Human-Centric Integration of Extended Reality Technologies in Industry 5.0: A Comprehensive Review for Manufacturing

Yuhang Jiang

Advisor: Dr. Vincenzo Cutrona

Department of Innovative Technology (DTI)

University of Applied Science and Arts of Southern Switzerland (SUPSI)

August 2024

***Abstract*--XR technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), have significantly enhanced productivity and process optimization in manufacturing, while also improving worker training and safety. As manufacturing transitions from the technology-centric Industry 4.0 to the more human-centered Industry 5.0, the role of XR technologies has become increasingly prominent. This paper systematically analyzes the impact of XR technologies on manufacturing processes across different application scenarios, exploring their effects on worker acceptance, ergonomics, and data privacy, and proposes strategies to address these challenges. Ultimately, this paper provides valuable references for the future design and application of XR technologies, contributing to the development of a more sustainable and human-centric manufacturing industry.**

***Keywords:* Extended Reality (XR), Industry 5.0, Human-Centric Design, Worker Training and Safety**

1. Introduction

Extended Reality (XR) is an umbrella term that encompasses a range of immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies are increasingly recognized as transformative tools within the manufacturing sector, offering new possibilities for enhancing productivity, optimizing processes, and improving worker training and safety [1].

As the manufacturing industry transitions from Industry 4.0 to Industry 5.0, there is a significant shift from a focus on automation and digitalization to a more human-centric approach [2]. Industry 5.0 seeks to harmonize the collaborative efforts of humans and advanced technologies, fostering a symbiotic relationship that leverages the strengths of both. This new paradigm emphasizes sustainability, customization, and the integration of human creativity and innovation into manufacturing processes [3]. XR technologies are poised to play a pivotal role in this transformation, as they provide immersive tools that enhance operational efficiency while prioritizing the well-being and engagement of human workers.

In the context of Industry 5.0, XR technologies such as VR, AR, and MR are not just tools for enhancing efficiency; they are also integral to creating a more sustainable and human-centered manufacturing environment. These technologies facilitate a deeper integration of human skills and insights into the manufacturing process, ensuring that technology serves to augment rather than replace human capabilities [4]. Moreover, XR can help address critical challenges in manufacturing, such as improving ergonomics, reducing cognitive load, and enhancing collaborative efforts between humans and machines [5].

In recent years, reviews have largely focused on exploring various advanced XR technologies and their implementation frameworks in manufacturing (see Table 1), with in-depth analyses of how these technologies enhance productivity and optimize processes. However, these studies often overlook a crucial aspect: the potential risks and additional burdens that XR technologies may impose on human users. Particularly within the context of Industry 4.0, the emphasis has predominantly been on technology-driven automation and digital transformation, with relatively little attention paid to human factors. With the advent of Industry 5.0, the emphasis on human-centric design has become a defining characteristic of this new industrial era. Compared to Industry 4.0, Industry 5.0 is not merely about technological advancement; it is about the deep integration of technology and humanity, focusing on how technology can better serve people, enhancing employee work experience and safety. Therefore, understanding the psychological and physiological impacts of XR technologies on users, and exploring how to optimize design to mitigate these effects, is of paramount importance.

The aim of this paper is to fill this gap by systematically analyzing the impact of XR technologies on human users in manufacturing applications. It explores how to enhance the functionality of these technologies while minimizing the burden on users. This approach not only helps to improve the effectiveness of technology application but also provides an important reference framework for future XR design, making it more aligned with the human-centric values of Industry 5.0.

Table 1: Summary of some related review articles in recent years

Article	Publication Year	Main Content	Identified Shortcomings
Augmented reality in support of intelligent manufacturing – A systematic literature review [6]	2020	Discusses the role of Augmented Reality (AR) in supporting intelligent manufacturing, including applications and technical advantages.	Lacks in-depth analysis of implementation challenges and user experience issues.
A Review of Extended Reality (XR) Technologies for Manufacturing Training [7]	2020	Systematically reviews the state of XR technologies for industrial applications.	Lacks comprehensive discussion on the latest technological advancements and future trends.
UX in AR-Supported Industrial Human–Robot Collaborative Tasks: A Systematic Review [8]	2021	Studies user experience in AR-supported industrial human-robot collaboration.	Narrow scope; does not cover a wide range of industrial application scenarios.
Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review [9]	2022	Explores the challenges and opportunities of AR/VR technologies in manufacturing systems within the context of Industry 4.0.	Insufficient comparative analysis of different technologies; lacks empirical data support.
Future of industry 5.0 in society: human-centric solutions, challenges and prospective research area [10]	2022	Provides an overview of Industry 5.0, emphasizing human-machine collaboration, the role of advanced technologies, and future research directions.	The paper lacks a detailed exploration of the human and social factors associated with XR technology deployment, particularly its impact on worker well-being, acceptance, and training in industrial environments.
Towards Data and Model Interoperability for Industrial Extended Reality in Manufacturing [11]	2023	Investigates the importance of data and model interoperability in industrial XR applications.	Focuses primarily on technical aspects, neglecting user interaction and experience considerations.
A state-of-the-art survey on Augmented Reality-assisted Digital Twin for futuristic human-centric industry transformation [12]	2023	Explores the application of AR-assisted digital twins in future human-centric industry transformations.	Theoretical focus; lacks practical implementation cases and empirical evidence.
Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review [13]	2023	Discusses the transition towards human-centric smart manufacturing in Industry 5.0, focusing on the integration of humans and advanced technologies.	The paper does not provide an in-depth analysis of the specific human factors and social implications related to the deployment of XR technologies in manufacturing environments.
Extended Reality (XR) Toward Building Immersive Solutions: The Key to Unlocking Industry 4.0 [14]	2024	Evaluates the potential of XR technologies in creating immersive solutions, focusing on applications in Industry 4.0.	Fails to adequately address security and privacy issues associated with XR technologies.
Resource-Constrained EXtended Reality Operated With Digital Twin in Industrial Internet of Things [15]	2024	Examines the use of XR technologies integrated with digital twins in resource-constrained environments of the Industrial Internet of Things (IIoT)	Insufficient discussion on the scalability and practical usability of the solutions proposed.

Contribution of the paper:

This paper contributes to the field by providing a comprehensive review of Extended Reality (XR) technologies within the context of Industry 5.0, specifically focusing on their impact on human users in manufacturing. The paper not only highlights the potential of XR technologies to enhance productivity and safety but also offers practical strategies to minimize the burden on users. By aligning these technologies with human-centric values, the paper sets the stage for future research and development in XR design, making it a valuable resource for both academic researchers and industry practitioners.

Structure of the paper:

The paper is structured as follows (also shown in Figure 1):

- Introduction: Provides an overview of XR technologies and their relevance in the transition from Industry 4.0 to Industry 5.0.
- Methodology: Describes the systematic approach used for literature review and data extraction, detailing the research questions and the process for selecting relevant studies.
- Key Technologies: Discusses the essential hardware and software components of XR technologies, including their applications in manufacturing.
- Impact on Manufacturing: Analyzes the effects of XR technologies on various aspects of manufacturing, such as efficiency, accuracy, worker safety, and training.
- Human Factors: Explores the social and ergonomic implications of XR technology adoption, with a focus on user acceptance, well-being, and data privacy.
- Challenges and Future Directions: Highlights the technical and ethical challenges of XR technologies and suggests areas for future research.
- Conclusion: Summarizes the key findings and emphasizes the importance of aligning XR technology development with human-centric principles.

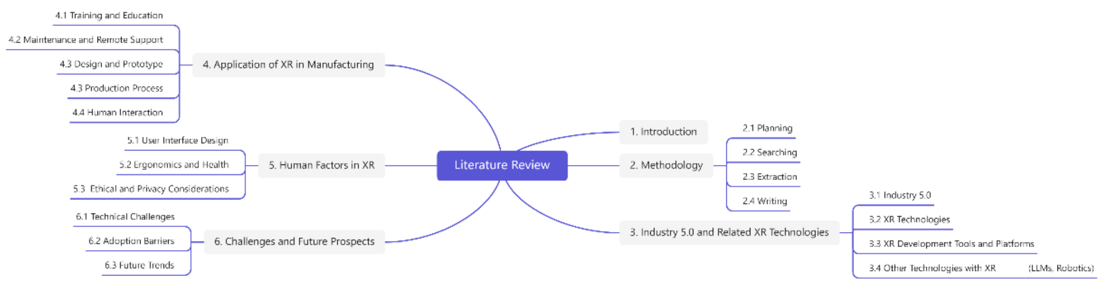

Figure 1: Structure of the paper

2. Methodology

In this section, the methodology of the literature is described. And the work flow is shown in Figure 2.

2.1 Planning

First, we need to define the scope of our research. This literature aims to summarize XR applications in manufacturing and explore the impact of these applications on human. Based on he above ideas, we propose the following research questions:

Question 1: What are the key technologies in XR applications for Industry 5.0? (Answered in Section 3)

The objective was to identify and categorize the essential technologies driving XR applications in Industry 5.0. This includes understanding the hardware, such as head-mounted displays (HMDs), hand-held devices, and sensors, as well as software platforms and development environments like Unity and Unreal Engine. By examining these technologies, the aim is to assess how they enhance productivity, efficiency, and customization in manufacturing processes. Understanding these key technologies helps to highlight the advancements that support the transition towards Industry 5.0.

Question 2: How do different XR applications impact manufacturing? (Answered in Section 4)

The goal was to analyze the effects of various XR technologies, including AR, VR, and MR, on manufacturing processes. This involves assessing their influence on efficiency, accuracy, worker safety, and training. By evaluating the practical benefits and potential drawbacks of integrating these technologies, the objective is to provide a comprehensive understanding of their effectiveness in manufacturing environments. This includes case studies and empirical data to illustrate the real-world applications and outcomes of XR technologies.

Question 3: What are the social and human factors associated with the adoption of XR technologies in industrial environments? (Answered in Section 5)

This question seeks to uncover the social implications and human factors related to the use of XR technologies in industry. The review will explore issues such as worker acceptance, the impact on worker well-being, ergonomics, and the training required for effective use of XR tools. Addressing these factors is crucial for understanding the broader implications of XR technology adoption and for developing strategies to mitigate potential negative effects on the workforce. This helps ensure a smooth transition and effective implementation of XR in industrial settings.

Question 4: How does the integration of XR technologies affect data security and privacy in industrial applications? (Answered in Section 5)

The objective was to investigate the challenges and considerations related to data security and privacy when implementing XR technologies in industrial settings. This includes examining potential vulnerabilities, the importance of protecting sensitive information, and strategies to ensure compliance with data protection regulations. By highlighting best practices and potential solutions, the review aims to provide a framework for maintaining robust security and privacy standards while leveraging XR technologies. This ensures that the benefits of XR can be realized without compromising data integrity and security.

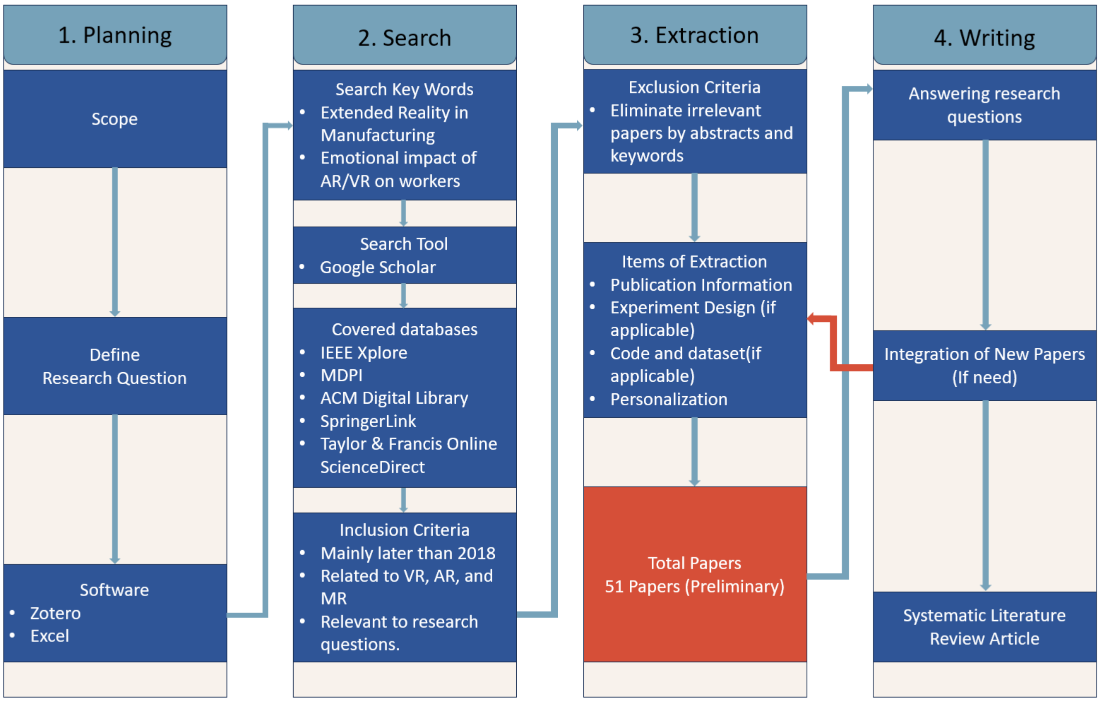

Figure 2: Work Flow of Literature Review

2.2 Searching

To perform the systematic search, a set of search strings was defined to search the databases. The literature search tool employed in this study was Google Scholar, which integrates multiple database platforms. The collected papers primarily originate from IEEE Xplore, MDPI, ACM Digital Library, SpringerLink, Taylor & Francis Online, and ScienceDirect. The publication dates of the papers are predominantly from 2018 to 2024. Additionally, the selected literature must be relevant to the research field, serving as an initial screening step to ensure the inclusion of pertinent studies.

2.3 Extraction

The extraction process in this literature review involves several critical steps to ensure the inclusion of high-quality and relevant papers. This phase is designed to refine the initial pool of collected papers through systematic criteria and detailed evaluation.

2.3.1 Exclusion Criteria

The initial exclusion criteria are applied to eliminate irrelevant papers based on abstracts and keywords. This step ensures that only papers closely aligned with the research questions and objectives are retained for further analysis. Key factors considered include:

- Eliminating Irrelevant Papers by Abstracts and Keywords: Papers are first screened based on their abstracts and keywords to quickly identify their relevance to the research questions. This helps in narrowing down the large pool of initial search results to those directly pertinent to XR technologies in Industry 5.0.
- Other Exclusion Factors: Additional criteria include removing duplicate documents, excluding papers not published in English, and focusing on studies published after 2020 to ensure the review includes the most current research.

2.3.2 Items of Extraction

The extraction process involves gathering detailed information from each selected paper. This detailed extraction helps in building a comprehensive understanding of the state of research and identifying key insights. The items of extraction include:

- Publication Information: Details such as the title, authors, journal name and publication date are recorded for citation and reference purposes.
- Experiment Design (if applicable): Information on the experimental setup, methodologies, and procedures used in the studies. This helps in understanding the robustness and validity of the research findings.
- Code and Dataset (if applicable): If the papers provide access to code or datasets, these are noted and collected for further analysis. This can be crucial for replication studies and for leveraging existing data in new research.
- Personalization: Any elements of personalization in the studies, such as tailored XR solutions for specific industrial applications, are documented. This helps in understanding the customization and adaptability of XR technologies in various manufacturing contexts.

2.3.3 Outcome

The total number of papers retained after this extraction process is 51. These papers form the basis for the systematic literature review, providing a rich dataset for detailed analysis and discussion. The extraction process ensures that the review is comprehensive, up-to-date, and relevant, capturing the latest advancements and challenges in XR technologies within the framework of Industry 5.0.

2.4 Writing

The final step in the research process involves synthesizing the findings into a comprehensive and coherent systematic literature review article. This phase is crucial as it integrates all the information gathered and analyzed in the previous steps to answer the defined research questions and provide a thorough overview of the current state of knowledge in the field of XR applications in Industry 5.0.

2.4.1 Answering Research Questions

In this stage, the focus is on addressing the research questions formulated during the planning phase. Each question is systematically answered based on the evidence collected from the selected papers. This involves:

- Summarizing the key findings related to each research question.
- Highlighting the most significant studies and their contributions.
- Discussing the implications of these findings for both theory and practice.

2.4.2 Integration of New Papers

During the writing process, it is essential to stay up-to-date with the latest research developments. As new relevant papers are published, they are integrated into the review to ensure that the article reflects the most current knowledge. This ongoing integration is achieved by:

- Continuously monitoring databases and academic journals for new publications.
- Evaluating the relevance and quality of new papers.
- Incorporating significant new findings into the corresponding sections of the review.

2.4.3 Systematic Literature Review Article

The culmination of this process is the production of a systematic literature review article. This document is structured to provide a clear and comprehensive analysis of XR technologies in Industry 5.0, covering:

- An introduction that sets the context and significance of the review.
- A methodology section that details the search strategy, inclusion and exclusion criteria, and the extraction process.
- A results section that presents the findings in relation to the research questions.
- A discussion section that interprets the findings, discusses their implications, and identifies gaps and future research directions.

- A conclusion that summarizes the key points and emphasizes the contributions of the review.

By following this structured approach, the final article aims to contribute valuable insights to the field and serve as a reliable resource for researchers and practitioners interested in XR technologies and their applications in Industry 5.0.

3. Industry 5.0 and Related XR Technologies

3.1 Industry 5.0

The term Industry 5.0 refers to the next phase in industrial development following Industry 4.0. While Industry 4.0 focuses on the digitalization and interconnectivity of machines and processes, Industry 5.0 emphasizes human-centirc solutions, sustainable practices, and advanced technologies that facilitate collaboration between humans and machines [16]. The characteristics of each stage from Industry 1.0 to 5.0 are shown in Figure 1.

Industry 5.0 aims to bring a human touch back to manufacturing. It emphasizes the collaboration between humans and intelligent machines, leveraging human creativity and expertise while using robots for repetitive tasks. This approach enhances the customization and personalization of products [2].

Industry 5.0 leverages advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Extended Reality (XR) to create smarter and more efficient production systems. These technologies enable better decision-making, real-time monitoring, and predictive maintenance, enhancing overall productivity and reducing downtime [17].

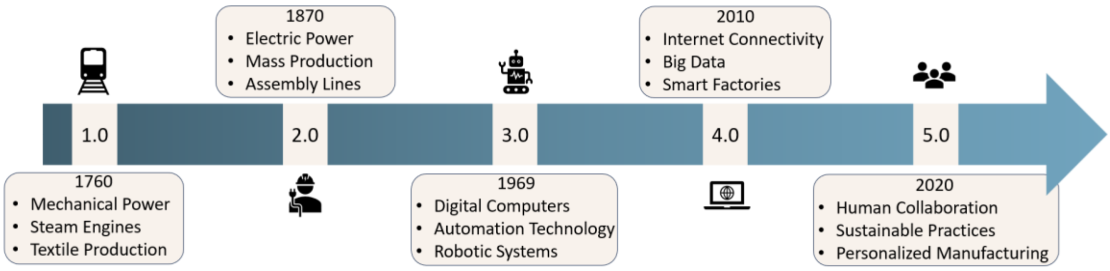

Figure 1: From Industry 1.0 to 5.0

3.2 XR Technologies

Extended Reality (XR) is an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). These technologies blend physical and virtual worlds, offering varied levels of immersion and interaction.

- Virtual Reality (VR): Creates a fully immersive digital environment, isolating the user from the real world. VR typically requires a head-mounted display (HMD) and often includes hand controllers for interaction. Popular applications range from gaming and entertainment (e.g., Oculus Rift, HTC Vive) to training simulations and virtual tours [18].

- Augmented Reality (AR): Enhances the real world with digital overlays. AR applications use cameras and sensors to superimpose virtual objects onto the physical environment, providing contextual information and interactive experiences. Common examples include mobile apps like Pokémon GO and tools used in industrial maintenance and training [19].
- Mixed Reality (MR): Integrates real and virtual worlds to produce new environments where physical and digital objects coexist and interact in real-time. MR technologies, such as Microsoft HoloLens, enable more complex interactions by mapping the physical space and responding to real-world elements.

The development of Extended Reality (XR) technologies relies heavily on advancements in hardware, software, and connectivity, each contributing significantly to the overall user experience and application capabilities. Below is an overview of the key hardware components in XR technologies and their specific roles:

Head Mounted Visualization Device (HMVD):

- HMVDs are core devices in Virtual Reality (VR) and Mixed Reality (MR) applications, providing immersive visual and auditory experiences. These devices include see-through displays (e.g., HoloLens) and fully enclosed headsets (e.g., Oculus Rift), which use high-resolution screens and 3D audio to enhance user immersion.

Hand-Held Visualization Device (HHVD):

- HHVDs are typically used in Augmented Reality (AR) applications, primarily leveraging the cameras, GPS, and accelerometers in mobile devices. Smartphones and tablets serve as HHVDs, enabling AR experiences through these sensors. Additionally, AR glasses (e.g., Microsoft HoloLens, Google Glass) represent an advanced form of HHVDs, combining see-through displays with powerful sensor arrays to deliver enhanced AR functionality.

Sensors and Cameras:

- Sensors and cameras are crucial in MR and advanced AR applications, enabling devices to track user movements and map the surrounding environment. Key sensors include:
    - Depth Sensors (e.g., Kinect): Capture user movements and perform real-time 3D modeling.
    - Eye-Tracking Sensors: Enhance user experience by optimizing rendering and interaction based on eye movements.
    - Gesture Recognition Sensors: Capture hand movements for more natural

interaction.

- LIDAR (Light Detection and Ranging) Sensors: Precisely map the environment, enhancing the integration of virtual content with the real world.

Haptic Feedback Devices:

- Haptic feedback devices provide tactile feedback, making virtual interactions feel more realistic. These devices range from simple vibration feedback to more sophisticated force feedback and full-body suits:
  - Force Feedback Gloves: Simulate the weight, hardness, and texture of objects.
  - Full-Body Haptic Suits: Deliver full-body tactile feedback, enhancing the sense of presence and interaction in virtual environments.

Audio Systems:

- Sound is a critical factor in enhancing immersion. 3D audio engines and spatial audio systems deliver realistic sound experiences by accurately positioning sound sources, allowing users to perceive sound coming from various directions, further enhancing immersion.

Networking and Connectivity:

- Low-latency networking is essential for real-time data transmission in XR applications, particularly in multi-user collaborative environments. Key technologies include:
  - 5G Networks: Support high bandwidth and low latency communication.
  - Edge Computing: Brings computational resources closer to the data source, reducing latency and improving response times.

Wearable Devices:

- Other wearable devices, such as biometric sensors and brain-computer interfaces (BCI), further enhance interaction depth and personalization in XR environments. These devices can monitor users' physiological states and dynamically adjust the content in XR applications, providing a more personalized and immersive experience.

Hardware devices are diverse, with HMVD devices being the most widely used. Table 2 lists commonly used HMVD devices, excluding those that were once popular but have since been discontinued or whose product lines are no longer updated.

Table 2: Commonly used HMVD equipment

Company	Device	Release Year	Type	Configuration	Applications

Microsoft	HoloLens 2	2019	AR	Mixed reality headset with eye tracking, iris recognition, and voice commands. Uses Qualcomm Snapdragon 850 Compute Platform. Display: 2k 3:2 light engines, Resolution: 1440x936, MEMS display. Weight: 566g.	[20-24]
	HoloLens 1	2016	AR	Mixed reality headset with gesture and voice recognition. Uses Intel 32-bit architecture. Display: 2 HD 16:9 light engines. Weight: 579g.	[25-28]
HTC	Vive XR Elite	2023	MR	Mixed reality headset with full-color passthrough, combining VR and AR capabilities. High-resolution display with 6DOF tracking. Compatible with SteamVR and Viveport platforms.	[29]
	Vive Pro 2	2021	VR	High-end VR headset with 5K resolution (2448 x 2448 pixels per eye), 120Hz refresh rate, 120-degree FOV. Requires connection to a high-performance PC. Compatible with SteamVR and Viveport.	——
	Vive Pro 1	2018	VR	VR headset with 2880 x 1600 combined resolution (1440 x 1600 pixels per eye), 90Hz refresh rate, 110-degree FOV. Compatible with SteamVR and Viveport platforms.	[30-31]
Lenovo	ThinkReality VRX	2022	VR	VR headset with full-color passthrough and 6DOF mixed reality capabilities. Powered by Qualcomm Snapdragon XR2 processor, designed for enterprise training, virtual meetings, and immersive simulations. Supports Lenovo’s ThinkReality software platform for remote management and content distribution.	——
	ThinkReality A3	2021	AR	AR smart glasses supporting up to 5 virtual displays, equipped with dual 8MP RGB cameras for video recording and streaming. Suitable for enterprise applications such as remote collaboration, 3D visualization, and virtual monitor expansion. Compatible with Windows PCs and select Motorola smartphones. Focused on enterprise applications.	——
	Mirage VR S3	2020	VR	VR headset developed in collaboration with Pico, focused on enterprise-level immersive learning and training. Features a 4K display for clear visual experiences. Standalone device, designed for enterprise customers, does not require external devices.	——
Meta	Oculus Quest 3	2023	VR	Standalone VR headset with Qualcomm Snapdragon XR2 Gen 2 platform, offering higher resolution displays (2064 x 2208 pixels per eye), 120Hz refresh rate, and mixed reality capabilities with full-color passthrough. Improved comfort and slimmer design compared to Quest 2.	——
	Oculus Quest 2	2020	VR	Standalone VR headset with Snapdragon XR2 platform, 6GB RAM, and up to 256GB storage. Resolution: 1832 x 1920 pixels per eye. Refresh Rate: 120 Hz.	[32-33]
Apple	Apple Vision Pro	2024	AR	AR headset with dual 4K micro-OLED displays, M2 chip, 12 cameras for spatial awareness, eye tracking, hand tracking.	——

3.3 XR Development Tools

Software platforms and development environments (see Table 3) are vital for creating XR applications.

- Game Engines: Unity3D [34] and Unreal Engine [35] are popular choices for XR development due to their robust tools and cross-platform support.

- AR Development Kits: ARKit (Apple) [36] and ARCore (Google) [37] offer frameworks for building AR applications on mobile devices.
- MR Platforms: Windows Mixed Reality [38] and HoloLens SDK provide tools for developing MR experiences.

Table 3: Common platforms for developing XR tools

Software Framework	Features/Functions Description
Unity3D	Unity is a cross-platform game engine widely used for XR development, popular due to its robust tools and cross-platform support. It supports AR, VR, and MR development, suitable for various devices.
Unreal Engine	Unreal Engine is another popular cross-platform game engine, widely used for high-end VR and MR experience development. It is known for its realistic graphics and powerful physics engine, suitable for applications requiring high-quality visual effects.
ARKit (Apple)	ARKit is an AR development toolkit provided by Apple for iOS devices, supporting AR applications on iPhones and iPads. It offers deep integration with device cameras, sensors, and CPU/GPU for efficient AR experiences.
ARCore (Google)	ARCore is an AR development platform provided by Google, used for building augmented reality experiences on Android devices. It enables motion tracking, environmental understanding, and light estimation, providing stable AR experiences and supporting cross-platform development.
Windows Mixed Reality	Windows Mixed Reality is a platform provided by Microsoft, supporting the development of MR experiences (such as HoloLens). It offers a range of development tools and SDKs to enable immersive MR experiences.
HoloLens SDK	The HoloLens SDK is a development toolkit provided by Microsoft for its HoloLens devices, supporting the creation of MR applications. It includes features like spatial mapping, gesture recognition, and eye tracking, suitable for MR applications in industrial, medical, and other fields.

3.4 Other Technologies with XR

3.4.1 Large Language Model

In today's manufacturing industry, with the advancement of Industry 4.0 and the continuous development of smart manufacturing, large language models (LLMs) are rapidly becoming essential tools for enhancing automation and intelligence in manufacturing. These models, such as GPT-4 and its variants, are equipped with powerful natural language processing capabilities, allowing them to handle vast amounts of textual data, understand complex contexts, and generate meaningful responses. This provides innovative solutions for various application scenarios within the manufacturing sector [39].

In the paper "Harnessing Large Language Models for Cognitive Assistants in Manufacturing" [40], the authors thoroughly explore how large language models (LLMs) can be applied as cognitive assistants in the manufacturing sector, providing intelligent support for task planning and execution. The study demonstrates how

LLMs are used to analyze and understand complex manufacturing tasks in real-time, offering detailed guidance and feedback to operators through natural language interaction. The research showcases how LLMs, when combined with XR technology, create an intelligent assistance system for operators within manufacturing environments. This system interacts with operators via voice and text commands, monitors production processes in real-time, and dynamically adjusts task planning based on the actual conditions of the production line. This capability is particularly crucial when dealing with multi-step and multi-variable manufacturing tasks, as LLMs, with their powerful natural language processing and reasoning abilities, help operators quickly identify problems and take optimal actions. Additionally, the study mentions that LLMs not only assist operators in completing routine tasks but also analyze historical data and production parameters to predict potential production bottlenecks and provide proactive recommendations. This foresight and real-time adjustment capability make LLMs not just passive tools in manufacturing but intelligent assistants that actively optimize production processes.

In the paper "VR-GPT: Visual Language Model for Intelligent Virtual Reality" [41], the researchers combine visual language models with VR technology, using the Unity engine to develop a natural language-driven user interaction system. This system guides users through complex operational tasks via real-time speech recognition and feedback, enhancing the efficiency and accuracy of task execution. This study indicates that the application of LLMs in manufacturing is not limited to static task planning but can also optimize various aspects of the production process through dynamic interaction.

In the paper "Mixed Reality IoT Smart Environments with Large Language Model Agents" [42], the authors integrate LLMs with the Internet of Things (IoT) and XR technology to create an intelligent mixed reality environment. This environment can dynamically adjust task planning and provide guidance based on operators' commands and environmental context. This combination significantly enhances the flexibility and responsiveness of production operations, enabling complex manufacturing tasks to be completed more efficiently.

3.4.2 Robotics

Robotics is the field focused on designing and building robots that can perform tasks autonomously or with human guidance. It combines engineering, computer science, and AI to create machines used in industries like manufacturing, healthcare, and space exploration. Robotics enhances efficiency, safety, and productivity, and its integration with technologies like Extended Reality (XR) is driving innovation in various applications. The most notable application is human-machine collaborative assembly.

Sung Ho Choi and colleagues[43] proposed an extended reality (XR)-based approach to safe human-robot collaboration by calculating the minimum distance between the human operator and the robot in real-time. The system uses multiple sensors to scan the real environment and create a virtual space in XR, where the virtual robot is synchronized with the real robot. This synchronization ensures the visualization of safety distances and provides task assistance and safety information to the operator. By utilizing XR devices like HoloLens 2, the method enhances safety and efficiency during operations.

Carriero et.al. [44] developed an augmented reality (AR) toolkit for bi-directional interaction in human-robot collaboration. The system enables humans and robots to work together in a shared workspace and enhances the understanding and prediction of robot behaviors through AR technology. Users interact with the robot via an AR interface and receive real-time visual feedback, improving the safety and efficiency of collaborative tasks. This AR toolkit offers human operators more intuitive robot path planning and task execution guidance, making collaboration smoother and more efficient.

Matsas et.al. [45] proposed a virtual reality training system (VRTS) for human-robot collaboration in manufacturing tasks. The system simulates human-robot cooperation in real-time using a serious game format, focusing on safety issues during collaboration. Through immersive virtual reality interaction, users gain enhanced situational awareness and improve their perception and reaction to robot movements via visual and auditory warnings. This system not only increases user immersion in the virtual environment but also serves as a platform for studying the acceptability of human-robot collaboration and optimizing collaborative tasks in manufacturing.

Solanes, et.al. [46] explored the use of force feedback technology for safe object transportation in human-robot collaboration. By integrating force feedback devices, the system allows human operators to sense and control the force exerted by the robot during heavy object handling, preventing accidents and hazards. This system enables more precise interaction between operators and robots, allowing operators to adjust their strategies based on force feedback, thus enhancing both the precision and safety of task execution. This approach is particularly suitable for manufacturing environments requiring high-precision collaboration, such as assembly lines and heavy material handling.

4. Application of XR in Manufacturing

4.1 Training and Education

In the era of Industry 5.0, the demand for highly skilled workers in manufacturing has significantly increased. Extended Reality (XR) technology has been widely applied in manufacturing training and education, aiming to enhance workers' skills, ensure safety, and optimize production processes. Firstly, XR can simulate real working environments, allowing workers to train in a safe, risk-free setting, thereby reducing potential occupational hazards. For example, VR is widely used in the initial and learning stages of training, creating virtual layers that ensure workers' safety and help avoid risks associated with actual operations. Related applications are shown in Table

4.

Table 4: Application of XR in Training and Education

References	Personalization	Benefits	Potential Risks
Assessment of virtual reality-based manufacturing assembly training system [47]	Utilizing VR for the training of assembly operations within manufacturing processes. It incorporates various VR tools, including visual and haptic feedback, to enhance training realism and effectiveness.	VR simulation of assembly processes reduces errors and training time, enhancing understanding in a risk-free environment.	High initial setup costs and potential resistance to change due to new technology adoption.
Designing a Technological Pathway to Empower Vocational Education and Training in the Circular Wood and Furniture Sector through Extended Reality [48]	Integrates extended reality (XR) in vocational training for the wood and furniture sector, employing interactive simulations to engage learners.	Enhanced skill acquisition, increased engagement, and adaptability to various learning styles.	Requires significant investment in technology and ongoing maintenance.
Development of an Extended Reality-Based Collaborative Platform for Engineering Education Operator 5.0 [49]	Develops a collaborative platform using XR to simulate engineering environments, focusing on teamwork and real-time problem solving among students.	Promotes remote education by supporting interaction with complex machinery and fostering a skilled digital workforce.	Technical challenges in implementation and potential over-reliance on virtual scenarios for practical skills training.
Gamified Virtual Reality Training Environment for the Manufacturing Industry [50]	Utilizes gamification in VR training to enhance motivation and learning outcomes in manufacturing settings. Includes real-time feedback and progress tracking.	Increases motivation and learning outcomes through engaging, game-like training environments with higher retention rates.	Risk of cognitive overload and distraction from core learning objectives.
Virtual Reality-Based Engineering Education to Enhance Manufacturing Sustainability in Industry 4.0 [51]	Applies VR in engineering education to simulate sustainable manufacturing processes, with a focus on minimizing environmental impact.	Educates and instills a responsibility towards sustainable practices through virtual scenarios of manufacturing impacts.	Potential high costs and the complexity of integrating VR with existing educational frameworks.

4.2 Maintenance and Remote Support

In manufacturing, Extended Reality (XR) technology has seen significant advancements in maintenance and remote support applications. By integrating Augmented Reality (AR) and Virtual Reality (VR), companies can improve the efficiency and accuracy of equipment maintenance, particularly for complex or hard-to-reach components. XR enables technicians to receive real-time guidance and visual overlays, enhancing their ability to perform precise repairs. Additionally, remote experts can provide support, reducing downtime and ensuring maintenance tasks are completed accurately, ultimately boosting equipment reliability and operational efficiency. Related applications are shown in Table 5.

Table 5: Application of XR in Maintenance and Remote Support

Reference	Personalization	Benefits	Potential Risks
Creating an Open-Source Augmented Reality Remote Support Tool for Industry: Challenges and Learnings [52]	Development of an open-source AR framework for remote maintenance and collaboration, enhancing efficiency.	Facilitates customization and adaptation to specific maintenance needs, reducing dependence on proprietary solutions.	Potential technical challenges in maintaining and updating the open-source framework, ensuring compatibility and security.
Real-Time Remote Maintenance Support Based on Augmented Reality (AR) [53]	Uses AR for real-time remote maintenance, providing interactive communication channels between technicians and engineers.	Improves immediacy and effectiveness of maintenance operations, reducing downtime and enhancing operational efficiency.	Challenges related to network dependency, real-time data transmission, and ensuring stable and secure communication channels.
Remote Video Collaboration During COVID-19 [54]	Implements Remote Video Collaboration (RVC) with AR to facilitate equipment installation, maintenance, and training amid travel restrictions.	Ensures continuity of production activities despite logistical challenges, utilizing AR for enhanced interactive support.	Intellectual property concerns with remote access to sensitive information, plus potential resistance to adopting new remote operation models.
Supporting Remote Maintenance in Industry 4.0 through Augmented Reality [55]	Employs off-the-shelf mobile and AR technologies for effective remote maintenance by connecting skilled operators with onsite personnel.	Allows for effective and efficient remote guidance and troubleshooting, reducing the need for expert physical presence.	Dependence on the reliability of mobile and AR technologies, which may face operational challenges in industrial environments.

4.3 Design and Prototype

In manufacturing, Extended Reality (XR) technologies, particularly Virtual Reality (VR) and Augmented Reality (AR), have significantly enhanced flexibility and efficiency in design and prototyping. Several case studies from various papers demonstrate how these technologies are practically applied to improve product design and testing processes. By integrating XR, companies can rapidly iterate on designs, visualize prototypes in real-time, and conduct virtual testing, leading to faster development cycles and more innovative products, ultimately optimizing the overall design workflow. Related applications are shown in Table 6.

Table 6: Application of XR in Design and Prototype

Reference	Personalization	Benefits	Potential Risks
Semi-Immersive Virtual Turbine Engine Simulation System [56]	Utilizes a semi-immersive VR system for aircraft turbine engine assembly verification. Features stereoscopic visuals, surround sound, and haptic feedback, along with a special software architecture for VR, including collision detection for assembly interference checks.	Enhances interaction with the model, providing a realistic experience that aids in detailed verification of assembly processes and part design, improving planning operations.	May require high computational capabilities and can be resource-intensive to simulate complex products, possibly limiting field of view and realism.

Exploring the Benefits of Virtual Reality Technologies for Assembly Retrieval Applications [57]	The system supports intuitive interaction through gestures and voice commands, emphasizing its role in efficiently conveying complex assembly similarities and reducing the need for physical prototypes, thereby speeding up design modifications and cost savings.	Speeds up the validation process of assembly procedures, especially beneficial in complex and detailed assemblies where traditional methods are cumbersome and error-prone.	Dependent on the accuracy and quality of VR systems; limitations in technology may lead to less effective training or planning.

4.4 Production Process

In the manufacturing industry, the use of extended reality (XR) technology is reshaping the production process, especially through the application of augmented reality (AR) and virtual reality (VR) technology, providing unprecedented visual support and interaction methods for production lines.

These studies (see Table 7) show that by introducing XR technology, the production process of the manufacturing industry can achieve more efficient operations, more precise quality control, and lower error rates. With the continuous development and application of these technologies, it is expected that the production efficiency and product quality of the manufacturing industry will be further improved in the future.

Table 7: Application of XR in Production Process

Reference	Personalization	Benefits	Potential Risks
Quality Assurance and Process Control in Virtual Reality [58]	Focuses on VR-based systems for process control, employing adaptive algorithms that tailor the VR environment according to real-time data from the production line.	Enhances monitoring accuracy and operational efficiency, allowing for quicker response times and adjustments in production processes.	Relies heavily on the accurate synchronization of virtual and real environments, risking delays or errors in response to real-world changes.
The Production Quality Control Process, Enhanced with Augmented Reality Glasses [59]	Utilizes AR glasses to overlay digital information directly onto production components, customized to display relevant data based on the user's tasks and location within the factory.	Improves the accuracy of quality control inspections and speeds up the training process for new employees by providing contextual information and guidance.	Dependence on AR device reliability and the potential for decreased effectiveness if visual overlays are inaccurate or misaligned.
Using Augmented Reality for Industrial Quality Assurance [60]	Employs AR to assist operators on the shop floor by overlaying step-by-step instructions and quality checkpoints directly onto work pieces, with dynamic adjustment based on the task at hand.	Significantly reduces errors and operational time by providing real-time, situational feedback and instructions, improving overall quality assurance.	If AR guidance is incorrect or if there are technical failures, it could lead to significant operational disruptions and quality control issues.
Dialogue Enhanced Extended Reality Interactive System for the Operator 4.0 [61]	Integrates voice interaction into AR systems, allowing operators to customize and interact with the AR environment using natural	Enhances user engagement and allows for more flexible, intuitive interaction with quality control processes, potentially increasing	Complexity of maintaining accurate voice recognition in noisy industrial environments, which could lead to misunderstandings or

	language processing to adjust instructions or get additional information as needed.	adherence to standards.	incorrect data display.

4.5 Human Interaction

In the manufacturing industry, Extended Reality (XR) technology demonstrates how to effectively integrate human operators with complex machine systems for human-machine interaction. Table 8 summarizes specific application cases, illustrating how XR technology plays a role in the design of human-machine collaboration sites, machine operation, and human-machine collaboration. Human-centric design is the focus of Industry 5.0, and in the next section, we will focus on the key design considerations related to human factors in XR.

Table 8: Application of XR in Human Interaction

Reference	Personalization	Benefits	Potential Risks
An Approach Based on VR to Design Industrial Human-Robot Collaborative Workstations [62]	Explores the use of VR in designing workstations for human-robot collaboration, enabling risk-free testing and optimization of human-machine interactions before real-world implementation.	Facilitates safe and efficient design of collaborative spaces, minimizing risks and allowing for optimization before actual deployment.	Depends heavily on the fidelity of VR simulations to actual working conditions; discrepancies can lead to ineffective or unsafe designs.
Extended Reality Application Framework for a Digital-Twin-Based Smart Crane [63]	Develops an XR framework using AR and VR to enhance operator interaction with a smart crane. Integrates real-time viewing and operation of complex mechanical components, utilizing digital twin technology for precise and efficient operations.	Improves operational precision and efficiency by allowing operators to interact more intuitively with the crane components.	High reliance on the accuracy of the digital twin model and the XR system's performance, which could affect operational safety if inaccurate.
Using Virtual Manufacturing to Design Human-Centric Factories [64]	Utilizes VR to simulate human-machine interaction scenarios to optimize workstation design and task planning. Focuses on ergonomics to enhance operator comfort and productivity, using tools like Unity 3D, HTC VIVE, Xsens for tracking, and Leap Motion for gesture recognition.	Enhances workstation design for better ergonomics, reducing inefficiencies and improving operator comfort and factory productivity.	Initial high costs for VR setup and potential issues with integrating VR tools into existing manufacturing systems.

5. Human Factors in XR

The rapid development of Extended Reality (XR) technology has not only driven revolutionary progress in the digital world but has also profoundly impacted various aspects of human-computer interaction. This chapter will explore two key areas: user interface design and ergonomics, which together form the foundation for optimizing user experience and operational safety. User interface design focuses on enhancing user immersion and operational efficiency through visual and interactive design, while ergonomics considers the impact of equipment design and usage environment on users' physical and mental well-being. Next, we will delve into these two areas in detail, aiming to improve the humanization and acceptability of XR technology through innovation in technology and design.

5.1 User Interface Design

In the realm of Extended Reality (XR) technology, user experience and interface design emerge as pivotal components within industrial applications. Throughout user engagement, the User Interface (UI) represents the most utilized and intimately interacted facet. A meticulously crafted UI can markedly diminish the cognitive burden on users, augment operational efficiency, and elevate overall user satisfaction. Table 9 delineates a variety of adverse consequences stemming from suboptimally designed elements.

Table 9: Adverse consequences stemming from suboptimally designed elements

Poorly designed aspects	Detail	Impact
Poor Integration of Learning Modalities	XR interfaces that poorly integrate different learning modalities—such as auditory, visual, and kinesthetic—can increase cognitive load. This is particularly problematic when the interface forces users to split their attention between different types of content, such as text and images, which are not effectively integrated.	This can lead to misunderstandings, errors in task execution, and increased cognitive load, reducing overall learning outcomes.
Inadequate User Feedback and Interaction	If the XR interface does not provide adequate feedback or allows for intuitive interaction, users may find the system unresponsive or difficult to manipulate. This is often due to poor tactile feedback or unintuitive motion controls.	Poor user experience and increased frustration can result, which diminishes the learning efficiency and can lead to poor retention of information.
Overwhelming Information Presentation	Interfaces that overload users with information without prioritizing content or allowing customization to user preferences can overwhelm users, particularly in educational settings where paced learning is crucial.	This can overload the cognitive capacity of users, leading to reduced information processing efficiency and lower overall engagement with the learning material.

Aiming to address these negative issues, the design of XR User Interfaces (UI) has become a popular research direction. From a modality perspective, this involves the integration of multimodalities. Zimmerer et al. [65] explores how the use of multimodal interfaces can decrease the cognitive load in digital tabletop gaming. The results indicate that integrating visual, auditory, and tactile feedback significantly reduces cognitive stress during complex game tasks, thereby enhancing the player's gaming experience and performance. From an interface design perspective, Xia et al. [66] compared the effects of color in real-world and virtual reality environments on cognitive performance. The findings suggest that color configurations have a significant impact on users' cognitive and emotional states in virtual environments, providing crucial guidance for visual design in VR applications. The impact of interface layout design on learning efficiency on mobile learning platforms was explored. Studies have shown that vertical and horizontal layouts have significantly different impacts on user learning efficiency, where vertical layouts contribute to faster information processing speed and higher learning satisfaction. Zhang et al. [67] explored the impact of interface layout design on learning efficiency on mobile learning platforms. Research indicates that vertical and horizontal layouts significantly affect user learning efficiency differently, with vertical layouts aiding in the enhancement of information processing speed and learning satisfaction.

From the perspective of user psychological cognition, Zhou et al. [68] studied how personality traits affect user trust in human-machine collaboration under conditions of uncertainty and cognitive load. Experiments involving 42 participants found that the display of uncertainty can increase trust under low cognitive load conditions, but reduces trust under high cognitive load conditions. Different personality traits have varying impacts on trust, providing valuable insights for human-machine interaction design. Bellman et al. [69] explored the impact of feedback mechanisms on task performance and user preferences for interfaces. The study assessed, through experimental methods, how different types of feedback (positive and negative) influence task execution. Results show that appropriate feedback can significantly enhance task performance, and users' interface preferences vary according to their personal characteristics and task requirements. Han et al. [70] studied cognitive load issues in highly immersive virtual reality environments. Using experimental methods, the study explored how different virtual reality tasks demand and impact users' cognitive resources. It was found that a moderate cognitive load can enhance user experience and performance in highly immersive environments, but excessive load may lead to cognitive overload.

5.2 Ergonomics and Health

When exploring the ergonomics and health impacts of XR technology, we must focus on the physical comfort and health risks for users during prolonged use of these devices. This section will specifically discuss the ergonomic principles that should be considered in the design of XR devices, as well as how to mitigate the negative health effects on users through design improvements.

Key Areas of Improvement in XR Ergonomics

Weight Distribution:

Many XR devices are front-heavy, which can cause neck strain. Research often explores ways to distribute the weight more evenly, such as by using lighter materials or by adjusting the design to balance the weight across the head.

Fit and Adjustability:

Adjustable straps and customizable padding are essential to ensure that XR devices fit a wide range of users comfortably. This also includes the design of nose bridges and facial interfaces to minimize pressure points.

Heat Management:

XR devices generate heat during use, which can be uncomfortable for the wearer. Studies often look into materials and ventilation systems that improve airflow and reduce heat buildup.

Optical Comfort:

The position of lenses and the quality of the display can affect eye strain. Improvements in optics, such as adjustable interpupillary distance (IPD) and reducing the screen-door effect, are common areas of focus.

User Interaction:

The design of controllers and hand tracking systems can also affect ergonomics. Natural hand positioning, button placement, and the use of haptic feedback are all areas where research is often conducted to improve comfort.

The discomfort symptoms that may be caused by wearing VR/AR are as follows:

Table 10: Discomfort symptoms caused by wearing VR/AR.

Symptom	Description
Cybersickness and Visual Discomfort	**Cybersickness** is primarily caused by sensory conflicts between visual and vestibular systems, leading to symptoms like nausea, dizziness, and visual discomfort. [71]
	Visual strain due to VR exposure can lead to eye fatigue and headaches, often exacerbated by the mismatch between accommodation and vergence in stereoscopic displays. [72]
Physical Discomfort	**Weight of VR headsets** contributes significantly to discomfort, particularly in the neck and shoulders, due to increased muscle strain and pressure on the head. [73]
	Design and fit of VR headsets have a direct impact on physical comfort, with heavier headsets generally leading to shorter periods of tolerable use. [74]
Visual Strain	**Prolonged exposure to digital screens**, including VR, can lead to visual strain, dry eyes, and discomfort. This is often due to a combination of factors including screen flicker, poor resolution, and the close proximity of screens to the eyes. [75]
	3D stereoscopic content in VR can exacerbate eye strain and visual discomfort due to vergence-accommodation conflicts, which require constant eye adjustment to maintain a clear image. [76]
	Brain wave studies have shown that VR, especially when viewed on larger screens, can cause significant visual fatigue, which is reflected in changes in brain wave activity and increased visual load. [77]
Spatial Disorientation and Balance Issues	**Virtual reality environments** can cause spatial disorientation and balance issues due to mismatches between visual inputs from the VR system and the body's vestibular and proprioceptive senses. This can lead to increased postural instability and balance problems, sometimes persisting after the VR session has ended. [78]
	Full-immersion VR games, especially those with changing backgrounds, have been found to significantly affect static balance, leading to dizziness and other adverse effects such as eye fatigue. [79]
Mental Fatigue	**Cognitive load** in VR environments can lead to mental fatigue, particularly when users engage in complex tasks or face information overload. Studies have shown that VR environments can increase

	cognitive load, leading to reduced performance and increased mental strain. [80]
	Prolonged use of VR can induce mental fatigue, which impairs cognitive functions such as attention and task performance. This has been observed in both simulated and real-world environments. [81-82

The XRSISE [31] system enhances XR training ergonomics through advanced technologies. It uses Digital Human Models (DHM) to simulate tasks and assess ergonomic risks, allowing for preemptive adjustments to reduce physical strain. Its Biophysical Assessment Module analyzes biomechanics such as posture and muscle strain, enabling ergonomic optimization of virtual environments. The system personalizes training scenarios to individual ergonomic needs via virtual profiles, ensuring active engagement in safe, optimized settings. Moreover, it features real-time ergonomic feedback tools that facilitate immediate adjustments during training sessions, enhancing both safety and comfort. These integrated elements underscore XRSISE's commitment to embedding ergonomic principles deeply within industrial XR training systems, aiming to elevate safety, comfort, and efficiency.

Zhang et al. [83] investigated the impact of significant anatomical contractions on user comfort in virtual reality (VR) and augmented reality (AR) environments. By using surface electromyography (EMG) sensors, the authors measured and modeled the substantial strain levels experienced by users when using head-mounted displays (HMDs). The study proposed a biophysically-based computational model capable of predicting users' maximum contraction levels (MCL) during and before head movements, thereby forecasting potential discomfort. Through user experiments and exploratory studies, the accuracy of the model was evaluated, and its potential to optimize visual target layouts to reduce bottlenecks was demonstrated. The model's success shows that prior to designing and deploying VR/AR applications, computer-based predictions can help reduce user discomfort, providing a new direction for future health-focused VR/AR design.

5.3 Ethical and Privacy Considerations

As Extended Reality (XR) technology advances, especially in manufacturing, ethical and privacy concerns have become critical discussion points. The integration of XR in industrial settings involves the collection of significant personal and operational data, raising issues around data security, user consent, and potential misuse. The immersive nature of XR further complicates these concerns, making it essential to address them to ensure responsible and ethical deployment of the technology. This section will explore these ethical and privacy challenges and discuss strategies to mitigate them in the context of XR's application in manufacturing.

Holderman et al. [84] outline the essential privacy, safety, and wellbeing considerations necessary for AR and VR technologies. They emphasize privacy-centric technology practices across hardware and application layers, ethical and transparent information collection, especially regarding indigenous and minority cultures, and the need for privacy by design in open-source XR frameworks. The paper serves as a crucial reminder of the societal impacts these technologies may have, pushing for developers and companies to adopt responsible design practices

Maurice et al. [85] discuss the ethical and social considerations for the introduction of human-centered technologies in workplaces, particularly focusing on collaborative robots, exoskeletons, and wearable sensors. The study addresses both the potential and the challenges of these technologies in improving working conditions, particularly in reducing the prevalence of musculoskeletal disorders among workers. However, it underscores that while these technologies can improve physical safety, their successful deployment hinges on addressing ethical and social aspects to ensure technology acceptance.

Indiparambil [86] delves into the complex socio-ethical issues associated with on-the-job surveillance, emphasizing the clash between the potential benefits of surveillance, such as increased profitability and productivity, and its ethical pitfalls, particularly the pervasive invasion of privacy. The paper critically evaluates both the technological frameworks that facilitate surveillance and the justifications often cited for its use, such as workplace safety and risk management. Indiparambil argues that the moral and social implications of surveillance often transcend the immediate benefits touted by organizations, urging a reevaluation of ethical practices in workplace monitoring. The study highlights the dual nature of surveillance as both a method of coercive control and a form of care, exploring how these dimensions influence organizational behavior and employee perceptions. Indiparambil proposes an ethics of workplace surveillance founded on trust and transparency, suggesting modifications to traditional surveillance practices to better align them with ethical principles and legal compliance.

By integrating these insights, it becomes clear that while XR technologies offer substantial benefits, they also require careful consideration of ethical and privacy issues to ensure they make a positive contribution to society and do not infringe on individual rights. A comprehensive framework for addressing these issues is crucial, and the involvement of stakeholders from various sectors is essential to ensure these technologies are implemented responsibly and with respect for user autonomy and privacy. To provide a comprehensive framework for guiding ethical and privacy considerations in Extended Reality (XR) technology, we can systematically explore four key aspects:

1. Policy and Regulation

Privacy Laws and Standards: Establish and maintain global and regional privacy laws and standards that cover the application of XR technology.

Transparency: Ensure transparency in the collection and use of personal data in XR applications, enabling users to understand how their data is handled.

Compliance Audits: Conduct regular ethical and privacy compliance audits to ensure that technology applications adhere to legal and regulatory frameworks.

2. Design Principles

Privacy by Design: Incorporate privacy protection measures during the design and development stages of XR systems, using Privacy Enhancing Technologies (PETs).

Data Minimization: Collect only the minimum amount of data necessary to perform specific functions.

User Control and Consent: Provide mechanisms for users to control their data and the extent of its sharing.

3. Technology and Tools

Encryption and Anonymization Technologies: Use advanced encryption and data anonymization technologies to ensure the security of user data.

Ongoing Technology Updates: Keep up with technological advancements and regularly update systems and software to guard against new security threats.

Vulnerability Management: Establish a systematic approach to identify, assess, and remediate security vulnerabilities.

4. Education and Training

Developer and Operator Training: Train developers and operators on ethics and privacy, enhancing their awareness in the design and implementation of XR applications.

User Education: Educate users on how to safely use XR technology and their rights regarding privacy and data protection.

Public Awareness: Raise public awareness about the ethical and privacy issues related to XR technology through public discussions and media collaborations.

Figure 3: XR Technology Ethics and Privacy Framework

6 Challenges and Future Prospects

As Extended Reality (XR) technology becomes increasingly integrated into manufacturing, it presents significant potential but also faces various technical challenges, adoption barriers, and uncertainties about future developments. In this chapter, we will explore these aspects in detail and look ahead to the future trends of XR technology.

6.1 Technical Challenges

Despite the significant progress of XR technology, several technical challenges remain. Current XR devices face limitations in terms of computing power, display resolution, battery life, and user comfort; for instance, the front-heavy design of many XR devices can cause neck fatigue during extended use, and both weight distribution and heat management require further optimization to enhance the user experience. Additionally, creating high-quality XR content demands substantial resources and expertise, particularly in manufacturing, where producing accurate 3D models and realistic virtual environments tailored to diverse industrial needs remains a challenging task. To ensure immersive experiences and user satisfaction, XR systems must process vast amounts of data in real-time and provide low-latency feedback, which places high demands on computing power and network connectivity, especially in multi-user environments and cloud-based XR applications. Moreover, as XR devices are increasingly used in manufacturing, ensuring the secure storage and transmission of sensitive data and protecting user privacy have become critical technical challenges, particularly in scenarios involving industrial secrets.

6.2 Adoption Barriers

While XR technology holds great potential in manufacturing, several barriers hinder its adoption. High initial investment costs and ongoing maintenance expenses present major obstacles for many companies, particularly small and medium-sized enterprises, which face significant financial burdens when purchasing XR devices, developing custom content, and training employees. Additionally, XR technology is still rapidly evolving, and many aspects remain immature, with a lack of industry standards. This can result in compatibility issues between devices and platforms from different vendors, making adoption more challenging for companies. Furthermore, the implementation of XR technology requires professionals with relevant technical expertise, who are currently scarce in the market, necessitating substantial investment in training existing staff or recruiting new talent. Finally, for some workers in traditional manufacturing sectors, adapting to and using XR technology may involve psychological barriers and a steep learning curve, leading to resistance and adaptation difficulties as companies introduce these new technologies.

6.3 Future Trends

Looking ahead, the application of XR technology in manufacturing will continue to expand and deepen as the technology advances and the market matures. Future XR devices are expected to become lighter, more power-efficient, and offer higher display resolutions and computing power, with the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) providing more intelligent solutions for manufacturing. Additionally, XR technology will further enhance collaboration across regions and teams, playing a crucial role in remote maintenance, real-time production monitoring, and global manufacturing. The combination of XR with digital twin technology will increasingly blur the line between the virtual and real worlds. As technology advances and costs decrease, companies will find it easier to customize XR solutions to meet their specific needs, maximizing productivity and employee satisfaction. Furthermore, as XR technology becomes more widely adopted in industry, the establishment of standards and ecosystems will improve interoperability between devices and platforms, thereby lowering adoption barriers for companies.

Conclusion

This work has systematically explored the role of Extended Reality (XR) technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), in the context of Industry 5.0, with a particular focus on their impact on human users in manufacturing environments. By addressing four key research questions, this study offers a comprehensive understanding of the technological advancements, practical applications, and human-centric considerations that are essential for the successful integration of XR technologies in the manufacturing sector. The following are he answers to the four questions raised in this article:

- Key Technologies in XR Applications for Industry 5.0 (Question 1): The analysis has identified and categorized the critical technologies driving XR applications in Industry 5.0, including advanced hardware like head-mounted displays (HMDs), hand-held devices, and various sensors. Software platforms such as Unity and Unreal Engine also play a crucial role in enhancing the capabilities of these technologies. These advancements are pivotal in improving productivity, efficiency, and customization within manufacturing processes, thereby supporting the transition towards a more human-centered industrial paradigm.
- Impact of XR Applications on Manufacturing (Question 2): The study has shown that XR technologies significantly influence manufacturing processes by enhancing efficiency, accuracy, worker safety, and training. AR, VR, and MR applications enable more precise and interactive training, reduce error rates, and improve the overall quality of manufacturing operations. The practical benefits of these technologies are evident in case studies and empirical data, demonstrating their effectiveness in real-world manufacturing environments.
- Social and Human Factors Associated with XR Technologies (Question 3): The integration of XR technologies in industrial settings brings about important social implications and human factors that must be addressed. The study highlights the need for considering worker acceptance, well-being, and ergonomics in the design and deployment of XR applications. Ensuring that these technologies augment rather than replace human capabilities is essential for aligning with the human-centric values of Industry 5.0. Strategies to mitigate potential negative effects on the workforce, such as cognitive load and physical strain, have been proposed to facilitate smoother adoption.
- Data Security and Privacy in XR Applications (Question 4): The study also examined the challenges related to data security and privacy when implementing XR technologies in industrial applications. As XR technologies collect and process significant amounts of data, ensuring the protection of sensitive

information and compliance with data protection regulations is critical. The paper discusses best practices and potential solutions to maintain robust security and privacy standards, allowing organizations to leverage the benefits of XR technologies without compromising data integrity.

In conclusion, XR technologies hold immense potential for transforming manufacturing processes in the era of Industry 5.0. However, their successful implementation requires careful consideration of the technological, human-centric, and ethical challenges identified in this study. By addressing these challenges and aligning XR applications with the values of Industry 5.0, the manufacturing industry can achieve greater sustainability, efficiency, and worker well-being. This paper provides a valuable reference framework for future XR design and application, ensuring that these technologies contribute positively to the evolution of a more human-centered industrial landscape.

REFERENCES

[1] Cipresso, Pietro, et al. "The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature." Frontiers in psychology 9 (2018): 2086.

[2] Ivanov, Dmitry. "The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives." International Journal of Production Research 61.5 (2023): 1683-1695.

[3] Rožanec, Jože M., et al. "Human-centric artificial intelligence architecture for industry 5.0 applications." International journal of production research 61.20 (2023): 6847-6872.

[4] Egger, Johannes, and Tariq Masood. "Augmented reality in support of intelligent manufacturing–a systematic literature review." Computers & Industrial Engineering 140 (2020): 106195.

[5] Yang, Jialu, et al. "Review of human-machine interaction towards industry 5.0: human-centric smart manufacturing." International design engineering technical conferences and computers and information in engineering conference. Vol. 86212. American Society of Mechanical Engineers, 2022.

[6] Egger, Johannes, and Tariq Masood. "Augmented reality in support of intelligent manufacturing–a systematic literature review." Computers & Industrial Engineering 140 (2020): 106195.

[7] Doolani, Sanika, et al. "A review of extended reality (xr) technologies for manufacturing training." Technologies 8.4 (2020): 77.

[8] Khamaisi, Riccardo Karim, et al. "UX in AR-supported industrial human–robot collaborative tasks: a systematic review." Applied Sciences 11.21 (2021): 10448.

[9] Eswaran, M., and MVA Raju Bahubalendruni. "Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review." Journal of Manufacturing Systems 65 (2022): 260-278.

[10] Adel, Amr. "Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas." Journal of Cloud Computing 11.1 (2022): 40.

[11] Bernstein, William Z., et al. "Towards data and model interoperability for industrial extended reality in manufacturing." Journal of Computing and Information Science in Engineering 23.6 (2023): 060804.

[12] Yin, Yue, et al. "A state-of-the-art survey on Augmented Reality-assisted Digital Twin for futuristic human-centric industry transformation." Robotics and Computer-Integrated Manufacturing 81 (2023): 102515.

[13] Zhang, Chao, et al. "Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review." Advanced Engineering Informatics 57 (2023): 102121.

[14] Alhakamy, A'aeshah. "Extended Reality (XR) Toward Building Immersive Solutions: The Key to Unlocking Industry 4.0." ACM Computing Surveys 56.9 (2024): 1-38.

[15] Kamdjou, Hugues M., et al. "Resource-Constrained eXtended reality operated with digital twin in industrial Internet of Things." IEEE Open Journal of the Communications Society (2024).

[16] Ivanov, Dmitry. "The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives." International Journal of Production Research 61.5 (2023): 1683-1695.

[17] Yang, Jialu, et al. "Review of human-machine interaction towards industry 5.0: human-centric smart manufacturing." International design engineering technical conferences and computers and information in engineering conference. Vol. 86212. American Society of Mechanical Engineers, 2022.

[18] Milgram, Paul, et al. "Augmented reality: A class of displays on the reality-virtuality continuum." Telemanipulator and telepresence technologies. Vol. 2351. Spie, 1995.

[19] Cipresso, Pietro, et al. "The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature." Frontiers in psychology 9 (2018): 2086.

[20] Seeliger, Arne, Raphael P. Weibel, and Stefan Feuerriegel. "Context-adaptive visual cues for safe navigation in augmented reality using machine learning." International Journal of Human–Computer Interaction 40.3 (2024): 761-781.

[21] Lu, Xueshi, et al. "itext: Hands-free text entry on an imaginary keyboard for augmented reality systems." The 34th Annual ACM Symposium on User Interface Software and Technology. 2021.

[22] Wysopal, Abby, et al. "Level-of-detail ar: Dynamically adjusting augmented reality level of detail based on visual angle." 2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR). IEEE, 2023.

[23] Seeliger, Arne, Long Cheng, and Torbjørn Netland. "Augmented reality for industrial quality inspection: An experiment assessing task performance and human factors." Computers in Industry 151 (2023): 103985.

[24] Tu, Xinyi, et al. "TwinXR: Method for using digital twin descriptions in industrial eXtended reality applications." Frontiers in Virtual Reality 4 (2023): 1019080.

[25] Morales Mojica, Cristina M., et al. "A holographic augmented reality interface

for visualizing of MRI data and planning of neurosurgical procedures." Journal of Digital Imaging 34 (2021): 1014-1025.

[26] Pfeuffer, Ken, et al. "ARtention: A design space for gaze-adaptive user interfaces in augmented reality." Computers & Graphics 95 (2021): 1-12.

[27] Lei, Xin, Yueh-Lin Tsai, and Pei-Luen Patrick Rau. "Harnessing the visual salience effect with augmented reality to enhance relevant information and to impair distracting information." International Journal of Human–Computer Interaction 39.6 (2023): 1280-1293.

[28] Kolla, Sri Sudha Vijay Keshav, Andre Sanchez, and Peter Plapper. "Comparing software frameworks of augmented reality solutions for manufacturing." Procedia Manufacturing 55 (2021): 312-318.

[29] Filippidis, Achilleas, et al. "VR Isle Academy: A VR Digital Twin Approach for Robotic Surgical Skill Development." arXiv preprint arXiv:2406.00002 (2024).

[30] Šarić, Matko, et al. "Extended reality telemedicine collaboration system using patient avatar based on 3D body pose estimation." Sensors 24.1 (2023): 27.

[31] Pavlou, Michail, et al. "XRSISE: An XR training system for interactive simulation and ergonomics assessment." Frontiers in Virtual Reality 2 (2021): 646415.

[32] Sardar, Suman Kalyan, et al. "Ergonomic risk assessment of manufacturing works in virtual reality context." International Journal of Human–Computer Interaction 40.14 (2024): 3856-3872.

[33] Chang, Eunhee, Yongjae Lee, and Byounghyun Yoo. "A user study on the comparison of view interfaces for VR-AR communication in XR remote collaboration." International Journal of Human–Computer Interaction (2023): 1-16.

[34] Unity Technologies. (2022). Unity Manual. Retrieved from https://docs.unity3d.com/Manual/index.html

[35] Epic Games. (2022). Unreal Engine Documentation. Retrieved from https://docs.unrealengine.com/en-US/index.html

[36] Apple Inc. (2022). ARKit. Retrieved from Augmented Reality - Apple Developer

[37] Google LLC. (2022). ARCore. Retrieved from https://developers.google.com/ar

[38] Microsoft Corporation. (2020). Windows Mixed Reality. Retrieved from https://docs.microsoft.com/en-us/windows/mixed-reality/

[39] Bozkir, Efe, et al. "Embedding Large Language Models into Extended Reality: Opportunities and Challenges for Inclusion, Engagement, and Privacy." Proceedings of the 6th ACM Conference on Conversational User Interfaces. 2024.

[40] Kernan Freire, Samuel, et al. "Harnessing large language models for cognitive

assistants in factories." Proceedings of the 5th International Conference on Conversational User Interfaces. 2023.

[41] Konenkov, Mikhail, et al. "Vr-gpt: Visual language model for intelligent virtual reality applications." arXiv preprint arXiv:2405.11537 (2024).

[42] Khelifi, Syrine, and Alexis Morris. "Mixed Reality IoT Smart Environments with Large Language Model Agents." 2024 IEEE 4th International Conference on Human-Machine Systems (ICHMS). IEEE, 2024.

[43] Choi, Sung Ho, et al. "An xr-based approach to safe human-robot collaboration." 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW). IEEE, 2022.

[44] Carriero, Graziano, et al. "Human-robot collaboration: An augmented reality toolkit for bi-directional interaction." Applied Sciences 13.20 (2023): 11295.

[45] Matsas, Elias, and George-Christopher Vosniakos. "Design of a virtual reality training system for human–robot collaboration in manufacturing tasks." International Journal on Interactive Design and Manufacturing (IJIDeM) 11 (2017): 139-153.

[46] Solanes, J. Ernesto, et al. "Human–robot collaboration for safe object transportation using force feedback." Robotics and Autonomous Systems 107 (2018): 196-208.

[47] Abidi, Mustufa Haider, et al. "Assessment of virtual reality-based manufacturing assembly training system." The International Journal of Advanced Manufacturing Technology 105.9 (2019): 3743-3759.

[48] Ortega-Gras, Juan-José, et al. "Designing a technological pathway to empower vocational education and training in the circular wood and furniture sector through extended reality." Electronics 12.10 (2023): 2328.

[49] Mourtzis, Dimitris, and John Angelopoulos. "Development of an Extended Reality-Based Collaborative Platform for Engineering Education: Operator 5.0." Electronics 12.17 (2023): 3663.

[50] Ulmer, Jessica, et al. "Gamified virtual reality training environment for the manufacturing industry." 2020 19th international conference on mechatronics-mechatronika (ME). IEEE, 2020.

[51] Virtual Reality-Based Engineering Education to Enhance Manufacturing Sustainability in Industry 4.0

[52] Aschauer, Andrea, Irene Reisner-Kollmann, and Josef Wolfartsberger. "Creating an open-source augmented reality remote support tool for industry: challenges and learnings." Procedia Computer Science 180 (2021): 269-279.

[53] Mourtzis, Dimitris, Vasileios Siatras, and John Angelopoulos. "Real-time remote maintenance support based on augmented reality (AR)." Applied Sciences 10.5

(2020): 1855.

[54] Cavaleri, Joey, et al. "Remote video collaboration during COVID-19." 2021 32nd Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC). IEEE, 2021.

[55] Masoni, Riccardo, et al. "Supporting remote maintenance in industry 4.0 through augmented reality." Procedia manufacturing 11 (2017): 1296-1302.

[56] Abidi, Mustufa H., et al. "Semi-immersive virtual turbine engine simulation system." International Journal of Turbo & Jet-Engines 35.2 (2018): 149-160.

[57] Lupinetti, Katia, et al. "Exploring the benefits of the virtual reality technologies for assembly retrieval applications." International conference on augmented reality, virtual reality and computer graphics. Cham: Springer International Publishing, 2019.

[58] Ratava, J., et al. "Quality assurance and process control in virtual reality." Procedia Manufacturing 38 (2019): 497-504.

[59] Szajna, Andrzej, et al. "The production quality control process, enhanced with augmented reality glasses and the new generation computing support system." Procedia computer science 176 (2020): 3618-3625.

[60] Alves, Joao Bernardo, et al. "Using augmented reality for industrial quality assurance: a shop floor user study." The International Journal of Advanced Manufacturing Technology 115.1 (2021): 105-116.

[61] Serras, Manex, et al. "Dialogue enhanced extended reality: Interactive system for the operator 4.0." Applied Sciences 10.11 (2020): 3960.

[62] Prati, Elisa, et al. "An approach based on VR to design industrial human-robot collaborative workstations." Applied Sciences 11.24 (2021): 11773.

[63] Yang, Chao, et al. "Extended reality application framework for a digital-twin-based smart crane." Applied Sciences 12.12 (2022): 6030.

[64] Peruzzini, Margherita, et al. "Using virtual manufacturing to design human-centric factories: an industrial case." The international journal of advanced manufacturing technology 115.3 (2021): 873-887.

[65] Zimmerer, Chris, et al. "Reducing the cognitive load of playing a digital tabletop game with a multimodal interface." Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems. 2022.

[66] Xia, Guobin, et al. "A comparative study of colour effects on cognitive performance in real-world and VR environments." Brain sciences 12.1 (2021): 31.

[67] Zhang, Mingming, Guanhua Hou, and Yeh-Cheng Chen. "Effects of interface layout design on mobile learning efficiency: a comparison of interface layouts for mobile learning platform." Library hi tech 41.5 (2023): 1420-1435.

[68] Zhou, Jianlong, Simon Luo, and Fang Chen. "Effects of personality traits on user trust in human–machine collaborations." Journal on Multimodal User Interfaces 14.4 (2020): 387-400.

[69] Bellman, Steven, and Kyle B. Murray. "Feedback, task performance, and interface preferences." European Journal of Information Systems 27.6 (2018): 654-669.

[70] Han, Jining, Qiyu Zheng, and Yunan Ding. "Lost in virtual reality? Cognitive load in high immersive VR environments." Journal of Advances in Information Technology 12.4 (2021).

[71] Caserman, Polona, et al. "Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook." Virtual Reality 25.4 (2021): 1153-1170.

[72] Carnegie, Kieran, and Taehyun Rhee. "Reducing visual discomfort with HMDs using dynamic depth of field." IEEE computer graphics and applications 35.5 (2015): 34-41.

[73] Kim, Eunjee, and Gwanseob Shin. "User discomfort while using a virtual reality headset as a personal viewing system for text-intensive office tasks." Ergonomics 64.7 (2021): 891-899.

[74] Sarig-Bahat, Hilla, Patrice L. Tamar Weiss, and Yocheved Laufer. "Neck pain assessment in a virtual environment." Spine 35.4 (2010): E105-E112.

[75] Mehra, Divy, and Anat Galor. "Digital screen use and dry eye: a review." Asia-Pacific journal of ophthalmology 9.6 (2020): 491-497.

[76] Shibata, Takashi, et al. "The zone of comfort: Predicting visual discomfort with stereo displays." Journal of vision 11.8 (2011): 11-11.

[77] Lee, Chun-Chia, Hsiu-Sen Chiang, and Meng-Hsing Hsiao. "Effects of screen size and visual presentation on visual fatigue based on regional brain wave activity." The journal of supercomputing 77 (2021): 4831-4851.

[78] Nishiike, Suetaka, et al. "The effect of visual-vestibulosomatosensory conflict induced by virtual reality on postural stability in humans." The Journal of Medical Investigation 60.3.4 (2013): 236-239.

[79] Park, SoHu, and GyuChang Lee. "Full-immersion virtual reality: Adverse effects related to static balance." Neuroscience letters 733 (2020): 134974.

[80] Li, Chunping, et al. "Cognitive load measurement in the impact of VR intervention in learning." 2022 International Conference on Advanced Learning Technologies (ICALT). IEEE, 2022.

[81] Xiageyiqi Mun, Sungchul, Eun-Soo Kim, and Min-Chul Park. "Effect of mental fatigue caused by mobile 3D viewing on selective attention: An ERP study." International Journal of Psychophysiology 94.3 (2014): 373-381.

[82] Zeuwts, Linus HRH, et al. "Mental fatigue delays visual search behaviour in young cyclists when negotiating complex traffic situations: A study in virtual reality." Accident Analysis & Prevention 161 (2021): 106387.

[83] Zhang, Yunxiang, Kenneth Chen, and Qi Sun. "Toward Optimized VR/AR Ergonomics: Modeling and Predicting User Neck Muscle Contraction." ACM SIGGRAPH 2023 Conference Proceedings. 2023.

[84] Callie Holderman, Eakta Jain, Michael Running Wolf, and Liv Erickson. 2022. Privacy, Safety and Wellbeing: Solutions for the Future of AR and VR. In ACM SIGGRAPH 2022 Panels (SIGGRAPH '22). Association for Computing Machinery, New York, NY, USA, Article 1, 1–2. https://doi.org/10.1145/3532718.3535620

[85] Maurice, Pauline, et al. "Ethical and social considerations for the introduction of human-centered technologies at work." 2018 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO). IEEE, 2018.

[86] Indiparambil, Jijo James. "Privacy and beyond: Socio-ethical concerns of 'on-the-job'surveillance." Asian Journal of Business Ethics 8.1 (2019): 73-105.