual reality sessions without the presence of pertinent adverse symptomatology. *Frontiers in Human Neuroscience, 13*, Article 417.

Kweon, S. H., Kweon, H. J., Kim, S. J., Li, X., Liu, X., & Kweon, H. L. (2017). A brain wave research on VR (virtual reality) usage: Comparison between VR and 2D video in EEG measurement. In *Advances in Human Factors and Systems Interaction: Proceedings of the AHFE 2017 International Conference on Human Factors and Systems Interaction* (pp. 194-203). Springer International Publishing.

Laato, S., Xi, N., Spors, V., Thibault, M., & Hamari, J. (2024). Making sense of reality: A mapping of terminology related to virtual reality, augmented reality, mixed reality, XR and the metaverse. In *Proceedings of the 57th Hawaii International Conference on System Sciences* (pp. 6625-6634).

Lambooij, M. M., IJsselsteijn, W. W., Fortuin, M. M., & Heynderickx, I. I. (2009). Visual discomfort and visual fatigue of stereoscopic displays: A review. *Journal of Imaging Science and Technology, 53*, 1-14.

Lang, B. (2017, April 6). *New HTC vives weigh 15% less than they did at launch.* Road to VR. https://www.roadtovr.com/htc-vive-weight-15-percent-lighter-than-original-headset-vs-oculus-rift-comparison

Lawrenson, J. G., Hull, C. C., & Downie, L. E. (2017). The effect of blue-light blocking spectacle lenses on visual performance, macular health and the sleep-wake cycle: A systematic review of the literature. *Ophthalmic and Physiological Optics, 37*, 644-654.

LeBlanc, V. R. (2009). The effects of acute stress on performance: implications for health professions education. *Academic Medicine*, *84*(10), S25-S33.

Leppink, J. (2017). Cognitive load theory: Practical implications and an important challenge. *Journal of Taibah University Medical Sciences, 12*(5), 385-391.

Li, G., Rempel, D. M., Liu, Y., & Harris-Adamson, C. (2020). The design and assignment of microgestures to commands for virtual and augmented reality tasks.*Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 64*(1), 2061-2063.

Luger, T., Bosch, T., Veeger, D., & de Looze, M. (2014). The influence of task variation on manifestation of fatigue is ambiguous – A literature review. *Ergonomics, 57*(2), 162-174.

Lukosch, S., Billinghurst, M., Alem, L., & Kiyokawa, K. (2015). Collaboration in augmented reality. *Computer Supported Cooperative Work, 24*, 515-525.

Luo, N., Wang, X., Van, F., Ye, Z. C., & Qian, F. (2015). Integrated simulation platform of chemical processes based on virtual reality and dynamic model. *Computer Aided Chemical Engineering, 37*, 581-586.

Mahapatra, M., & Pillai, R. (2018). Technostress in organizations: A review of literature. *Research Papers*, *99.*

Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction, 60,* 225-236. https://doi.org/10.1016/j.learninstruc.2017.12.007

Manjrekar, S., Sandilya, S., Bhosale, D., Kanchi, S., Pitkar, A., & Gondhalekar, M. (2014). CAVE: An emerging immersive technology--A review. In *2014 UKsim-AMSS 16th International Conference on Computer Modelling and Simulation* (pp. 131-136). IEEE.

Marklin, R. W., Toll, A. M., Bauman, E., Simmins, J. J., Ladisa, J. F., & Cooper, R. (2020). Do head-mounted augmented reality devices affect muscle activity and eye strain of utility workers who do procedural work? Studies of operators and manhole workers. *Human Factors, 64*(2), 305-323.

Marzoli, F., Bortolami, A., Pezzuto, A., Mazzetto, E., Piro, R., Terregino, C., Bonfante, F, & Belluco, S. (2021). A systematic review of human coronaviruses survival on environmental surfaces. *Science of The Total Environment, 778*, Article 146191.

Merbah, J., Gorce, P., & Jacquier-Bret, J. (2020). Effects of environmental illumination and screen brightness settings on upper limb and axial skeleton parameters: How do users adapt postures? *Ergonomics, 63*(12), 1561-1570.

Mittelstädt, J. M., Wacker, J., & Stelling, D. (2018). VR aftereffect and the relation of cybersickness and cognitive performance. *Virtual Reality, 23*, 143-154.

Monteiro, P., Gonçalves, G., Coelho, H., Melo, M., & Bessa, M. (2021). Hands-free interaction in immersive virtual reality: A systematic review. *IEEE Transactions on Visualization and Computer Graphics, 27*(5), 2702-2713.

Moore, N., Dempsey, K., Hockey, P., Jain, S., Poronnik, P., Shaban, R. Z., & Ahmadpour, N. (2021). Innovation during a pandemic: Developing a guideline for infection prevention and control to support education through virtual reality. *Frontiers in Digital Health, 3,* Article 628452.

Mourtzis, D., Zogopoulos, V., Katagis, I., & Lagios, P. (2018). Augmented reality based visualization of CAM instructions towards Industry 4.0 paradigm: A CNC bending machine case study. *Procedia CIRP, 70*, 368-373.

Mullen, G., & Davidenko, N. (2021). Time compression in VR. *Timing & Time Perception, 9*(4), 377-392.

Németh, J., Tapasztó, B., Aclimandos, W., Kestelyn, P. G., Jonas, J. B., de Faber, J. T., Janulevičienė, I., Grzybowski, A., Nagy, Z. Z., Pärssinen, O., Guggenheim, J. A., Allen, P. M., Baraas, R. C., Saunders, K. J., Flitcroft, D. I., Gray, L. S., Polling, J. R., Haarman, A. E. … Resnikoff, S. (2021). Update and guidance on management of myopia. European Society of Ophthalmology in cooperation with International Myopia Institute. *European Journal of Ophthalmology, 31*, 853-883.

Nichols, S. (1999). Physical ergonomics of virtual environment use. *Applied Ergonomics, 30*(1), 79-90.

O'Brolcháin, F., Jacquemard, T., Monaghan, D. S., O'Connor, N. E., Novitzky, P., & Gordijn, B. (2015). The convergence of virtual reality and social networks: Threats to privacy and autonomy. *Science and Engineering Ethics, 22*, 1-29.

Oh, H., & Son, W. (2022). Cybersickness and its severity arising from virtual reality content: A comprehensive study. *Sensors (Basel, Switzerland), 22*(4), Article 1314.

Orru, G., & Longo, L. (2018). The evolution of cognitive load theory and the measurement of its intrinsic, extraneous and germane loads: A review. In *Human Mental Workload: Models and Applications: Second International Symposium, H-WORKLOAD 2018, Revised Selected Papers 2* (pp. 23-48). Springer International Publishing.

OSHA.gov (2019, June 20). *Preventing fire and/or explosion injury from small and wearable lithium battery powered devices* [Safety and Health Information Bulletin]. https://www.osha.gov/sites/default/files/publications/shib011819.pdf

Owens, M. E., & Beidel, D. C. (2015). Can virtual reality effectively elicit distress associated with social anxiety disorder? *Journal of Psychopathology and Behavioral Assessment, 37*, 296-305.

Palmarini, R., Erkoyuncu, J. A., Roy, R., & Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing, 49*, 215-228.

Parker, A. J. (2016). Vision in our three-dimensional world. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1697), Article 20150251.

Patterson, R. E. (2015). Basics of human binocular vision. In R. E. Patterson (Ed.), *Human factors of stereoscopic 3D displays* (pp. 9-21). Springer. https://doi.org/10.1007/978-1-4471-6651-1_2

Paul, G., & Briceno, L. (2021). A conceptual framework of DHM enablers for ergonomics 4.0. In *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021) Volume V: Methods & Approaches 21* (pp. 403-406). Springer International Publishing.

Peña, J., Craig, M., & Baumhardt, H. (2022). The effects of avatar customization and virtual human mind perception: A test using Milgram's paradigm. *New Media & Society*, *0*(0). https://doi.org/10.1177/14614448221127258

Porta, C. M., Frerich, E. A., Hoffman, S., Bauer, S., Jain, V. M., & Bradley, C. (2024). Sexual violence in virtual reality: A scoping review. *Journal of Forensic Nursing, 20*(1), 66-77.

Ramadan, M. Z., & Alhaag, M. H. (2018). Evaluating the user physical stresses associated with watching 3D and 2D displays over extended time using heart rate variability, galvanic skin resistance, and performance measure. *Journal of Sensors, 2018*, Article 2632157.

Rauschnabel, P. A., Felix, R., Hinsch, C., Shahab, H., & Alt, F. (2022). What is XR? Towards a framework for augmented and virtual reality. *Computers in Hhuman Behavior, 133*, Article 107289.

Rauschnabel, P. A., He, J., & Ro, Y. K. (2018). Antecedents to the adoption of augmented reality smart glasses: A closer look at privacy risks. *Journal of Business Research, 92*, 374-384.

Reason, J. T., & Brand, J. J. (1975). *Motion sickness.* Academic Press.

Rivera, M. L., Mora-Serrano, J., & Oñate, E. (2024). A critical review of how EXtended Reality (XR) has addressed key factors influencing safety on construction projects (fSCPs). *Archives of Computational Methods in Engineering, 31*, 2015-2048.

Roberts, S. C., Havill, N. L., Flores, R. M., Hendrix II, C. A., Williams, M. J., Feinn, R. S. ... Murray, T. S. (2022). Disinfection of virtual reality devices in health care settings: In vitro assessment and survey study. *Journal of Medical Internet Research, 24*(12), Article e42332.

Sabelman, E., & Lam, R. (2015). The real-life dangers of augmented reality. *IEEE Spectrum, 52*(7), 48-53.

Saghafian, M., Sitompul, T. A., Laumann, K., Sundnes, K., & Lindell, R. (2021). Application of human factors in the development process of immersive visual technologies: Challenges and future improvements. *Frontiers in Psychology, 12*, Article 634352.

Salinas, D., Munoz-La Rivera, F., & Mora-Serrano, J. (2022). Critical analysis of the evaluation methods of extended reality (XR) experiences for construction safety. *International Journal of Environmental Research and Public Health, 19*(22), Article 15272.

Santos, I. H., Soares, L. P., Carvalho, F. G., & Raposo, A. B. (2012). A collaborative virtual reality oil and gas workflow. *International Journal of Virtual Reality, 11*(1), 1-13.

Schober, M. (2017, April 13). Will VR and AR make us feel lonely and isolated? The hidden danger of VR and AR technology. Retrieved the 20.5.2024 from https://medium.com/@mariusschober/will-vr-and-ar-make-us-feel-lonely-and-isolated-33c4790b5d56

Schubert, R. S., Hartwig, J., Müller, M., Groh, R., & Pannasch, S. (2016). Are age differences missing in relative and absolute distance perception of stereoscopically presented virtual objects? In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology* (pp. 307-308). Association for Computing Machinery.

Sharma, R. C., & Zamfiroiu, A. (2023). Cybersecurity threats and vulnerabilities in the metaverse. In *2023 International Conference on Intelligent Metaverse Technologies & Applications (iMETA)* (pp. 1-7). IEEE.

Shen, R., Weng, D., Guo, J., Fang, H., & Jiang, H. (2019). Effects of dynamic disparity on visual fatigue caused by watching 2D videos in HMDs. In *Image and Graphics Technologies and Applications: 14th Conference on Image and Graphics Technologies and Applications, Revised Selected Papers 14* (pp. 310-321). Springer Singapore. https://doi.org/10.1007/978-981-13-9917-6_30

Shields, G. S., Sazma, M. A., & Yonelinas, A. P. (2016). The effects of acute stress on core executive functions: A meta-analysis and comparison with cortisol. *Neuroscience & Biobehavioral Reviews, 68*, 651-668.

Skarbez, R., Smith, M., & Whitton, M. C. (2021). Revisiting Milgram and Kishino's reality-virtuality continuum. *Frontiers in Virtual Reality*, *2*, 647997.

Smaili, N., & de Rancourt-Raymond, A. (2022). Metaverse: Welcome to the new fraud marketplace. *Journal of Financial Crime, 31*(1), 188-200.

Souchet, A. D., Lourdeaux, D., & Hancock, P. A. (2023a). Design guidelines for limiting and eliminating virtual reality-induced symptoms and effects at work: A comprehensive, factor-oriented review. *Frontiers in Psychology, 14*, Article 1161932.

Souchet, A. D., Lourdeaux, D., Pagani, A., & Rebenitsch, L. (2023b). A narrative review of immersive virtual reality's ergonomics and risks at the workplace: Cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload. *Virtual Reality, 27*(1), 19-50.

Speicher, M., Feit, A. M., Ziegler, P., & Krüger, A. (2018). Selection-based text entry in virtual reality. In *Proceedings of the 2018 CHI conference on human factors in computing systems* (pp. 1-13).

Spiegel, J. S. (2017). The ethics of virtual reality technology: Social hazards and public policy recommendations. *Science and Engineering Ethics, 24*, 1537-1550.

Stanney, K. M., Lawson, B. D., & Oman, C. M. (Eds) (2021). Cybersickness in virtual reality versus augmented reality. *Frontiers Media*. https://doi.org/10.3389/978-2-88971-812-2

Stanney, K. M., Lawson, B. D., Rokers, B., Dennison, M. S., Fidopiastis, C. M., Stoffregen, T. A., Weech, S., & Fulvio, J. M. (2020). Identifying causes of and solutions for cybersickness in immersive technology: Reformulation of a research and development agenda. *International Journal of Human–Computer Interaction, 36*(19), 1783-1803.

Stauffert, J., Niebling, F., & Latoschik, M.E. (2020). Latency and cybersickness: Impact, causes, and measures. A review. *Frontiers in Virtual Reality, 1*, Article 582204.

Stephenson, N. (1992). *Snow crash*. Bantam Books.

Stoffregen, T. A., & Smart, L. J. (1998). Postural instability precedes motion sickness. *Brain Research Bulletin, 47*(5), 437-448.

Strzałkowski, P., Bęś, P., Szóstak, M., & Napiórkowski, M. (2024). Application of virtual reality (VR) technology in mining and civil engineering. *Sustainability, 16*(6), Article 2239.

Tähkämö, L., Partonen, T., & Pesonen, A. K. (2019). Systematic review of light exposure impact on human circadian rhythm. *Chronobiology international*, *36*(2), 151-170.

Takac, M., Collett, J., Blom, K. J., Conduit, R., Rehm, I. C., & De Foe, A. (2019). Public speaking anxiety decreases within repeated virtual reality training sessions. *PLoS ONE, 14*(5), Article e0216288.

Tan, D. S., Gergle, D., Scupelli, P., & Pausch, R. (2003). With similar visual angles, larger displays improve spatial performance. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 217-224). Association for Computing Machinery.

Tarafdar, M., Cooper, C. L., & Stich, J. F. (2019). The technostress trifecta-techno eustress, techno distress and design: Theoretical directions and an agenda for research. *Information Systems Journal, 29*(1), 6-42.

Tatic, D., & Tesic, B. (2015). Improvement of occupational safety systems by the application of augmented reality technologies. In *2015 23rd Telecommunications Forum Telfor (TELFOR)* (pp. 962-965). IEEE.

The Area. (2024a). *AR safety risks in industry*. https://thearea.org/wp-content/uploads/2018/10/AREA-Safety-Infographic.pdf

The Area. (2024b). *Augmented reality for enterprise alliance.* https://thearea.org/

Thorp, S., Sævild Ree, A., & Grassini, S. (2022). Temporal development of sense of presence and cybersickness during an immersive VR experience. *Multimodal Technologies and Interaction, 6(5),* Article 31.

Tian, F., Zhang, Y., & Li, Y. (2021). From 2D to VR film: A research on the load of different cutting rates based on EEG data processing. *Information, 12*(3), Article 130. https://doi.org/10.3390/info12030130

Tian, N., Lopes, P., & Boulic, R. (2022). A review of cybersickness in head-mounted displays: Raising attention to individual susceptibility. *Virtual Reality, 26(4), 1409-1441.*

Truly, A. (2023, January 12). *HTC Vive XR Elite vs. Meta Quest Pro: Mixed-reality showdown*. Digital Trends. https://www.digitaltrends.com/computing/htc-vive-xr-elite-vs-meta-quest-pro/

Turnbull, P. R., & Phillips, J. R. (2017). Ocular effects of virtual reality headset wear in young adults. *Scientific Reports, 7*(1), Article 16172.

Tychsen, L., & Thio, L. L. (2020). Concern of photosensitive seizures evoked by 3D video displays or virtual reality headsets in children: Current perspective. *Eye and Brain, 12*, 45-48.

Upadhyay, U., Kumar, A., Sharma, G., Gupta, B. B., Alhalabi, W., Arya, V., & Chui, K. T. (2023). Cyberbullying in the metaverse: A prescriptive perception on global information systems for user protection. *Journal of Global Information Management*, *31*(1), 1-25.

Urey, H., Chellappan, K. V., Erden, E., & Surman, P. (2011). State of the art in stereoscopic and autostereoscopic displays *Proceedings of the IEEE, 99*, 540-555.

van Acker, B. B., Parmentier, D. D., Vlerick, P., & Saldien, J. (2018). Understanding mental workload: From a clarifying concept analysis toward an implementable framework. *Cognition, Technology & Work, 20,* 351-365. https://doi.org/10.1007/s10111-018-0481-3

van Lopik, K. V., Sinclair, M. A., Sharpe, R., Conway, P. P., & West, A. A. (2020). Developing augmented reality capabilities for industry 4.0 small enterprises: Lessons learnt from a content authoring case study. *Computers in Industry, 117*, Article 103208.

van Tulder, M., Malmivaara, A., & Koes, B. (2007). Repetitive strain injury. *The Lancet*, *369*(9575), 1815-1822. https://doi.org/10.1016/S0140-6736(07)60820-4

Vi, S., Silva, T. S., & Maurer, F. (2019). User experience guidelines for designing HMD extended reality applications. In *Human-Computer Interaction–INTERACT 2019: 17th IFIP TC13 International Conference, Proceedings, Part IV 17* (pp. 319-341). Springer International Publishing.

Vladimir, K., Staša, P., Beneš, F. (2014). The potential of automatic identification and augmented reality in mining. In *Mine Planning and Equipment Selection: Proceedings of the 22nd MPES Conference* (pp. 1205-1213). Springer International Publishing.

Vovk, A., Wild, F., Guest, W., & Kuula, T. (2018). Simulator sickness in augmented reality training using the Microsoft HoloLens. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (pp. 1-9). Association for Computing Machinery.

Wang, Y., Tian, Y., Wang, J., Cao, Y., Li, S., & Tian, B. (2022). Integrated inspection of QoM, QoP, and QoS for AOI industries in metaverses. *IEEE/CAA Journal of Automatica Sinica, 9*(12), 2071-2078.

Wang, Y., Wu, Y., Chen, C., Wu, B., Ma, S., Wang, D., Li, H., & Yang, Z. (2021). Inattentional blindness in augmented reality head-up display-assisted driving. *International Journal of Human–Computer Interaction, 38*(9), 837-850.

Warner, N., & Teo, J. T. (2021). Neurological injury from virtual reality mishap. *BMJ Case Reports CP, 14*, Article e243424.

Whyte, J. K., Bouchlaghem, N. B., Thorpe, A., & Mccaffer, R. (2000). From CAD to virtual reality: Modelling approaches, data exchange and interactive 3D building design tools. *Automation in Construction, 10*(1), 43-55.

Widyanti, A., & Hafizhah, H. N. (2021). The influence of personality, sound, and content difficulty on virtual reality sickness. *Virtual Reality, 26*(2), 631-637.

Wiederhold, B. K. (2022). Sexual Harassment in the Metaverse. *Cyberpsychology, Behavior, and Social Networking, 25(8),* 479-480.

Wismer, A., Reinerman-Jones, L., Teo, G., Willis, S., McCracken, K., & Hackett, M. (2018). A workload comparison during anatomical training with a physical or virtual model. In *Augmented Cognition: Users and Contexts: 12th International Conference, AC 2018, Proceedings, Part II* (pp. 240-252). Springer International Publishing. https://doi.org/10.1007/978-3-319-91467-1_20

Yan, Y., Chen, K., Xie, Y., Yiming, S., & Yonghong, L. (2018). The effects of weight on comfort of virtual reality devices. In *Advances in Ergonomics in Design: Proceedings of the AHFE 2018 International Conference on Ergonomics in Design* (pp. 239-248). Springer International Publishing.

Zhang, H. (2017). Head-mounted display-based intuitive virtual reality training system for the mining industry. *International Journal of Mining Science and Technology, 27*(4), 717-722.

Zhang, L., Wade, J. W., Bian, D., Fan, J., Swanson, A. R., Weitlauf, A. S., Warren, Z., & Sarkar, N. (2017). Cognitive load measurement in a virtual reality-based driving system for autism intervention. *IEEE Transactions on Affective Computing, 8*(2), 176-189.

Zhao, X., Zhang, M., Fan, X., Sun, Z., Li, M., Li, W., & Huang, L. (2023). Extended reality for safe and effective construction management: State-of-the-art, challenges, and future directions. *Buildings, 13*(1), Article 155.

Zhu, Y., Wang, X., & Qi, X. (2023). VR immersive social user interaction under metaverse. In *Second International Conference on Electronic Information Engineering, Big Data, and Computer Technology (EIBDCT 2023)* (Vol. 12642, pp. 770-774). SPIE.

Zhu, Y., Wang, X., & Qi, X. (2023, May). VR immersive social user interaction under metaverse. In *Second International Conference on Electronic Information Engineering, Big Data, and Computer Technology (EIBDCT 2023)* (Vol. 12642, pp. 770-774). SPIE.

Zielasko, D., & Riecke, B. E. (2020). Sitting vs. standing in VR: Towards a systematic classification of challenges and (dis)advantages. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 297-298). IEEE. https://doi.org/10.1109/VRW50115.2020.00067

Ziker, C., Truman, B., & Dodds, H. (2021). Cross reality (XR): Challenges and opportunities across the spectrum. In J. Ryoo, & K. Winkelmann (Eds), *Innovative learning environments in STEM higher education. Opportunities, challenges, and looking forward* (pp. 55-77). Springer.

Annex: Methodology of the study

Literature review

Selection criteria for papers

To investigate the effects of virtual reality (VR), augmented reality (AR), and the metaverse in occupational safety and health (OSH), specific inclusion and exclusion criteria were defined prior to the beginning of the literature selection process.

Inclusion criteria

- **Time frame**. Publications from 2016 to September 2023. This period is selected based on the significant developments in VR and AR technologies, particularly after the release of the first Oculus in 2016. However, articles published before 2016 were included from additional searches, previous knowledge of the article author, or from the backward snowballing method applied from the primary search. Due to the rapidly evolving field, articles published between September 2023 and February 2024 were also included when relevant during the revision phase of the article if encountered by the article author.
- **Language and accessibility**. Articles must be written in English and be accessible for review.
- **Publication type**. Peer-reviewed articles or grey literature.
- **Content relevance**. Articles must explicitly mention VR, AR (or also MR and XR, as these are commonly used terminologies), or metaverse technologies, focusing on their implications in ergonomics, safety, health (including mental health) and the workplace environment.
- **Keywords**. Papers should mention specific keywords (detailed below) related to OSH concerns in the context of these technologies.

Exclusion criteria

- **Language limitations**. Non-English papers or those containing sections in other languages.
- **Availability**. Incomplete or inaccessible articles.
- **Content irrelevance**. Papers not addressing the specified keywords or OSH concerns related to VR, AR, MR, XR and the metaverse in workplace contexts.
- **Specialised populations**. Studies involving clinical populations or non-workplace-related technology usage. Some exceptions were made if the articles described risks and factors related indirectly to OSH.

Keywords for initial paper selection

The search incorporated a range of keywords, including terms: ‘cybersickness’ or ‘simulator sickness’, ‘nausea’, ‘dizziness’, ‘visual fatigue’, ‘muscle fatigue’, ‘ergonomic risks’, ‘musculoskeletal disorders’, ‘stress’, ‘anxiety’, ‘work intensity’ or ‘intensification’, ‘mental workload’ or ‘cognitive load’, ‘lone work’ or ‘isolation’, ‘autonomy’ or ‘job control’, ‘trust’, ‘worker privacy’ or ‘data privacy’, ‘transparency’, ‘accident’, ‘falls’, ‘trips and slips’, ‘collision’, ‘occupational health’ or ‘workplace safety’ or ‘work-related disorder’ or ‘work-related disease’ or ‘work-related accident’, ‘occupational risks’ and ‘occupational hazards’, ‘OSH risks’ and ‘OSH hazards’, ‘work risks’ and ‘hazards’, ‘mental health’, and the terms: ‘work’, ‘virtual reality’, ‘augmented reality’, ‘mixed reality’, ‘extended reality’, or ‘metaverse’.

Furthermore, for each of the industrial uses for which the article focused on, further separate research was done using the keywords: (‘chemical sector’ OR ‘construction’ OR ‘healthcare’ OR ‘manufacturing’ OR ‘military’ OR ‘mining’ OR ‘oil’ OR ‘gas’) AND ‘VR’ OR ‘AR’ OR ‘metaverse’.

The research was conducted using Scopus, Web of Science, ACM digital library, IEEE xplore and Google Scholar, focusing on articles dealing with workplace contexts and reporting these keywords in the titles, abstracts and keywords.

A backward snowball method was used for identifying additional relevant literature, beginning from the initially identified sources. This was necessary especially for finding additional studies delving into the use and the criticalities of XR and metaverse technologies in specific sectors. Further articles were also added based on prior knowledge of the study author.

The study author selected the works that were determined to be more pertinent or relevant for the scope of the article.

Interviews

Overview

The study includes six interviews with a total of seven interviewees (within six interview sessions), encompassing a diverse range of perspectives related to XR in OSH (see Table 1). According to the agreed study data protection framework, the people interviewed first received a Privacy Statement informing them about the processing of their personal data.as part of the study. All information about the interviewees and as well as information collected during the interviews were kept anonymous. This was done anonymising the interview script after the recording and creating interview summaries/notes that reported the main information gathered from each of the interviews without details that may directly or indirectly disclose the people interviewed. Any reference to the interviews in the text is made in a fully anonymous way.

Participant demographics

- **Profiles**: OSH specialists in the XR sector, industry operators and supervisors with direct experience in XR, national and international safety experts, interest group representatives of XR technology, and industrial stakeholders (see Table A 1).

Interview structure

- **Format**: Semi-structured interviews, incorporating both qualitative and quantitative elements.
- **Data analysis strategy. Content analysis,** in which the answers were analysed to extract common themes and insights.
- **Adaptation**. The interview script is tailored to suit the diverse contexts and expertise of the interviewees. The interview script was developed to be easily adaptable to various contexts and to be tailored to the answers received from the people interviewed. The people interviewed often preferred to talk freely about their direct experience or their expertise.
- **Narrative reporting**. Findings from the interviews are reported in a narrative way within article, including reference to specific facts narrated by the interviewed when fitting the scope of the article or reported generally.

Table A 1 below features the interview number, as referred to in the main article, and a short description of the role and expertise of the people interviewed.

Table A 1: Interview number and interviewees' description

Interview number	Role and expertise of the interviewee
1	Expert and consultant in the field of OSH and XR/metaverse technologies.
2	Coordinator of an organisation dedicated to promoting the integration of Augmented Reality technology within the business sector.
3	Senior advisor for business and industry, with expertise on safety and inclusivity.
4	Head of the health and safety unity for an industry organisation (national level). Direct experience with training operations using XR.
5	Senior advisor at national unit of the authority for labour inspection.
6	Technical expert of safety operation in a company developing XR solutions.
7	Operators' supervisor and first-hand user of XR technologies in the context of high-risk industries.

Author**:** Simone Grassini, Associate Professor, Department of Psychosocial Science, University of Bergen, Cognitive and Behavioral Neuroscience Lab, University of Stavanger (Norway).

Project Management: Emmanuelle Brun and Maurizio Curtarrelli - European Agency for Safety and Health at Work (EU-OSHA).