A Survey of Biophilic Design and Immersive Technologies in Enhancing Human-Computer Interaction

Abstract

This survey explores the integration of biophilic design and immersive technologies, such as virtual reality (VR) and augmented reality (AR), in enhancing human-computer interaction (HCI). By blending natural elements with digital interfaces, these technologies promote user engagement, psychological well-being, and cognitive performance across various domains. The study highlights VR's potential in education, healthcare, and social contexts, demonstrating its capacity to improve learning outcomes, facilitate complex medical procedures, and enhance social interactions. The integration of biophilic design principles further supports mental and physical health, creating environments that resonate with innate human affinities for nature. The survey also examines the role of multi-sensory experiences, eye-tracking, and EEG technologies in optimizing user interactions by providing real-time feedback and adaptive content. Ethical and inclusive design considerations are emphasized to ensure accessibility and user satisfaction. Future research directions include addressing challenges such as motion sickness, refining design techniques, and exploring personalized solutions to enhance the effectiveness of immersive technologies. This comprehensive approach underscores the transformative potential of biophilic design and immersive technologies in revolutionizing HCI and creating engaging, inclusive, and effective digital environments.

1 Introduction

1.1 Integration of Biophilic Design and Immersive Technologies

The integration of biophilic design with immersive technologies, such as virtual reality (VR), transforms human-computer interaction by merging natural elements with advanced digital interfaces, thereby fostering environments that enhance psychological and physical well-being [1]. This extension into digital realms allows immersive technologies to replicate biophilic environments, providing similar benefits [2].

Bae [3] explores VR's capacity to enhance empathy through biophilic design, highlighting how immersive experiences can create emotional connections. In educational contexts, biophilic design supports learning by fostering engaging environments [4], a point reinforced by Pellas [5], who categorizes research on VR in education and its efficacy in enhancing learning outcomes.

Macchini [6] emphasizes VR's role in improving user comfort and performance, particularly through Body-Machine Interfaces (BoMIs) for teleoperating non-anthropomorphic robots, which illustrates immersive technologies' potential for intuitive human-computer interactions. Elfarri's concept of 'capability level' [7] categorizes digital twins based on functionality, which can be enhanced through biophilic and immersive design principles.

Yamagami's proposed Two-in-One design space [8] facilitates accessible bimanual interactions in VR, reinforcing the synergy between biophilic design and immersive technologies. Basu's evaluation

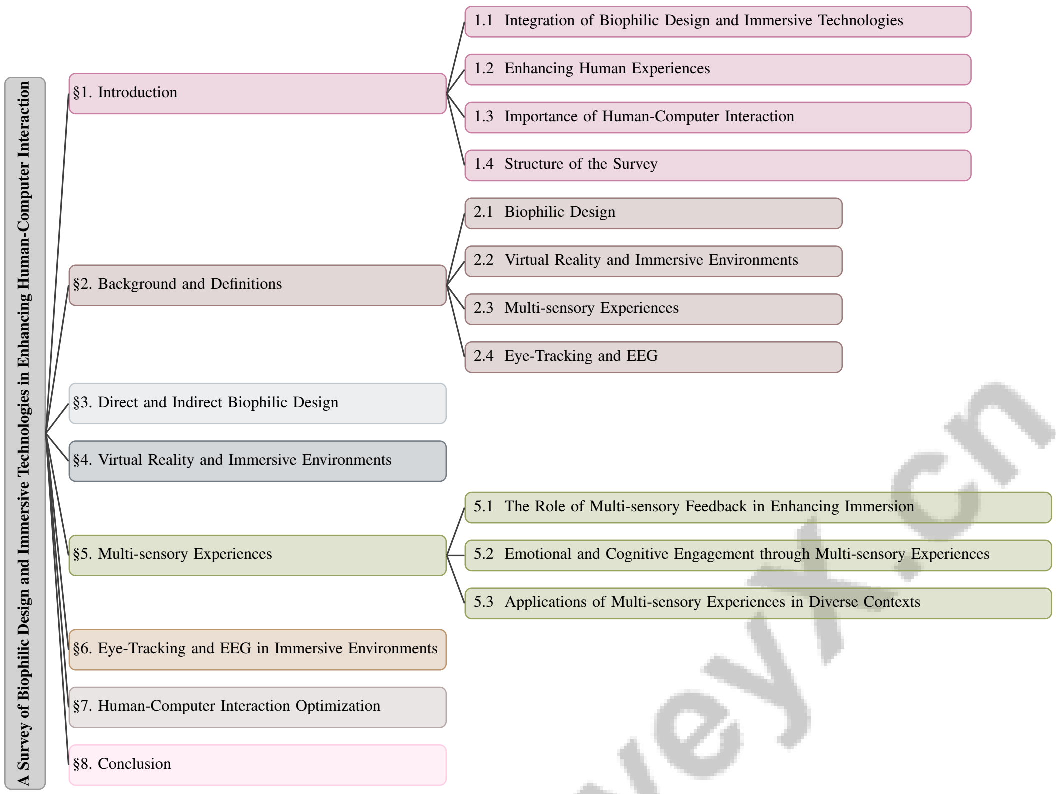

Figure 1: chapter structure

[9] of user navigation performance in immersive versus non-immersive VR environments underscores the importance of user familiarity with interface types for effective interaction.

Yang [10] addresses limited immersion in VR displays, advocating for new methods to enhance user engagement. Chen [11] proposes augmenting 2D documents with immersive technologies, including VR, MR, voice interfaces, and generative AI, to improve understanding and interaction workflows.

The integration of biophilic design and immersive technologies significantly enhances human-computer interaction by improving aesthetic appeal and functionality while fostering environments that resonate with human needs and behaviors. This synergy addresses the psychological and physical benefits of nature connection, leveraging technologies like VR and AR to create responsive spaces that adapt to users' emotional states. By aligning design principles with human biology and psychology, these environments promote well-being and facilitate effective interactions, ultimately transforming user engagement [12, 11, 13, 14].

1.2 Enhancing Human Experiences

The integration of immersive technologies, such as VR, AR, and the Internet of Things (IoT), enriches human experiences by fostering deeper engagement and satisfaction. These technologies enhance cognitive functions and provide enjoyable interactions; for instance, VR improves spatial presence and embodiment in controlling non-anthropomorphic drones, highlighting user engagement's importance [6]. The convergence of IoT within the Metaverse further emphasizes the necessity for immersive experiences to maintain user engagement and satisfaction [15].

In educational and collaborative contexts, immersive environments surpass traditional setups by facilitating enhanced collaboration and sense-making [16]. Social VR programs also target social engagement and cognitive impairment among older adults, contributing to enriched experiences by addressing specific needs [17].

Biophilic design, when combined with immersive technologies, significantly improves living conditions by addressing biological and psychological needs, particularly in extreme climates [18]. This

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approach not only reconnects individuals with nature, enhancing health and well-being but also aligns with immersive technologies' goals of creating environments that intuitively meet human needs.

Recent advancements in immersive technologies demonstrate their potential to enhance user experiences across various domains. By integrating VR, AR, and MR into applications like document interaction and virtual companions, these technologies significantly improve engagement and satisfaction. Immersive environments also facilitate safer training for hazardous tasks while gamifying experiences to boost motivation and knowledge retention. Virtual companions adapt to users' emotional states, addressing issues such as social isolation and cognitive enhancement. These findings collectively highlight that prioritizing user engagement and satisfaction is crucial for the successful implementation of immersive technologies, leading to more meaningful human experiences [11, 19, 14].

1.3 Importance of Human-Computer Interaction

Effective human-computer interaction (HCI) is essential in modern technology, facilitating the seamless integration of advanced technologies into daily life and enhancing user experience and accessibility. The complexities of collaboration in immersive environments, such as VR and AR, present significant challenges for user interaction and communication [20], necessitating sophisticated HCI frameworks to improve engagement and satisfaction.

In medical care, integrating AI with VR technologies offers advancements in diagnostics and treatment, contingent upon robust HCI systems that ensure accurate outcomes [21]. Similarly, guiding small Unmanned Aerial Systems (sUAS) to achieve specific objectives while maintaining collective behaviors illustrates the importance of effective human-swarm interaction, a subset of HCI requiring innovative management approaches [22].

The educational sector also benefits from effective HCI, particularly in integrating VR in STEM education. Designing HCI interfaces is critical for enhancing student experiences, promoting a learner-centered approach that improves educational outcomes [5]. Moreover, the lack of contact with nature among modern individuals, especially children, correlates with negative impacts on health [1], emphasizing biophilic design's role in HCI to reconnect users with natural elements and promote well-being.

Developing natural user interfaces in mobile and immersive environments poses challenges as traditional input methods are often limited by physical constraints. Effective HCI is vital for creating intuitive interaction models that enhance user experience. Furthermore, the ecological validity of VR research, particularly in spatial navigation, relies on effective HCI to ensure that responses in virtual environments reflect real-world behaviors. These considerations underscore HCI's critical importance in contemporary technology development and implementation. Focusing on accessibility and effectiveness enhances user satisfaction across diverse fields. Recent research shows how immersive technologies can transform traditional 2D document interactions into richer experiences, addressing cognitive challenges in content understanding and creation. Additionally, studies reveal that effective HCI design principles can significantly improve students' comprehension and application of user experience concepts, fostering a user-centered approach to interface design [11, 23].

1.4 Structure of the Survey

This survey systematically explores the intersection of biophilic design and immersive technologies in enhancing human-computer interaction. The introduction establishes the synergy between these elements, emphasizing their transformative potential for user experiences. The background and definitions section provides foundational knowledge on key concepts such as biophilic design, virtual reality, and multi-sensory experiences, establishing a common ground for subsequent discussions.

The survey delves into specific aspects of biophilic design, distinguishing between direct and indirect approaches within virtual environments. The following section examines VR and immersive environments, focusing on innovative strategies to boost user engagement and enhance the sense of presence. It explores effective simulations of natural and extreme environments, drawing insights from studies assessing VR's impact on user experience, including subjective evaluations of presence and objective measures like neurophysiological responses. This highlights VR's potential to create realistic, interactive experiences in contexts like cultural heritage representation and serious gaming, facilitating deeper user involvement and learning outcomes [11, 24, 19, 25].

The discussion then shifts to multi-sensory experiences, emphasizing their contribution to user immersion and emotional engagement. Various studies illustrate how VR and AR can transform traditional 2D document interactions into immersive experiences, improve emotional expression through innovative communication tools, and utilize multimodal interactions for idea visualization. These advancements enrich user experiences and promote effective communication across diverse contexts, including education, healthcare, and conflict resolution [11, 26, 27, 28, 29]. The applications of these experiences across diverse contexts are also explored, demonstrating their versatility and impact.

Subsequently, the survey analyzes eye-tracking and EEG technologies in monitoring and enhancing user interactions within immersive environments, underscoring the importance of physiological data in optimizing experiences.

The survey concludes by focusing on optimizing human-computer interaction through biophilic design and immersive technologies, addressing ethical and inclusive design considerations. It highlights promising future directions and research opportunities in the interdisciplinary realm of immersive information experiences and the Industrial Metaverse, emphasizing the need for innovative applications that leverage emerging technologies like augmented and mixed reality, generative AI, and opportunistic edge computing to enhance 2D document interactions and industrial operations. By outlining the concept of the Meta-Operator and identifying key challenges and potential applications for Industry 5.0, this article serves as a valuable resource for researchers aiming to advance human-centric, sustainable solutions in these evolving fields [11, 30].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Biophilic Design

Biophilic design integrates natural elements into built environments to foster connections with nature, addressing the psychological barriers prevalent in urban settings [31]. It promotes exploration and alleviates mental fatigue, enhancing psychological well-being and interpersonal connections [4]. When combined with immersive technologies like VR and AR, biophilic design creates dynamic environments that cater to users' emotional needs, enriching engagement [32, 17]. This approach is particularly beneficial in extreme environments, where challenges such as limited natural light are mitigated through innovative design [18]. Techniques like the Two-in-One method enhance accessibility for users with mobility limitations [8], while systems like the 'Tangible Web' incorporate real-world data into virtual environments to boost immersion [10].

Biophilic principles refine the concept of digital twins, enhancing their intuitiveness [7]. The integration of responsible AI and mobile edge computing supports the creation of engaging environments [15]. By fostering connections with nature and promoting psychological well-being, biophilic design, enhanced by immersive technologies, transforms domains such as healthcare and education through VR and AR advancements [14, 29, 25, 33].

2.2 Virtual Reality and Immersive Environments

Virtual Reality (VR) and immersive environments simulate natural settings, providing interactive, three-dimensional experiences that enhance spatial presence and engagement [34]. These technologies are utilized in education, healthcare, and cultural heritage to create authentic experiences. In education, VR overcomes traditional limitations, offering immersive experiences crucial for effective learning and skill development. The NOMR method immerses students in scenarios that promote scientific practice [35], while VR's educational potential is further emphasized by its impact on pedagogical approaches [5].

In healthcare, VR is transformative, particularly in therapies for mindfulness and attention training [2], and in simulating emotionally charged situations for cognitive reappraisal practice [36]. Addressing challenges like motion sickness is essential for optimizing VR's effectiveness [37]. In cultural heritage, VR presents submerged archaeological sites engagingly [24]. Social VR frameworks enhance immersive experiences by categorizing user engagement dynamics [17].

The integration of VR with XR technologies expands immersive environments' capabilities, enhancing social interactions and combating isolation, especially among older adults [38]. Haptic technologies, such as electrotactile feedback, improve user performance in tasks requiring tactile discrimination, enhancing immersion [13]. VR and immersive environments thus play a crucial role in simulating natural settings, offering transformative potential across domains by leveraging immersive capabilities to create engaging user experiences [39].

2.3 Multi-sensory Experiences

Multi-sensory experiences enhance immersion in virtual environments by engaging various senses to create comprehensive user experiences. Integrating visual, auditory, haptic, and other modalities is vital for achieving desired immersion and presence. The Component Process Model (CPM) in VR enhances emotional differentiation through active participation, enriching emotional depth [26]. Menin's taxonomy categorizes immersive simulations based on display device, immersion level, interaction methods, and feedback types, underscoring multi-sensory experiences' significance in crafting compelling virtual environments [19].

The Photosphere to Cognition Engine (P2CE) method improves visual stimuli integration with cognitive analysis systems [40]. In VR neuroscience, challenges like technical complexity are significant, but multi-sensory experiences enhance learning, empathy, and social interactions. High-fidelity sensory integration is essential for enhancing presence, as emphasized by Peinl [41].

Advanced tactile feedback systems like Digit 360 and LinkGlide enhance the haptic dimension of virtual environments, providing realistic multi-contact tactile feedback and improving tactile pattern recognition [42, 43]. Argyriou's methodology encompasses experience and interaction design layers, specifying techniques for narrative, scene design, and user navigation, ensuring engaging virtual environments that facilitate deeper cognitive and emotional engagement [32].

2.4 Eye-Tracking and EEG

Eye-tracking and electroencephalogram (EEG) technologies advance the understanding and development of immersive environments by providing insights into user interactions through monitoring visual attention and neural activity. These technologies enable real-time assessments of cognitive processes and emotional responses, enhancing VR systems' design and effectiveness. Integrating eye-tracking within VR headsets allows dynamic focus adjustments based on gaze, reducing discomfort and enhancing experience [37]. This is particularly beneficial in VR training environments, where predicting cognitive load is crucial for personalizing experiences [44].

EEG complements eye-tracking by revealing neural activity underlying interactions. Integrating subjective experiences with neurophysiological measurements like EEG is essential for assessing VR effectiveness [24]. The TPM-Net uses multimodal physiological data, including EEG, to model time perception in VR [45]. Employing EEG alongside other measures provides a robust framework for evaluating presence and immersion [39].

These technologies extend to applications like enhancing digital twin frameworks through big data cybernetics, benefiting from EEG insights [7]. Comprehensive analyses of user experiences, encompassing emotional states and interactions with smart devices, highlight their potential to inform intuitive and effective human-computer interfaces [31]. By harnessing advancements in eye-tracking and EEG, immersive environments enrich user interactions, offering valuable insights into cognitive and emotional aspects, facilitating personalized and effective interactions in applications like VR for education, healthcare, and emotional expression technologies [19, 14, 24, 29, 46].

3 Direct and Indirect Biophilic Design

Exploring biophilic design involves understanding its varied expressions and applications. This section delineates the core principles of biophilic design, which establish a framework for integrating natural elements into both physical and virtual environments. These principles elucidate the mechanisms that strengthen the human-nature connection, ultimately enhancing well-being and user experience.

To further illustrate these concepts, Figure 2 presents a figure that depicts the hierarchical structure of biophilic design. This diagram details its foundational principles, differentiates between direct and indirect approaches, and highlights the integration of biophilic design in enhancing user experiences within virtual settings. By visually categorizing these elements, the figure serves as a valuable reference for understanding how biophilic design can be effectively applied in various contexts.

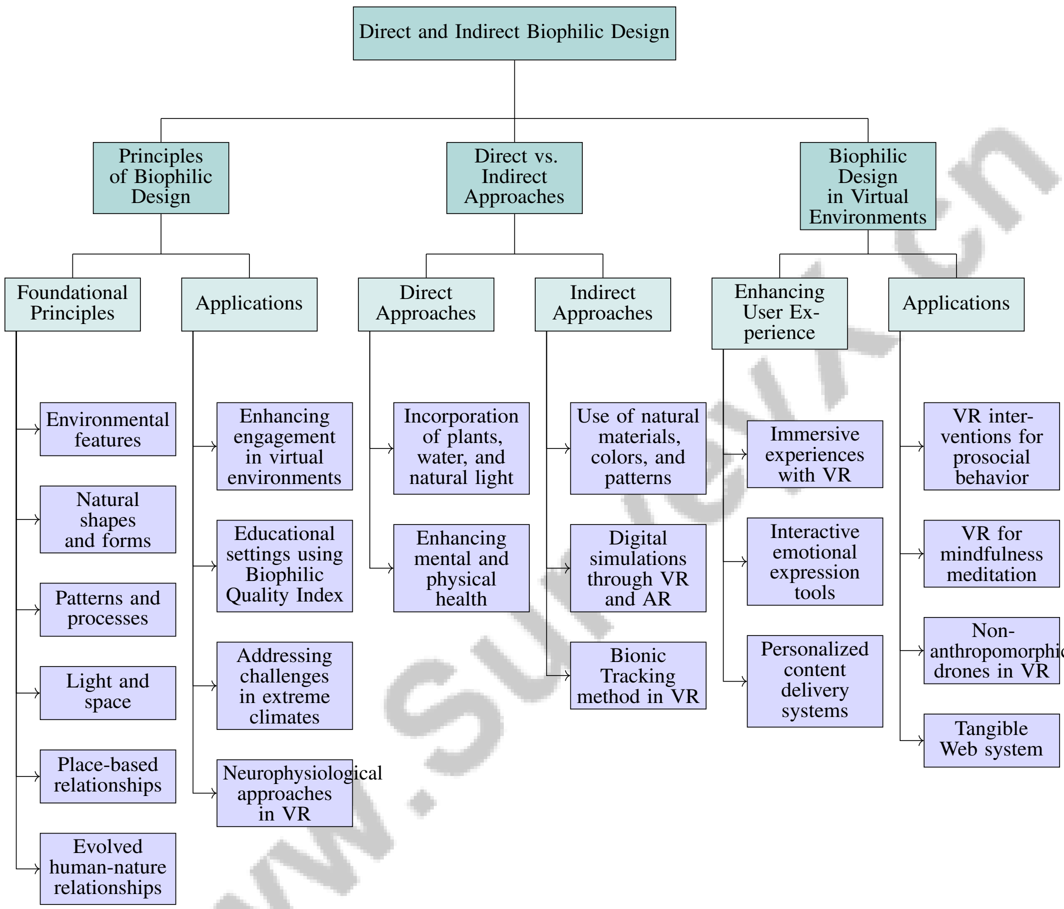

Figure 2: This figure illustrates the hierarchical structure of biophilic design, detailing its principles, approaches, and applications in virtual environments. The diagram categorizes the foundational principles of biophilic design, differentiates between direct and indirect approaches, and highlights the integration of biophilic design in enhancing user experiences within virtual settings.

3.1 Principles of Biophilic Design

Biophilic design integrates natural elements into built environments, fostering a connection to nature that enhances psychological and physiological well-being. Its foundational principles encompass environmental features, natural shapes and forms, patterns and processes, light and space, place-based relationships, and evolved human-nature relationships, collectively supporting environments that resonate with biophilia, an evolutionary adaptation that enhances human well-being through nature interaction [1].

The importance of biophilic design is notably significant in virtual environments, where it enhances user engagement and satisfaction. Incorporating biophilic elements into digital spaces fosters a sense of presence and plausibility, aligning with Slater's framework on user engagement, which categorizes it into Place Illusion (PI) and Plausibility (Psi). This complements technologies like AR and VR, creating immersive experiences that boost user engagement [15]. Research underscores VR's

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effectiveness in enhancing engagement, motivation, and learning outcomes, highlighting biophilic design's transformative potential in education [5].

In educational settings, biophilic design principles are operationalized through the Biophilic Quality Index (BQI), a standardized measure of learning environments' restorative qualities [4]. This benchmark underscores biophilic design's role in creating engaging and supportive learning spaces. The Two-in-One method further reinforces these principles by categorizing bimanual interactions and integrating computer assistance to enhance user engagement across diverse abilities [8].

Biophilic design also addresses challenges posed by extreme climates by optimizing environmental qualities to meet occupants' photobiological needs, ensuring effective use of natural light and other elements [18]. Incorporating neurophysiological approaches to assess emotional responses in virtual environments, such as those in the Metaverse, provides insights into the emotional depth and engagement potential of biophilic design [36].

As illustrated in Figure 3, the foundational principles of biophilic design are essential for creating environments that enhance physical, psychological, and social well-being. This figure highlights the application of biophilic design principles across various domains, including virtual environments, educational settings, and climatic adaptations. Key aspects such as user engagement and immersive experiences in virtual settings, the enhancement of learning environments and cognitive performance in educational contexts, and the adaptation to extreme climates through optimized lighting design and photobiological needs are emphasized. This design approach re-establishes the vital human-nature connection, fostering improved cognitive performance, emotional restoration, and overall life satisfaction in various settings, including educational institutions and workplaces. By integrating natural elements into architectural designs, biophilic design addresses the inherent human need for nature, leading to healthier and more creative spaces that support optimal human experiences [47, 1, 4, 12, 13]. By fostering connections with nature and promoting psychological well-being, biophilic design transforms interactions with both physical and virtual environments, enhancing quality of life.

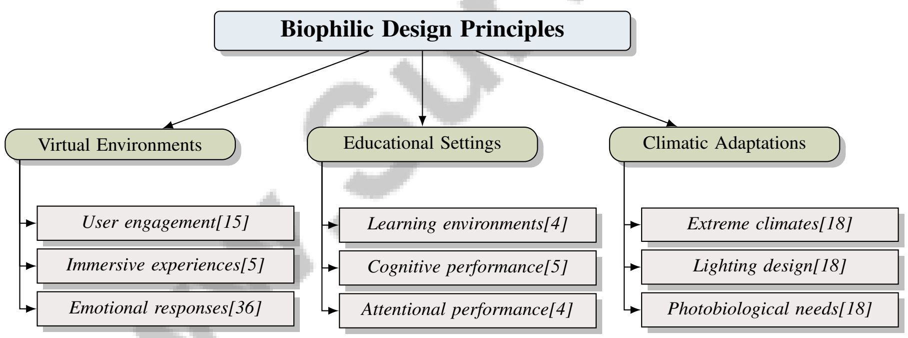


Figure 3: This figure illustrates the application of biophilic design principles across various domains, including virtual environments, educational settings, and climatic adaptations. It highlights key aspects such as user engagement and immersive experiences in virtual settings, the enhancement of learning environments and cognitive performance in educational contexts, and the adaptation to extreme climates through optimized lighting design and photobiological needs.

3.2 Direct vs. Indirect Approaches

Biophilic design encompasses direct and indirect approaches, each offering unique pathways for integrating natural elements into human environments. Direct biophilic design incorporates actual natural features—such as plants, water, and natural light—into the built environment, fostering an immediate connection to nature that enhances user experience and well-being [19]. This approach is prevalent in architectural designs prioritizing green spaces and natural lighting, promoting mental and physical health.

Conversely, indirect biophilic design employs representations and simulations of nature to evoke similar psychological benefits. This includes using natural materials, colors, and patterns, alongside digital simulations through technologies like VR and AR. VR's effectiveness in simulating natural environments is underscored by its ability to reduce cognitive workload and enhance task performance in immersive simulations [48]. The Bionic Tracking method exemplifies an indirect approach by utilizing smooth pursuit eye movements within VR to create a sense of presence and connection to nature without direct interaction [49].

The choice between direct and indirect biophilic design approaches often depends on the context and application objectives. In settings where integrating natural elements is challenging, such as urban environments or extreme climates, indirect approaches provide a viable alternative by simulating natural experiences digitally. The CogBRE platform illustrates this by applying principles of embodied and external cognition in VR to create supportive environments for complex tasks, showcasing the potential of indirect biophilic design to enhance cognitive engagement [50].

Both direct and indirect approaches contribute to biophilic design's overarching goals by promoting a connection to nature and improving user experiences. Their integration in immersive analytics stages, including task performance and cognitive load assessment, further underscores their relevance in contemporary design practices [51]. Understanding and applying these distinct approaches enable designers to create environments catering to diverse needs and preferences, enhancing human-computer interactions and overall well-being.

3.3 Biophilic Design in Virtual Environments

Biophilic design principles are increasingly applied in virtual environments to enhance user experiences by fostering connections with nature and promoting psychological well-being. This integration aligns with the broader objective of creating spaces that resonate with the innate human affinity for nature. In virtual settings, engagement and emotional connection principles are facilitated through methodologies such as immersive experiences leveraging VR technology, interactive emotional expression tools, and personalized content delivery systems. These approaches enhance user participation and foster deeper emotional resonance, particularly in educational contexts where VR can simulate real-world scenarios and promote empathy through embodied experiences [11, 25, 52, 3, 29].

The VR intervention 'Our Neighbor Hero' exemplifies biophilic design in virtual environments, promoting prosocial behavior and demonstrating VR's potential to enhance empathy and social interactions [3]. Similarly, integrating biophilic elements in VR mindfulness meditation training, such as a calming archery game environment, enhances user experience by providing immersive and soothing settings [2].

In enhancing user experiences with non-anthropomorphic drones, VR aligns with biophilic design principles by creating immersive environments that improve user interaction and control [6]. The Tangible Web system further showcases the integration of real-world environmental data into virtual reality, enhancing user engagement by bridging physical and virtual spaces [10].

The design methodology proposed by Argyriou significantly enhances user engagement and immersion in 360° immersive video applications, illustrating how biophilic design principles can be effectively implemented in virtual settings [32]. Additionally, integrating multi-contact tactile feedback systems, such as LinkGlide-S, enriches the sensory dimension of virtual interactions by providing realistic tactile feedback [43].

Exploring time perception and user experience in VR through physiological signals and environmental factors emphasizes the necessity for a new approach to understanding user interactions in virtual environments [45]. This approach underscores the importance of considering environmental and physiological aspects in designing immersive experiences.

Implementing biophilic design principles in virtual environments enhances user experience by promoting connections with nature, fostering engagement, and providing realistic sensory feedback. This approach not only improves psychological well-being by fostering a growth mindset and enhancing empathy through immersive virtual experiences but also transforms interactions in virtual environments by integrating emotional expression and personalized engagement, ultimately leading to more satisfying and effective user experiences across various contexts, including education, healthcare, and community collaboration [52, 3, 53, 33, 29].

4 Virtual Reality and Immersive Environments

4.1 Enhancing User Engagement and Presence

Enhancing user engagement and presence in virtual reality (VR) requires integrating design elements and interaction methodologies that leverage VR's immersive potential. The Two-in-One method by Yamagami exemplifies this by enabling tasks typically requiring bimanual input, thus increasing realism and immersion for users with limited mobility [8]. The Tangible Web method further enhances immersion by integrating real-time feedback from physical interactions into virtual settings [10]. In educational contexts, VR significantly boosts student engagement and learning outcomes, particularly in STEM fields, although challenges in implementation remain [5]. Basu's research highlights that tailored evaluation methods, distinguishing between gamer and non-gamer participants, enhance user engagement and presence, underscoring the importance of personalized strategies [9].

In Figure 4, the key methods and impacts on user engagement and experience in virtual reality environments are illustrated, emphasizing design strategies, educational implications, and personalized user experiences. Incorporating biophilic design elements in VR environments also improves attentional performance and restoration, benefiting student performance more than conventional settings [4]. Chen's approach demonstrates VR's potential to enhance cognitive engagement and user satisfaction by improving engagement, information retention, and efficiency in document interaction and creation [11]. A comprehensive strategy integrating innovative interaction techniques, tailored user experiences, and multimodal sensory feedback is essential to enrich user experiences, improve performance, and facilitate skill transfer in VR environments. Educational curricula for VR development should emphasize design thinking, prototyping, and evaluation skills, preparing designers to create immersive and user-centered applications [54, 55]. Addressing user preferences and leveraging VR's unique capabilities can craft immersive experiences resonating on multiple levels.

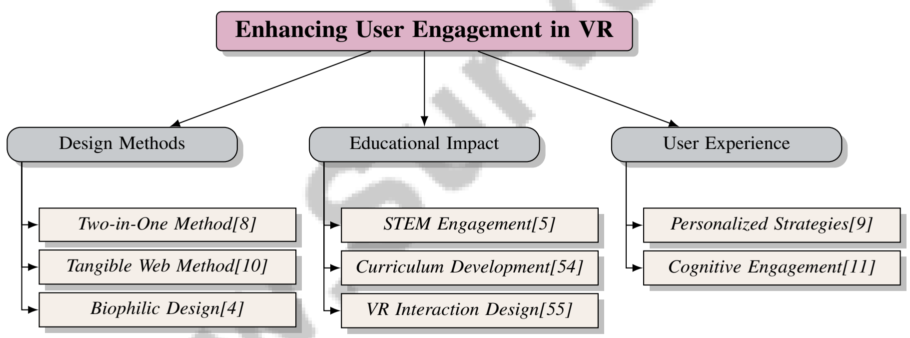


Figure 4: This figure illustrates the key methods and impacts on user engagement and experience in virtual reality environments, highlighting design strategies, educational implications, and personalized user experiences.

4.2 Simulating Natural and Extreme Environments

Virtual reality's (VR) ability to replicate natural and extreme environments is crucial for creating immersive experiences that enhance user engagement and cognitive restoration. High-fidelity VR environments significantly reduce stress and enhance cognitive restoration, outperforming low-fidelity or abstract environments, thereby demonstrating VR's potential to replicate settings that promote well-being [33]. Visual and auditory fidelity are critical for establishing a sense of presence, necessitating high-quality sensory integration for convincing virtual environments [41]. Techniques like discrete rotation around the user's position (InPlace) and rotation during teleportation (TeleTurn) enhance user orientation and control, improving realism and user experience [56]. Cognitive analysis methods, such as the Photosphere to Cognition Engine (P2CE), enhance cognitive assessments of photospheres, achieving higher F1 scores compared to direct processing methods, thereby enriching the immersive quality of VR environments [40]. The effectiveness of VR in simulating natural and extreme environments is augmented by high-fidelity sensory elements, including visual, auditory, and haptic feedback, alongside innovative interaction techniques that foster immersive user engagement. This enhances learning outcomes and real-world skill transfer across applications, including education, training, and environmental awareness [19, 25, 24, 54, 57]. By leveraging these capabilities, VR offers immersive experiences that replicate real-world environments while enhancing cognitive and emotional engagement.

5 Multi-sensory Experiences

5.1 The Role of Multi-sensory Feedback in Enhancing Immersion

Multi-sensory feedback is crucial in enhancing immersion within virtual environments by engaging multiple senses, thereby increasing realism and interactivity. As illustrated in Figure 5, the key methods for enhancing immersion in virtual environments include visual, haptic, and cognitive enhancements. Integrating visual, auditory, and haptic feedback augments user presence and engagement. Devices like LinkGlide-S simulate object stiffness through impedance control, enhancing tactile interaction [43]. Foveated Blurring Rendering (FBR) reduces visual discomfort by applying Gaussian blur to peripheral areas, improving presence [37]. Gamified elements, as seen in Argyriou's design, foster interaction and feedback, promoting deeper immersion [32]. The Two-in-One design space further enhances immersion for users with limited mobility by providing access to multi-sensory feedback scenarios [8].

Chen's method aligns virtual environments with cognitive capabilities, reducing mental load and improving engagement, highlighting the need for environments that cater to cognitive processes [11]. This integration streamlines user interactions and facilitates realistic experiences, enhancing learning outcomes and knowledge retention. Immersive VR experiences, particularly those incorporating auditory feedback, demonstrate increased engagement and performance in educational and training simulations [19, 25, 58, 54, 24]. Such approaches ensure engaging virtual experiences capable of fostering deeper cognitive and emotional connections.

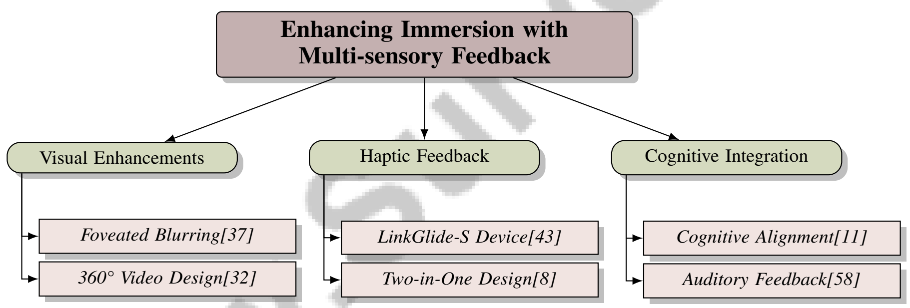


Figure 5: This figure illustrates the key methods for enhancing immersion in virtual environments through multi-sensory feedback, including visual, haptic, and cognitive enhancements.

5.2 Emotional and Cognitive Engagement through Multi-sensory Experiences

Multi-sensory experiences in virtual environments significantly enhance emotional and cognitive engagement by providing immersive stimuli that transcend traditional physical limitations. Integrating various sensory modalities fosters authentic emotional responses and deeper cognitive involvement, as evidenced by VR interventions promoting empathy and prosocial behaviors [3]. These interventions highlight VR's potential to evoke strong emotional responses, necessitating further exploration into the emotional impacts of immersive environments [36].

In educational contexts, multi-sensory experiences have improved students' epistemologies and self-efficacy in scientific inquiry, as demonstrated by the Novel Observations in Mixed Reality (NOMR) labs [35]. The Isness experience, assessed through participant feedback and the Mystical Experience Questionnaire (MEQ30), underscores the profound emotional and cognitive effects facilitated by multi-sensory VR experiences [59].

In therapeutic settings, multi-sensory experiences enhance engagement and outcomes, with haptic feedback influencing emotional and cognitive engagement, emphasizing tactile stimuli's importance in emotion-driven designs. EEG data during VR experiences provides insights into brain activity and engagement levels [24]. These experiences also enhance cognitive performance in biophilic designed environments, fostering a connection to nature [4]. Familiarity with interactive environments, such as prior video gaming exposure, enhances emotional and cognitive engagement in VR [9]. This comprehensive approach ensures multi-sensory experiences resonate with users, facilitating deeper learning and therapeutic outcomes [34].

5.3 Applications of Multi-sensory Experiences in Diverse Contexts

The integration of multi-sensory experiences across various fields significantly enhances user engagement, learning outcomes, and therapeutic interventions. In education, museums employ gamified and multi-sensory approaches to engage digitally native audiences, improving educational engagement and retention [60]. This approach leverages interactive technologies to create dynamic learning experiences catering to diverse preferences.

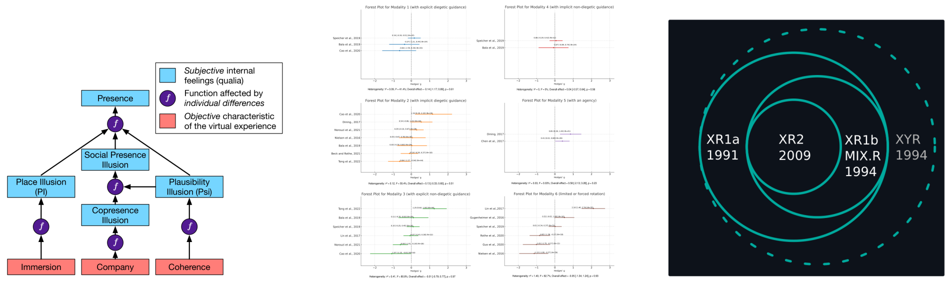
In healthcare, multi-sensory experiences enhance therapeutic interventions by providing immersive environments that facilitate cognitive and emotional engagement. Haptic feedback in VR therapy shows promise in improving patient outcomes by creating realistic therapeutic scenarios. These applications underscore the transformative potential of multi-sensory experiences in rehabilitation and mental health therapies, enhancing emotional well-being and cognitive rehabilitation. High-fidelity virtual environments for therapeutic practices, such as remote counseling and VR forest bathing, reduce stress and enhance cognitive functions [61, 62, 29, 33].

Biophilic design applications significantly enhance cognitive performance by fostering a deeper connection to nature. Environments incorporating natural elements and sensory stimuli improve attentional performance and perceived restorativeness among students, promoting well-being and productivity in workplace settings. Studies show biophilic learning environments outperform conventional ones in supporting cognitive processes and strengthening affiliation with nature. Introducing plants in office spaces increases perceived attention, creativity, and productivity, emphasizing integrating natural features into educational and workplace environments [47, 63, 4, 12, 13].

In entertainment and gaming, multi-sensory experiences revolutionize user interaction by offering immersive experiences that engage multiple senses. Advanced sensory feedback systems in gaming enhance realism and user engagement, particularly in VR applications, where immersive simulations increase sensory fidelity across modalities and contribute to higher learning gains and knowledge retention. Balancing elements influencing presence in VR is crucial, as minor negative factors can disrupt the immersive experience. Addressing challenges like motion sickness and accessibility to VR hardware is essential to maximize user experience [41, 64, 19].

The integration of multi-sensory experiences across various contexts highlights their adaptability and significant influence on enhancing user engagement and outcomes. Augmenting content with virtual elements and utilizing spatialized placements improves user comprehension and interaction quality, while multimodal sensory integration enhances overall performance and facilitates skill transfer. The potential for emotional expression in VR settings further enriches user experiences, particularly in educational and healthcare applications, indicating a broad spectrum of benefits derived from these innovative approaches [11, 65, 66, 54, 29]. By leveraging sensory modalities, these experiences create immersive environments that resonate with users, facilitating deeper cognitive and emotional connections across various fields.

As shown in Figure 6, visual representations such as flowcharts, forest plots, and Venn diagrams elucidate complex relationships and findings in the exploration of multi-sensory experiences and their applications across various contexts. The flowchart provides a structured view of how different subjective characteristics, such as "Presence" and "Social Presence Illusion," interrelate within virtual experiences, offering insight into user engagement and perception in digital environments. The forest plot presents a comparative analysis of studies examining the impact of explicit diegetic guidance on a specific modality, highlighting both positive and negative outcomes across a range of research. The Venn diagram illustrates the evolution of software projects through overlapping circles, reflecting the dynamic nature of software development in creating multi-sensory experiences. Together, these visual elements underscore the multifaceted applications and implications of multi-sensory experiences, offering a comprehensive overview of how these experiences are crafted and understood in diverse settings [67, 66, 68].



(a) The image depicts a flowchart illustrating the relationship between various subjective and objective characteristics of virtual experiences.[67]

(b) Forest Plot for Modality 1 (with explicit diegetic guidance)[66]

(c) The image represents a Venn diagram with four overlapping circles, each representing a different version of a software project.[68]

Figure 6: Examples of Applications of Multi-sensory Experiences in Diverse Contexts

6 Eye-Tracking and EEG in Immersive Environments

6.1 Monitoring User Attention and Cognitive Load

The integration of eye-tracking and electroencephalogram (EEG) technologies in immersive environments enhances the assessment of user attention and cognitive load, thereby improving user engagement. Eye-tracking facilitates real-time monitoring of gaze patterns, enabling adaptive visual rendering to mitigate perceived optical flow and evaluate cognitive load, particularly in virtual reality (VR) applications where user engagement is crucial [37, 44]. EEG complements this by providing insights into neural activity, essential for understanding cognitive processes during immersive experiences. In VR mindfulness training, EEG signals assess cognitive load and attention, allowing for dynamic content adaptation based on individual cognitive states, optimizing learning outcomes [2, 44]. In VR gaming, these technologies facilitate real-time analytics that adjust game difficulty and interaction complexity, enhancing user engagement and cognitive stimulation, highlighting the importance of personalized strategies in optimizing immersive experiences [15]. Recent studies demonstrate the effectiveness of these technologies in assessing cognitive load through metrics like pupil dilation and fixation duration, while EEG provides real-time insights into mental workload, enhancing user experience and performance [19, 69, 44, 70, 46].

Figure 7 illustrates the integration of eye-tracking and EEG technologies in monitoring user attention and cognitive load, highlighting their applications and effectiveness in immersive VR environments. This visual representation underscores the synergistic relationship between these technologies and their pivotal role in enhancing user engagement and cognitive assessment in virtual settings.

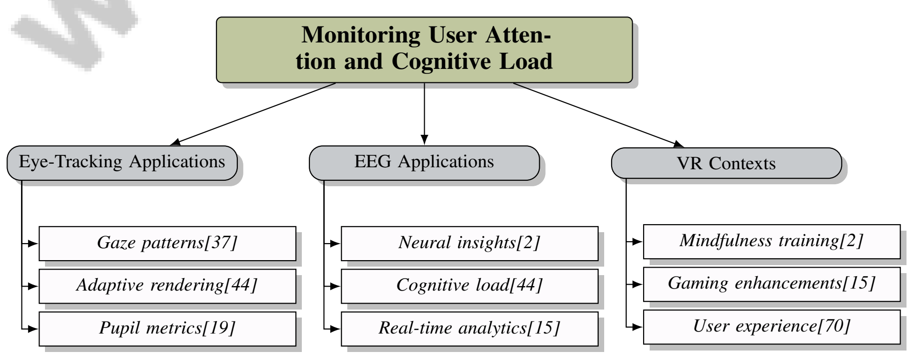


Figure 7: This figure illustrates the integration of eye-tracking and EEG technologies in monitoring user attention and cognitive load, highlighting their applications and effectiveness in immersive VR environments.

6.2 EEG Applications in Immersive Environments

EEG technology is instrumental in enhancing immersive experiences by monitoring neural activities that inform user interactions in virtual environments. Combining EEG with immersive technologies allows for real-time brain activity monitoring, crucial for understanding user engagement and cognitive load during VR experiences. Nasri's experimental setup using a VR-3 Varjo headset to capture eye movements and assess cognitive load through NASA-TLX scores exemplifies EEG's role in evaluating cognitive processes during VR training [44]. EEG's capacity for continuous, non-invasive monitoring enables dynamic adaptations in VR environments, enhancing user experience by personalizing content according to individual cognitive states. This is particularly beneficial in educational and therapeutic contexts, where tailored experiences significantly improve outcomes. Integrating EEG data with other physiological measures, such as eye-tracking and emotional responses, provides a holistic view of user interactions, leading to more effective immersive applications across various domains, including healthcare, education, and advanced manufacturing [44, 71, 72, 29]. Real-time feedback from EEG applications enhances user engagement by offering insights into emotional states and cognitive workload, facilitating dynamic task adjustments that foster personalized interactions. This has proven beneficial in adaptive VR gaming and cognitive workload management in flight simulations [73, 74, 52, 29]. By leveraging EEG technology, developers can create immersive environments responsive to user needs, fostering deeper cognitive and emotional connections. The integration of EEG into immersive environments represents a significant advancement in human-computer interaction, enhancing user experiences through real-time monitoring of neural activity and cognitive processes. Applications combining interactive storytelling with neurophysiological assessments have demonstrated increased user engagement and emotional responses, with EEG effectively capturing brain responses linked to presence and immersion. This paves the way for further exploration of cognitive engagement in virtual settings, improving training programs across various fields, including safety and rehabilitation [24, 29, 75, 19].

6.3 Enhancing User Interactions with Physiological Data

The use of physiological data from eye-tracking and EEG technologies is crucial for enhancing user interactions in immersive environments. These technologies provide real-time insights into user attention, cognitive load, and emotional states, essential for optimizing user experience and interaction design. Eye-tracking allows for dynamic visual content adjustments based on gaze patterns, reducing visual discomfort and enhancing engagement [37, 44]. EEG complements this by revealing the neural underpinnings of user interactions. The integration of EEG data with other physiological measures fosters a comprehensive understanding of user engagement and cognitive processes during immersive experiences [24]. This is exemplified by using EEG alongside eye-tracking to assess cognitive load and attention in VR training systems, enabling personalized adaptations that optimize learning outcomes [44]. Additionally, real-time feedback from these technologies allows for content adaptation based on individual cognitive states, enhancing the user experience. This is particularly beneficial in educational and therapeutic contexts, where personalized experiences can markedly improve outcomes. By harnessing physiological data, developers can create immersive environments that adapt to user preferences and actions, enhancing emotional and cognitive engagement. For example, advancements in emotion recognition and multimodal data, such as heart rate and electrodermal activity, can inform the development of VR experiences that foster deeper emotional connections across various contexts, including healthcare and education [26, 71, 29]. The integration of physiological data from eye-tracking and EEG technologies signifies a major advancement in human-computer interaction, enhancing user experiences through real-time monitoring of cognitive and emotional states. This facilitates immersive interactions, especially in virtual environments where emotional expression is critical. Recent research indicates that VR can elicit stronger emotional responses than traditional flat-screen gaming, while the incorporation of neurohaptic feedback and brain-computer interfaces presents promising opportunities for decoding touch sensations, further enriching user engagement and personalization across various applications, including healthcare and education [72, 71, 29]. This comprehensive approach ensures that virtual environments not only engage users but also effectively fulfill their intended purposes by fostering deeper cognitive and emotional connections.

7 Human-Computer Interaction Optimization

7.1 Ethical and Inclusive Design Considerations

Optimizing immersive technologies like virtual reality (VR) and augmented reality (AR) necessitates a comprehensive framework that emphasizes ethical and inclusive design to ensure accessibility, safety, and user satisfaction. Ethical considerations are crucial, especially concerning the deployment of eye-tracking and electroencephalogram (EEG) technologies for real-time monitoring in immersive settings. Caputo [37] underscores the ethical challenges of integrating eye-tracking technology aimed at enhancing user interactions while minimizing discomfort, highlighting the need for responsible tech deployment.

Inclusive design is essential for addressing diverse user needs, including those with mobility impairments. Yamagami's Two-in-One method [8] tackles accessibility challenges in VR applications, promoting inclusivity by ensuring VR systems accommodate various abilities. Privacy concerns in VR environments demand robust safety frameworks and boundary-aware designs. Lambeta [76] discusses the potential of local AI processing to reduce latency, while also raising ethical concerns about data privacy and user interaction security. Cabrera [43] highlights the ethical implications of haptic feedback technologies, emphasizing the importance of responsible design to enhance immersion without compromising ethical standards.

The integration of nature-related experiences in VR, as explored by Parsaee [18], illustrates how immersive technologies can enhance user well-being and engagement, aligning with the ethical imperative to foster positive outcomes. Nasri [44] also stresses the importance of ethical considerations in developing advanced machine learning models to improve prediction accuracy in dynamic VR environments.

Addressing these ethical and inclusive design considerations ensures that immersive technologies benefit all users. By prioritizing user rights and needs, developers can foster the responsible evolution of human-computer interaction technologies, addressing critical issues such as representation in virtual environments, data privacy, and inclusive design practices that enhance user engagement. Integrating these elements will create immersive technologies that captivate users while upholding their dignity and autonomy in increasingly complex digital landscapes [11, 55, 77, 78].

7.2 Future Directions and Research Opportunities

The convergence of biophilic design and immersive technologies offers extensive research opportunities to advance human-computer interaction. Future studies should explore the implications of diverse user profiles, such as gamers versus non-gamers, across a broader range of VR tasks, paving the way for interdisciplinary research [9]. Additionally, examining the integration of VR in various subject areas and the role of instructors in facilitating VR learning warrants further investigation through longitudinal studies [5].

In design techniques, future research should investigate methods to enhance immersive technologies, potentially suggesting new directions within the field [32]. This includes refining gesture interactions, integrating complex sensor systems, and exploring applications across gaming, education, and healthcare [10]. The refinement of methods and expansion to additional document types, alongside the integration of artificial intelligence (AI) to enhance document creation and interaction, represent significant research avenues [11].

For biophilic design, future work should focus on developing specific implementation guidelines for extreme climates and exploring adaptive building technologies to address environmental challenges [18]. Such efforts could lead to innovative solutions that enhance user experiences across diverse settings.

By pursuing a variety of innovative research avenues, the field can progress toward more sophisticated and inclusive human-computer interactions. This evolution will enhance responsiveness to user needs while ensuring that interactions fulfill their intended purposes. For example, integrating immersive technologies like VR and AR can transform traditional 2D document interactions into engaging experiences, addressing cognitive challenges users encounter. Moreover, developing persuasive user interfaces can mitigate technology addiction, while advancements in speech-to-text interfaces can enrich emotional expression in virtual environments, making interactions more meaningful.

Collectively, these efforts will contribute to a more adaptive and user-centered technological landscape [11, 25, 57, 29, 79].

8 Conclusion

The integration of biophilic design with immersive technologies presents a significant advancement in human-computer interaction (HCI), offering transformative potential across various domains by enhancing user engagement, psychological well-being, and cognitive performance. By incorporating natural elements into digital environments through virtual and augmented reality, these technologies create immersive experiences that are both engaging and effective. In medical settings, AI-enhanced VR technologies have demonstrated improvements in diagnostic accuracy and procedural efficacy, representing a paradigm shift in healthcare delivery.

In educational environments, VR learning platforms substantially enhance the learning experience by fostering a heightened sense of presence and engagement, surpassing traditional educational methods. Immersive serious games further exemplify VR's capability to effectively convey complex concepts, leading to superior learning outcomes. Additionally, the incorporation of biophilic design in educational spaces supports students' mental and physical health, contributing to more favorable learning conditions.

Socially, VR redefines interactions by enhancing engagement and facilitating reconnections, thereby strengthening social bonds. The emergence of emotional hijacking within the Metaverse underscores the need for further research into emotional manipulation and its effects on users, ensuring the responsible development of immersive technologies.

Future research should address challenges such as motion sickness and the mismatched profiles of participants to enhance the validity of VR outcomes. Additionally, exploring the effects of various zeitgebers on time perception in VR could inform the design of therapeutic applications. The findings highlight the transformative potential of biophilic design and immersive technologies in HCI, emphasizing the need for future efforts to optimize computational efficiency, address security and privacy concerns, and promote user-centered solutions for personalized protections in the Metaverse. Continued development and collaboration within the open science community are crucial for advancing this interdisciplinary field and ensuring the replicability of VR research.

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