Advances in Reliability, Safety and Security, Part 5 – Kołowrocki, Kosmowski (eds.)
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Advances in Reliability, Safety and Security
ESREL 2024
Monograph Book Series

Uses And Risks Of Augmented Reality In Occupational Settings

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Abstract

The rapid advancement of extended reality (XR) technologies like augmented reality (AR) is transforming digital interactions, particularly in occupational settings. This paper aims to enhance the scholarly discussion on AR's occupational applications and its associated risks, an area generally less examined than for other similar technologies. Our investigation examines various risks linked to AR use in work environments, encompassing health concerns, environmental perception challenges, ergonomic limitations, cognitive impacts, privacy issues, and socio-psychological effects. This study highlights the multifaceted implications of AR in professional settings and emphasizes the necessity of balancing technological advancements with user health and safety. The reported findings suggest that while AR offers significant benefits for work efficiency, safety, and modernization, its deployment must be carefully managed to mitigate potential negative effects on users and their environment. Within Occupational Safety and Health (OSH), these findings underline the importance of a user-centred technological implementation, that should aim at developing guidelines and best practices for AR implementation in the workplaces, focusing on minimizing health risks, ensuring ergonomic compatibility, and safeguarding mental well-being, thereby promoting safer and healthier workplaces.

Keywords: augmented reality, AR, uses, risks, hazards, dangers, ill effects

1. Introduction

The evolution of Extended Reality (XR) technologies has been a long technological journey, tracing its roots back to the mid-20th century with seminal innovations like Heilig's Sensorama and Sutherland's conceptual "Ultimate Display." Over the past decade, these technologies have undergone a remarkable transformation. Initially limited to niche sectors, XR technologies have now proliferated into both private and commercial realms. In the 21st century, we have witnessed XR's expansion across a diverse array of sectors, from gaming to several applications in the work environment. This past decade has been pivotal for the information technology landscape, witnessing transformative changes propelled by rapid technological development both in hardware and software. Such innovations have fundamentally reshaped the way users interact with both digital and physical realities (Rauschnabel et al., 2022). In response to these technological shifts, industry leaders have introduced an array of devices and concepts, thereby solidifying their foothold in this dynamic market. For instance, Microsoft has made significant inroads with its business-oriented Augmented Reality (AR) tool HoloLens (Rauschnabel, 2018). Meta has strategically entered the virtual-experiences domain through acquiring Oculus, a leading entity in Virtual Reality (VR). This move strategically aligns with Meta's ambition to blend VR with its social media platforms, thus creating a more immersive “metaverse” experience (Hoffman et al., 2014). Apple has been a pioneer in the promotion of AR as an innovation that will transform society. In 2017, Apple eased AR into mainstream use with the launch of ARKit. This technology has fostered a range of applications, from augmented guided tours to AR for vision impairment, showcasing Apple's commitment to leveraging AR for social and educational benefits (Loza Pacheco et al., 2019). Apple's role in developing user-friendly AR interfaces on devices like iPads has been instrumental in enhancing AR experiences, underscoring its impact across various sectors. Magic Leap's head-mounted display is developed with work-related applications in mind. Its successful incorporation into medical navigation systems (Frisk et al., 2022), demonstrates the precision and adaptability of such AR technologies for complex tasks. This strategic application underscores a growing trend: the emergence of immersive, task-specific AR solutions that are set to revolutionize industry-specific digital experiences. However, the rapid technological acceptance across various industries highlights a significant gap in research, especially regarding the potential risks and adverse outcomes related with the use of XR technologies. While initial studies have delved into issues like simulation sickness and cybersickness, there remains a need for a more comprehensive understanding of the risks involved, particularly as XR technologies become more embedded in both professional and personal environments. The increasing ubiquity of XR in daily life necessitates an expansion of current research efforts to ensure their safe and efficacious application across various domains. Notably, research has predominantly focused on Virtual Reality (VR), leaving AR relatively less scrutinized in terms of its risks and implications in the context of work-related applications. Understanding the potential impacts of AR technologies on the health of the users, privacy, and overall well-being is crucial for the scientific community dealing with immersive visual systems, as well as for Occupational Health and Safety (OSH) experts.

1.1. Terminology

The field of XR has been characterized by terminological confusion. It has been noted an inconsistent usage of these terms (Rauschnabel et al., 2022; Laato et al., 2024), and research has sometimes referred to these technologies within broader technological categories like "Digital Reality" (DR) (Haleem et al., 2022) and "Extended Reality" (XR) (Chuah, 2018). Some recent studies (Grassini and Laumann, 2021; Saghafian et al., 2021) have also grouped these technologies under the general terminology "Immersive Visual Technologies". Efforts to standardize these terminologies have been, and recently has been proposed the xReality framework (Rauschnabel et al., 2022). This model uses XR as a comprehensive terminology that combines AR and VR. It suggests using AR when the physical environment is integrated into the experience, and VR otherwise. This framework also accommodates shared experiences, including user interactions in digital spaces through AR or VR, recognizing varying sophistication levels in these experiences. In this article, we adopt the xReality framework definitions, using the term AR inclusively to cover technologies that blend the physical and digital worlds. In the present study, when referencing AR technologies, we encompass a variety of technological mediators including head-mounted displays (HMDs), smartphones, transparent screens, and others. Nonetheless, in this context, it is relevant to highlight that the predominant focus of our discussion of occupational risks concerns to AR technologies that include HMDs.

1.2. The present study

The present literature review aims to explore current applications of AR technologies in organizational settings. Additionally, it will examine the potential risks, adverse effects, as well as criticalities that may arise from the usage of these equipment in work-related environments. The objective of this research is to provide insights to potential users, developers, policymakers, and industry stakeholders about the possible dangers linked with AR technologies. Ultimately, the study intends to support the need for the creation of guidelines, policies, and best practices promoting an implementation of AR systems in occupational settings that is safe and accepted by the users. In doing so, it seeks to contribute to the sustainable growth of AR technologies, ensuring that their advantages are fully exploited while minimizing potential negative consequences.

2. Method

The process of selecting articles for review involved an assessment of their titles, abstracts, and keywords to determine their pertinence to the study's aims. An initial systematic approach was employed to select papers for the review, involving the use of keywords: "Adverse Effects," “Ill Effects,” “Risks," and terms related to the technology of interest: "Augmented Reality" and "Mixed Reality”. These keywords were used in the research engines of PubMed, Web of Science, IEEE Xplore, and ACM Digital Library to identify pertinent articles. For this study, the literature review process specifically excluded papers not written in English and those that did not incorporate the designated search keywords in their titles or abstracts. Additionally, any studies that did not align with the central focus on the ill effects, risks, or critical aspects of the technologies under investigation were omitted.

The literature search was extended through backward snowballing search method, to include further literature using the keywords “AR use” OR “AR usage” AND a keyword for each specific occupational sectors that were individuated as relevant in OSH. Moreover, the included literature involved in the review was progressively expanded, integrating the initial literature findings with other relevant articles and with the authors' existing knowledge on the topic. All the articles that were deemed fitting for the topic of investigation were included in the present study.

3. Results

Incorporating AR systems into various industry sectors has led to significant advancements, particularly in enhancing productivity, reliability, safety, and quality. The deployment of AR in OSH contexts is especially significant, particularly in sectors characterized by elevated OSH risks. This adoption of AR technologies spans across mobile and wearable platforms, underlining its versatility and widespread applicability (Martins et al., 2021; Wahana and Marfuah, 2021). The results section delineates the utilization of AR in specific industries, selected among those prevalently mentioned in scientific literature on XR technology adoptions and generally associated with substantial human hazards (Abdalla et al., 2017; Grassini and Laumann, 2021).

3.1. Uses of AR in work settings

Chemical: AR is being integrated in the chemical sector, improving efficiency, safety, and training. It's particularly useful in maintenance and emergency responses, providing field operators with real-time information, allowing for fast decision-making processes, and therefore reducing the risks of accidents, especially when integrated with digital twin technology (Buchner et al., 2022). In vocational training, AR fosters a learner-controlled, collaborative environment, meeting modern industry needs and supporting self-directed learning (Lester and Hofmann, 2020). Additionally, AR enhances the safety of the users, as well as the productivity in chemical plants (Nakai and Suzuki, 2016).

Construction: AR systems, in tandem with technologies as the Building Information Modelling (BIM) is adopted in the construction business for improving client interactions, process understanding, and potentially shortening project timelines. AR enhances project visualization and accuracy (Raziapov, 2022), improves spatial skills in construction education (Kim and Irizarry, 2020), and increases productivity in various construction aspects like training and safety (Adebowale and Agumba, 2022). Additionally, AR helps in reducing errors and improving quality in construction (Albahbah et al., 2021), and enhances on-site information retrieval and progress monitoring (Zollmann et al., 2014).

Education: AR is becoming increasingly used to improve traditional teaching and training methodologies, supporting and enhancing educational processes in various ways (Akçayır and Akçayır, 2017). AR helps reduce cognitive overload and diversify learning methods by adding rich media to real-world environments (Bower et al., 2014). In educational context, AR combined with game-based learning improves student motivation, knowledge transfer, and learning outcomes (Pellas et al., 2018). It also makes preschool education more engaging (Koca et al., 2019) and is effective in boosting student achievement and reducing cognitive load (Turan et al., 2018). In designing AR experiences, students show increased motivation and academic performance (Cabero-Almenara et al., 2019). AR is beneficial in teaching foreign languages to young learners (Redondo et al., 2019) and in subjects like natural sciences and engineering, enhancing learning experiences, motivation, and group cooperation (Alam et al., 2020; Osadchyi et al., 2021). Overall, AR technology has shown the potentials to be an effective medium effect on learning effectiveness across various educational disciplines (Malone et al., 2023).

Health Care Sector: AR is significantly transforming healthcare through innovations in medical practices and education, enhancing care quality. It introduces new methods for diagnosis, treatment, and patient education, revolutionizing healthcare delivery (Srivastava and Agnihotri, 2019). AR-based mobile applications offer scalable, cost-effective training frameworks, effectively simulating physiological symptoms for enhanced training (Leung et al., 2019). In surgeries, AR provides real-time patient data, improving surgical precision and safety (Singaram et al., 2022). It also aids in cardiac rehabilitation, introducing new methods for effective medical interventions (Ladkhedkar and Yadav, 2022). Additionally, AR offers immersive methods for surgical data interaction and can be used, for example, for planning complex surgeries (Desselle et al., 2020).

Manufacturing: In the Industry 4.0 era, AR assists small enterprises in training and repairs, simplifying content creation (van Lopik et al., 2020), as well as enhancing quality control in manufacturing with immersive, productivity-boosting interfaces (Ho et al., 2022). It digitalizes production lines, improves maintenance, and human-machine interactions (Gallala et al., 2019), and increases speed, accuracy, and economic efficiency in industrial systems (Ziaee and Hamedi, 2021). AR integration with Computerized Maintenance Management Systems (CMMS) is transforming manufacturing into smarter factories (Torres-Tinoco et al., 2019). Tools like MARMA help low-skilled operators with AR-guided maintenance (Konstantinidis et al., 2020), and AR in robotic manufacturing leads to cost-effective control systems (Caiza et al., 2020). Additionally, AR in

Computer-Aided Manufacturing (CAM) for processes like CNC bending improves efficiency and safety (Mourtzis et al., 2018). AR is widely integrated in the area of automotive industry, significantly speeding up shipment processes and offering insights for other sectors (Čujan et al., 2020). In aerospace manufacturing, AR enhances training, inspection, and productivity, aiding skill development and cost reduction (Frigo et al., 2016). In shipbuilding, AR facilitates the move towards Shipyards 4.0 by reforming design, manufacturing, and maintenance (Fraga-Lamas et al., 2018).

Military: AR is increasingly used in the military for various applications, enhancing tactical training and operational effectiveness. In training, AR merges virtual data with reality, providing soldiers with intuitive, interactive training that improves battlefield understanding (Mao and Chen, 2021). It also enhances human-machine interaction, displaying critical information about hidden enemy units, thereby improving situational awareness for pilots and ground forces (Curran et al., 2011). AR is explored for boosting situational awareness in command-and-control scenarios, applicable across various military functions and levels (Le Roux, 2011). The future envisioned integration of AR systems with artificial intelligence promises advanced possibilities in visual cognition and decision-making, particularly in applications like Aided Target Recognition-AiTR (Larkin et al., 2020).

Mining and Extraction: AR enhances workers security in mining operations by integrating with remote monitoring command control systems (CCS) and environmental sensors for emergency responses (Buddhan et al., 2019). Its combination with RFID technology aids in managing mining production and tracking moving equipment (Vladimir et al., 2014). AR support drone pilots inspecting mining systems, and therefore improving workers' security as well as the efficiency of the industrial operations (Keller et al., 2018). AR, alongside sensing technologies, is used in exploration activities through 3D visualization and autonomous sensor nodes (Kiziroglou et al., 2017). Smart Glass Applications in mining are analysing productivity and safety enhancements, altering mining workers' work patterns (Kim et al., 2019). AR is also used in planning and decision-making for post-mining land-use (Benndorf et al., 2022). AR integrates human factors in mining for improved security (Paul and Briceno, 2021), and the combination of AR and VR in education for employees in the mining industry, is shown for example in the possibility of creating interactive digital manuals, that can be used for safe simulation of potentially dangerous work environments (Daling et al., 2020).

Oil and Gas: AR has been adopted in oil and gas extraction and processing. This has led to significant improvements in operations, safety, training, and efficiency. It excels in training technical staff through high-fidelity simulations, particularly for offshore conditions, saving time and costs (Garcia et al., 2019). Productivity and cost reduction are aided by AR's advanced visualization, merging digital and physical worlds for better spatial data visualization, crucial for operations and assets monitoring. This overcomes limitations of traditional monitoring methods, with digital AR applications providing interactive training experiences (Clarke et al., 2019; Yaacob et al., 2021). AR also plays a vital role in managing process safety risks, offering intuitive digital interfaces for data interaction and training, and supporting remote collaboration in key global operations (Potts et al., 2019). In maintenance, AR reduces timeframes, particularly in challenging environments (Koteleva et al., 2021). Finally, AR wearables are essential in design, operation, and maintenance, aiding in surface engineering for oil and gas fields, station and line designs, and construction processes (Cheng et al., 2022).

Logistic: AR is widely implemented in the context of logistics as well as supply chain management, with the role of enhancing operational efficiency and competitiveness in areas such as warehousing, manufacturing, sales, outdoor logistics, planning, design, and human resource management (Rejeb et al., 2020). In logistics operations, including transportation and warehousing, AR is crucial for achieving flexibility and efficiency, particularly in the Industry 4.0 era (Sorkun, 2019). It plays a vital role in warehouse design, helping minimize inventory costs while maintaining service levels and providing important operational information (Mourtzis et al., 2019). AR also improves training, operations, and transport in logistics, enhancing resource training and processes like sorting and goods transport (Remondino, 2020). Additionally, the use of gamifications strategies in AR has been explored to increase interest in logistics careers, potentially attracting more professionals to the sector (Putz-Egger et al., 2022).

3.2. Risks related to the use of AR in work settings

Integrating immersive visualization systems as AR in OSH training offers promising advancements in industries exposed to hazards such as explosions, fire, and pollution (Wahana and Marfuah, 2021), and such technologies offer the opportunity to train the operators in safe spaces. Despite these benefits, the deployment of AR systems in workplace environments is indeed not without risks. There are concerns regarding the potential of AR HMDs to distract workers, consequently increasing the likelihood of accidents in environments where safety is paramount (Aromaa et al., 2020). Inadequately designed AR interfaces may act as sources of distraction, posing a significant safety risk (Kim et al., 2016). For instance, in certain applications, AR might cause users to misinterpret reality, as, for example misjudging the velocity of a vehicles and reaction time, potentially adding dangers in the workplaces where AR technologies are used (Sabelman and Lam, 2015). The implementation of AR in occupational safety systems introduces hazards linked to the device's form factor and usability, encompassing ergonomic challenges and potential distractions from the work environment. This is particularly concerning in high-risk settings (Tatić and Tešić, 2015).

The proliferation of AR equipment in the workplace has raised concerns about their direct impact on physical health. One of the primary health concerns associated with the prolonged use of AR devices is eye strain. The close proximity of display screens to the user's eyes in devices like AR HMDs can lead to visual discomfort and fatigue (Sabelman and Lam, 2015). Additionally, the illumination and screen settings of these devices have been implicated in causing disturbances to the user's circadian rhythms, potentially leading to sleep disturbances and related health issues (Kim et al., 2018; Tochimoto et al., 2021). However, findings regarding these possible risks are limited, and a comprehensive scientific investigation of the risks related to eyes and vision due to prolonged exposure to AR environments should be a priority in future research. While AR, akin to Virtual Reality (VR), might induce simulator sickness or cybersickness, recent studies have shown that these effects are relatively minimal in AR applications. For example, previous research indicated minimal symptoms associated with simulator or cyber sickness among participants. Most reported no discomfort, while only a few experienced mild symptoms (Vovk et al., 2018). This suggests that while AR may cause physical discomfort, the severity and prevalence of such effects seem to be generally low.

Psychological risks have also been analyzed in current scientific literature. XR technologies, particularly when used excessively or as an escape mechanism, can be linked to mental health concerns such as depersonalization/derealization disorder, anxiety, and depression. However, the psychological risks that are associated with XR and AR have primarily been hypothesized in relation to VR, and in traditional 2D gaming (Siegler 2017). Therefore, it is unclear whether these psychological risks are particular to XR and AR. Other studies suggested that the full immersion and physical engagement required by some AR applications may expose users to mental health risks, including increased levels of stress, anxiety, and depressive symptoms (Das et al., 2017). This aspect is particularly relevant for these environments where reliance on virtual interactions supersedes engagement with the real world, potentially leading to increased feelings of isolation and neglect of real-life social connections. However, these risks are commonly examined in gaming, and short-term uses of the technology as in the work and occupational settings may not be affected by the same problem. Especially, the challenges related to AR are often compared with those of VR. However, it is essential to distinguish between the two, as empirical evidence regarding the effect that AR systems can have on user psychology is empirically very limited. Concerns such as addiction (Rajan et al., 2018), social isolation in case of specific uses (Merkx and Nawijn, 2021), and depersonalization and derealization (Peckmann et al., 2022) have been linked to VR rather than AR, and have been studied in contexts that are not the common workplace uses of these instruments. The introduction of AR systems in workplace settings may increase the exposure to the users to stressors. For example, a study indicated that AR HMDs could contribute to psychological stress in drivers (Hwang et al., 2016).

The implementation of AR technologies could entail cognitive challenges for the users that are critical to consider in OSH. AR, due to its ability to interact with a user's perception of the physical world, poses risks to sensory and perceptual aspects, such as inadvertently induced visual adaptations or motion-induced blindness (i.e., a visual phenomenon where salient static visual stimuli intermittently "disappear" from perception in the presence of specific moving patterns) (Baldassi et al., 2018). These risks may potentially affect users' cognitive functions, including memory and decision-making. Although these risks have not yet been prominently manifested in AR technologies, their potential impact is significant due to the depth of interaction AR provides with the user's experience. In the context of in-vehicle AR systems, these technologies can influence the psychological state of drivers, potentially easing the stress for those with high interpersonal anxiety (Hwang et al., 2016). However, AR technologies, particularly in vehicle head-up displays (HUD), increase the cognitive workload involved in processing visual information while driving. These systems, while intended to enhance safety, might inadvertently overlay graphics onto real traffic scenarios, leading to performance degradation and heightened accident risk (Kim and Hwang, 2016). A study (Wang et al., 2021) revealed that AR HUDs in assisted driving scenarios could lead to inattentional blindness under high workload conditions.

AR applications present considerable security and privacy concerns due to their capability to capture data from the user's environment and overlay virtual output onto their perception of the world. This raises significant risks, including malicious or faulty AR output (Lebeck et al., 2018), and that there is potential for personal data captured by AR technologies to be utilized in ways that threaten privacy (King et al., 2020). These privacy risks extend to bystanders around AR devices, particularly with regards to the ease with which these devices can record surroundings without being noticed. Studies show that individuals prefer to be asked for permission before being recorded by AR devices and are interested in devices that block recording (Denning et al., 2014). Research on the acceptance of AR smart glasses (Rauschnabel et al., 2018) highlights a complex interplay between the perceived advantages of AR and privacy concerns. Users are drawn to the utilitarian, hedonic, and symbolic benefits of AR devices, yet are significantly deterred by the potential infringement of privacy, especially towards others. The privacy implications of AR are not limited to external parties but also affect the users themselves. HMDs featuring AR often have cameras that record users' gaze and surroundings, posing risks to both the user's privacy and the privacy of bystanders, who may be co-workers or other personnel involved in work tasks, as well as people passing. Consumer surveys indicate that AR technologies can adversely affect social settings, leading to issues such as non-consensual recording, conversational information asymmetry (i.e., a situation in which participants in a conversation have unequal knowledge or access to information, affecting the dynamics and outcomes of the interaction) due to AR-assisted data access, and distraction caused by visual overlays. These factors can disrupt social norms, diminish social cohesion, and compromise societal awareness, further exacerbating privacy and security concerns (Hein et al., 2018). It has also been observed that using AR systems, due to their reliance on various sensors gathering personal information, poses threats to control over personal information and freedom of choice regarding the collection and the use of personal information (Harborth, 2022).

The common implementation of AR through HMDs introduces significant considerations regarding posture and mobility in workplace environments. A critical aspect of deploying HMD-based AR systems is understanding their impact on users' real-world awareness and the potential induction of unsafe or uncomfortable working postures (Aromaa et al., 2020). Studies have indicated that wearing HMDs can adversely affect neck posture, which is particularly concerning in non-sedentary work settings. This highlights the need for improvements in the design of HMDs, particularly in terms of their field-of-view and weight, to reduce ergonomic risks and improve comfort for users (Sehrt et al., 2022). Moreover, AR technologies have been leveraged in the field of ergonomic design, facilitating the transition of design processes from traditional computer monitors to the actual workspace around the designer. This innovative application of AR aids in the creation of work environments that are more ergonomically adapted to the users' needs (Januszka and Krysta, 2018). While AR holds potential for improving occupational health and safety, its application, especially for prolonged uses, or when interacting with complex machinery, must be carefully considered for ergonomic implications. Inadequate AR systems can lead to musculoskeletal and ergonomic problems (Gašová et al., 2017).

4. Discussion

The widespread integration of AR across various industries can be attributed to its ability to enhance efficiency, improve safety, and revolutionize training methodologies, thereby addressing key operational challenges in these sectors. In industries such as automotive, aerospace, shipbuilding (Frigo et al., 2016; Fraga-Lamas et al., 2018; Čujan et al., 2020), and chemical (Nakai and Suzuki, 2016; Lester and Hofmann, 2020; Buchner et al., 2022), the integration of AR is driven by the need to speed up complex processes, enhance precision, and improve safety protocols. AR's real-time data visualization and interactive interfaces allow for quicker decision-making and more efficient management of resources. The construction industry uses AR to enhance project visualization, accuracy, and efficiency, helping to overcome various challenges (Zollmann et al., 2014; Albahbah et al., 2021; Raziapov, 2022). This integration addresses the industry's need for precise planning and execution while enhancing the quality of construction projects. In mining and extraction, AR is integrated to enhance the safety of the workers as well as to increase the efficiency of the mining operations (Vladimir et al., 2014; Kiziroglou et al., 2017; Keller et al., 2018; Buddhan et al., 2019; Kim et al., 2019; Daling et al., 2020; Paul and Briceno, 2021; Benndorf et al., 2022). This technology addresses the sector's unique challenges, such as operating in hazardous environments and the need for precise monitoring. In the oil and gas sector, AR technology enhances operations, safety, training, and efficiency. It addresses challenges linked to training technical staff and managing remote operations (Clarke et al., 2019; Garcia et al., 2019; Potts et al., 2019; Koteleva et al., 2021; Yaacob et al., 2021; Cheng et al., 2022). AR's advanced visualization capabilities are crucial for these industries, where precise monitoring and operation are paramount. Lastly, in transportation and warehousing, AR is utilized to enhance supply chain management and logistics, addressing the need for greater operational flexibility and efficiency (Mourtzis et al., 2019; Sorkun, 2019; Rejeb et al., 2020; Remondino, 2020; Putz-Egger et al., 2022). In education, AR's ability to reduce cognitive overload and present information in an engaging manner addresses the challenge of maintaining student interest and improving learning outcomes (Bower et al., 2014; Akçayır and Akçayır, 2017; Pellas et al., 2018; Turan et al., 2018; Malone et al., 2023). This technology makes learning more interactive and adaptable to various learning styles, thereby enhancing the educational process. Healthcare has embraced AR for its potential to transform medical practices and education, thereby improving patient care and surgical outcomes (Leung et al., 2019; Srivastava and Agnihotri, 2019; Desselle et al., 2020; Ladkhedkar and Yadav, 2022; Singaram et al., 2022). AR tackles the need for precision and real-time information in medical procedures, revolutionizing how healthcare is delivered and taught. In manufacturing, AR is integrated to address the challenges of training, quality control, and maintenance in the era of Industry 4.0, leading to smarter and more efficient factory operations (Gallala et al., 2019; Torres-Tinoco et al., 2019; Konstantinidis et al., 2020; van Lopik et al., 2020; Ziaee and Hamedi, 2021; Ho et al., 2022). AR technologies simplify complex processes and enhance human-machine interactions. The military sector utilizes AR to enhance tactical training and operational effectiveness, addressing the need for advanced training systems and improved situational awareness (Curran et al., 2011; Le Roux, 2011; Larkin et al., 2020; Mao and Chen, 2021). AR provides soldiers with realistic, interactive training environments.

Our results reveal that the eventual benefits of AR-driven innovation should be analyzed considering potential hazards. General safety concerns in the workplaces are among the most critical risks, principally in work settings particularly prone to hazards such as fires and explosions, fire, and pollution (Wahana and Marfuah, 2021). AR can significantly enhance OSH, providing safe and effective training, advanced sensors monitoring, and remote operations. However, poorly designed interfaces can distract workers, increasing accident risks (Kim and Hwang, 2016; Aromaa et al., 2020). For instance, misinterpretation risk-critical environmental information that can be leading to increased workplace exposure to dangers (Sabelman and Lam, 2015). This problem is further compounded in manufacturing settings where incorrect human-machine interaction due to AR can have severe implications (Tatić and Tešić, 2015; Sheikh Bahaei, 2020). Health risks, particularly regarding eye strain and circadian rhythm disruptions, are associated with long-term usage of AR devices like HMDs (Sabelman and Lam, 2015). While concerns about simulator sickness are less prevalent in AR compared to Virtual Reality (VR), the potential for general physical discomfort remains (Vovk et al., 2018).

Psychological risks have been investigated only marginally within AR. According to the available scientific literature, excessive or inappropriate use of AR can lead to mental health issues such as anxiety, depression, and stress in the context of AR gaming (Das et al., 2017). However, it is at the moment unsure how these effects may translate in AR uses in the occupational context. The introduction of AR in certain applications like driving has been shown to increase potential stressors (Hwang et al., 2016). The effect of AR on mental health, as shown in our results, presents a complex issue that shows a notable research gap. While the literature (Spiegel, 2017) has discussed VR's links to mental health concerns like anxiety and depression, the specific impacts of AR are not as clear. These risks are primarily examined within gaming applications, and their relevance to workplace setting remains uncertain. Currently, scientific literature does not provide enough robust evidence to support that there are specific risks for psychological health linked to the utilization of AR. Future studies should attempt to identify potential criticalities regarding psychological affections that may be specific to AR, especially in applications requiring prolonged usage of AR technologies. Technostress (i.e., a type of stress originating from using or keeping pace with technology) (Tarafdar et al., 2019) might also be linked to mandatory AR technology use in workplaces or operators' technology unpreparedness. While direct connections between AR usage and technostress are not yet established, further research is needed.

AR poses several challenges when it comes to situation awareness. The technology can affect sensory and perceptual aspects, potentially impacting cognitive functions like memory and decision-making (Baldassi et al., 2018). In driving scenarios, for example, AR head-up displays (HUD) can overload cognitive processing, leading to performance degradation and increased accident risk (Kim and Hwang, 2016). Security and privacy concerns are paramount with AR's ability to capture and overlay inputs from sensors in the user's environment. Risks include malicious AR output, misuse of private data, as well as infringement on bystanders' privacy (Denning et al., 2014; Hein et al., 2018; Lebeck et al., 2018; Rauschnabel et al., 2018). Ergonomically, AR, particularly when mediated through HMDs, poses risks related to posture and mobility. The design of these devices must consider their impact on real-world awareness and ergonomic safety, especially concerning neck posture and field-of-view (Aromaa et al., 2020; Sehrt et al., 2022). Innovative applications in ergonomic design show AR's potential for creating safer work environments, though its implementation in industrial settings demands sensible ergonomic assessment (Gašová et al., 2017; Januszka and Krysta, 2018).

5. Conclusions and future directions

In conclusion, the integration of AR in various occupational settings signals a transformative era. However, its deployment comes with several challenges that require careful consideration and a comprehensive approach. The potential distractions in high-risk environments, health risks, psychological implications, and ergonomic concerns are significant issues that need addressing. A user-centric design approach is imperative in minimizing distractions and health risks. This includes integrating user feedback into design iterations to make AR systems more intuitive and user-friendly.

Implementing strong safety protocols is essential in AR environments to prevent hazards. It's important to perform regular health and ergonomic checks to minimize risks from extended AR use, addressing issues like physical fatigue. Ensuring a balance between efficiency and safety, concentrating on data protection and user consent, is crucial for AR's future. Developing clear guidelines and policies will support AR's responsible use. Additionally, empirical research and industry-specific evaluations are needed to understand AR's workplace impact and refine the technology accordingly. Considering the numerous benefits AR has in boosting efficiency and promoting innovation, the technology's application in occupational context should be carefully managed and based on a rigorous strategy. Implementing user-centric design, ensuring high safety levels, and promoting continuous improvement using empirical data are vital for ensuring that AR application in occupational context will be sustained and responsible.

Acknowledgements

The research presented in this article incorporates elements derived from research conducted under a contract with the European Agency for Safety and Health at Work (EU-OSHA). Please note that the opinions and interpretations expressed in this article are those of the contractor alone, and these views should not be seen as reflective of or representing the official position of EU-OSHA.

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