Balancing Presence and Safety using Reaction Time in Mixed Reality

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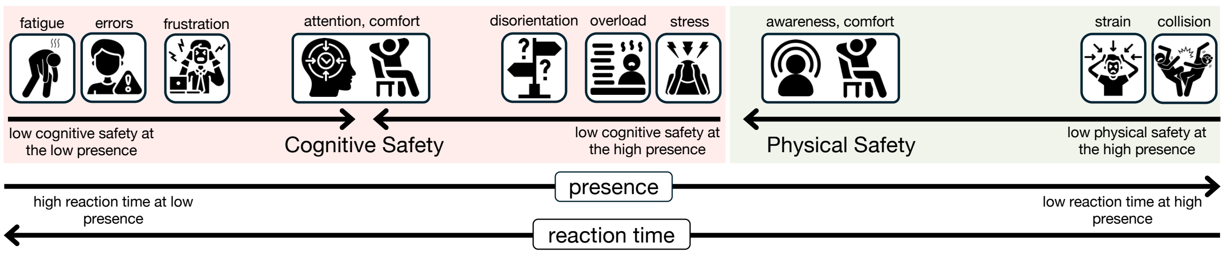

Figure 1: The interplay between presence, physical safety, and cognitive safety. Physical safety degrades as the presence increases due to the user's lack of physical world awareness and can lead to collisions and strain on the human body. Cognitive safety can degrade at high presence (cause stress, overload, and disorientation) and low presence (cause fatigue, human errors, and frustration). A recent, quantitative, and real-time measure of presence, *reaction time*, can help balance presence and safety.

Abstract

Mixed Reality (MR) offers immersive experiences across various fields. Presence, the sensation of "being there," is crucial for immersion. While high presence enhances user engagement, it also raises cognitive and physical safety concerns. This paper explores these dual safety concerns associated with high presence in MR environments. Recent work has shown that reaction time is an effective measure of presence, providing real-time, objective insights into cognitive load and engagement levels, with faster reaction times indicating higher presence. We propose using reaction time as a real-time metric to monitor and manage cognitive and physical safety issues in MR environments. We address the three key research questions: (1) the impact of presence on safety, (2) the effectiveness of reaction time as a safety measure, and (3) the challenges of maintaining safety without compromising experience.

Index Terms: Mixed Reality, Presence, Safety, Reaction Time

1 Introduction

Mixed Reality (MR) technology merges the physical and digital worlds, allowing users to interact with real and virtual elements simultaneously, creating immersive experiences [26, 22]. This blending offers opportunities for applications in various fields, such as education [1], training [36], healthcare [45, 7, 21], entertainment [43, 14], and beyond[50, 16, 23]. However, to achieve immersion, MR applications hinge on a critical component: the *sense of presence*[33, 11], the psychological sensation of "being there" in a virtual environment (VE)[46, 35, 18]. While high presence can enhance user engagement, it also increases safety concerns that must be addressed to ensure user well-being.

Traditional MR safety approaches primarily focus on user privacy [20, 30, 10, 13] and system security [3, 4, 8, 44, 24, 49], addressing issues like data protection, unauthorized access, content and user perception manipulation and so on [29], some highlighting privacy breach from performance data that may inadvertently expose users to risks related to surveillance or identity theft. These aspects, while crucial, do not encompass the broader spectrum of safety concerns in immersive MR environments. Cognitive and physical safety are two critical yet often overlooked areas that must be addressed to ensure a holistic approach to user safety. Cognitive safety involves managing mental load to prevent fatigue and decreased performance. Physical safety ensures users are aware of their surroundings to prevent accidents and discomfort.

Prior work has observed that high presence typically correlates with optimal cognitive engagement, whereas slower reaction times can indicate cognitive strain or distraction [19, 42]. Additionally, high presence, while enhancing immersion and engagement, can also reduce awareness of the physical environment, increasing the risk of accidents like collisions with objects. Given this correlation, a user's level of presence can be used as an indicator of the cognitive and physical safety of MR experiences. However, traditional methods of measuring presence use subjective posthoc questionnaires, which are difficult to conduct in the real world. In our earlier work, we explored objective and real-time measures of presence. Our work demonstrated that a user's reaction time to stimuli could be used as a measure of presence [5, 6]; high presence correlates with low reaction time and vice versa. Given this new measure, we can measure presence in real-world applications in real-time. Monitoring presence through reaction time can help in cognitive safety by providing insights into the user's cognitive load and engagement levels. This allows the detection of potential cognitive overload to prevent mental fatigue and ensure effective task performance. Similarly, monitoring a reaction time can indicate a user's level of physical world awareness and allow an application to take precautionary measures to regain that awareness.

By examining the interplay between presence or reaction time and safety issues, we aim to understand the trade-offs between maintaining a high presence and ensuring user safety. To this end, we ask the following research questions:

1. How does presence impact a user's cognitive and physical safety in MR environments?
2. How can reaction time be used as a metric to measure and manage cognitive and physical safety in MR environments?
3. What are the potential challenges in balancing high presence and user safety when using reaction time as a presence measure?

2 Impact of Presence on Cognitive and Physical Safety

This section provides an overview of how different elements of MR environments interact with cognitive and physical safety concerns,

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highlighting the trade-offs between maintaining a high presence and ensuring user safety, as illustrated in Figure 1. To investigate the impact of presence on cognitive and physical safety, we categorized various MR elements based on common presence subscales derived from presence studies [37, 34, 48, 38, 39], which we outline in Table 1 (details in §A). We describe the main elements below:

Immersive quality and spatial cues (place illusion [37]) can lead to cognitive disorientation and reduced awareness of physical surroundings, resulting in accidents such as collisions. For example, users deeply immersed in a virtual game might not notice real-world objects, leading to potential injuries [41]. When it comes to realism, high sensory realism can cause stress and disorientation, especially when users cannot differentiate between virtual and real elements. This heightened presence also reduces awareness of the physical environment. Lowering presence can alleviate stress and disorientation, but it might also decrease user engagement, focus, and overall immersion, which are critical for MR experiences.

Plausibility illusion [37] ensures the coherence of the virtual experience but can lead to emotional stress due to highly realistic scenarios [17], reducing physical awareness and increasing the risk of physical accidents. For instance, a VR simulation of a natural disaster for training purposes can cause significant anxiety and stress among users [31, 17]. While high presence is essential for this, reducing it could help mitigate emotional stress.

Scene and background elements can cause distraction, cognitive overload, and reduced performance due to overwhelming stimuli; lowering these details can improve focus and interaction quality, although it might negatively impact engagement and realism. A user interface can also cause frustration, errors, and physical strain if the controls or interface are not intuitive. Reducing presence can mitigate these issues but may impact usability and navigation. Interaction responsiveness also requires high presence to avoid frustration and fatigue [32], but if it causes strain, lowering presence may enhance comfort. High involvement in Content can lead to cognitive overload and distraction; reducing presence can alleviate these issues, though it might lessen the immersive experience.

Prolonged immersion/exposure can lead to physical discomfort, fatigue, eye strain, headaches, and musculoskeletal issues [27], with poor ergonomics. Users who spend extended periods wearing VR headsets often report these physical symptoms due to the strain on their bodies [40]. Both cognitive and physical fatigue are significant concerns, as extended sessions in immersive environments can exhaust users mentally and physically, diminishing their overall well-being and performance [19, 15]. In this case, lowering the presence can improve user comfort but might reduce the sense of immersion.

3 Managing Safety Using Reaction Time as Metric

Recent work has identified reaction time, the time it takes for a user to respond to a stimulus, as a metric for measuring presence [5, 6]. This section discusses how reaction time can also measure safety and manage cognitive and physical safety in MR environments.

Measuring cognitive safety. Reaction time provides insights into cognitive load and engagement levels [41]. Faster reaction times indicate high engagement and optimal cognitive load, while slower times suggest cognitive strain. Continuous monitoring allows MR systems to detect overload and adjust tasks. For example, if a user's reaction time slows, the system might reduce the complexity of tasks or provide more frequent breaks to prevent mental fatigue.

Preventing cognitive overload. High cognitive load can lead to decreased performance and mental fatigue. By setting baseline reaction times for users, MR systems can identify deviations that indicate cognitive overload. When a user's reaction time exceeds a certain threshold, the system can trigger interventions such as pausing the activity, simplifying the task, or offering guidance to help the user regain focus and manage their cognitive load.

Measuring physical unawareness. High presence in MR environments can reduce a user's awareness of their physical surroundings, increasing the risk of accidents. Monitoring reaction time can help gauge the level of presence and alert the system when the user is becoming too engrossed. If reaction times slow down significantly, indicating overimmersion [9], the system can introduce subtle cues to remind the user of their physical environment. These cues can include visual reminders, auditory alerts, or haptic feedback to enhance physical awareness without breaking presence.

Preventing physical discomfort. Extended use of MR can lead to physical discomforts, such as eye strain, headaches, and musculoskeletal issues [15]. Reaction time can serve as an early indicator of physical strain. For instance, prolonged slower reaction times might suggest the onset of fatigue or discomfort. The MR system can then prompt the user to take breaks, adjust their posture, or perform relaxation exercises. This proactive approach can help mitigate physical strain and enhance overall user comfort.

4 Presence and Safety Trade-off

Managing safety in MR environments using reaction time as a metric presents several challenges. While this approach offers a real-time, objective way to gauge user experience and cognitive load, balancing high presence and safety remains complex.

Real-Time adaptation. One major challenge is ensuring the MR system can adapt in real-time based on reaction time data. This requires advanced algorithms and responsive hardware capable of swiftly processing reaction time measurements and implementing necessary adjustments without interrupting the user experience. Ensuring the system's robustness and reliability is crucial to avoid any lag or inaccuracy that could not only compromise safety and immersion but can also induce cybersickness [28].

User intervariability. Reaction time varies significantly among individuals due to factors such as age, experience, and cognitive abilities [47]. A one-size-fits-all approach may not be effective. MR systems must calibrate and personalize reaction time thresholds for each user to ensure accuracy. Personalizing these thresholds adds complexity to system design and requires extensive user data to implement effectively.

Safety vs. experience trade-off. The ultimate challenge is balancing the need for high presence to maintain experience and immersion with the need for safety. High presence can enhance the immersive experience but also increases risks of cognitive overload and physical unawareness. Reaction time as a metric helps navigate this balance by providing real-time feedback, but it requires a nuanced approach to task interpretation and response. For example, introducing subtle cues to regain physical awareness must be done without breaking presence [2].

Other safety measures and practical limitations. Reaction time should not be the sole metric, integrating it with other safety measures, such as user feedback and physiological monitoring [25, 12], can provide a more comprehensive safety framework. Combining multiple metrics can help address the limitations of each individual measure, ensuring the accuracy and reliability of safety measurements in varied MR scenarios that require careful calibration and validation. Finally, the measurement must be seamlessly integrated into the MR system without causing disruptions or incurring costs.

5 Conclusion

This paper highlights the importance of addressing cognitive and physical safety alongside traditional security and privacy concerns, ensuring a comprehensive and holistic approach to user safety in MR environments. In summary, while reaction time presents a viable solution for managing safety in MR environments, its full potential can only be realized through extensive research and development. By continuing to investigate and refine these methods, we can create safer and more immersive MR experiences that do not compromise user well-being.

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A Appendix

This section discusses various elements of MR environments and their associated presence subscales individually. Understanding these components is crucial for creating immersive and engaging experiences while ensuring cognitive and physical safety. Each MR element and presence subscale shapes the user's experience, influencing engagement, realism, and comfort. We also explore the safety concerns linked to these elements in Table 1.

A.1 MR Elements

Immersive quality and spatial cues. refer to feeling physically present in a non-physical world. It encompasses elements that enhance the user's perception of the virtual space as a real place. It is critical for achieving a sense of immersion and making the virtual environment feel convincing and engaging.

Sensory realism. The extent to which the virtual environment replicates real-world sensory experiences, including visual, auditory, and haptic feedback. It improves user engagement by providing realistic and immersive sensory experiences.

Coherence. The degree to which events and elements in the virtual environment are perceived as real and logically consistent, ensuring the virtual experience is believable and emotionally engaging.

Scene setting. Involves the virtual environment's background elements and overall context, including lighting, textures, and ambient sounds. It sets the stage for interactions and enhances the immersive quality of the environment.

Task Complexity. Refers to the difficulty and intricacy of tasks that users perform within the MR environment. It affects cognitive load and user engagement, with more complex tasks requiring greater cognitive resources.

Background elements. These are secondary elements within the environment that can affect the user's focus and attention, influencing cognitive load and interaction quality, where high levels of distraction can reduce performance.

Interactive elements. components that users can manipulate or interact with, such as buttons, levers, and tools. They are essential for user engagement and the overall interactivity of the MR environment.

Interaction responsiveness. The accuracy and speed with which the system responds to user actions. It Ensures seamless and intuitive interactions, reducing frustration and enhancing user satisfaction.

Content. The narrative and activities within the MR environment that engage the user. High involvement in content can lead to deeper engagement and immersion.

User interface and navigation. The design and layout of controls and navigation tools that allow users to interact with the MR environment, ensuring ease of use and helping prevent errors and frustration.

Ergonomics. The design of the MR system to ensure user comfort and reduce physical strain. They are important for prolonged use, minimizing physical discomfort and fatigue.

A.2 Presence Subscales

Place illusion. The sensation of "being there" in the virtual environment is central to creating a convincing immersive experience.

Perceived realism. The degree to which the virtual environment appears real to the user. Use: Enhances user engagement by providing realistic and believable sensory inputs.

Plausibility illusion. The extent to which events in the virtual environment are perceived as plausible and logical. It affects the coherence and emotional impact of the virtual experience.

Environmental context. The background and contextual elements that make up the virtual setting. It supports immersion by providing a consistent and engaging backdrop for user interactions.

Task complexity. The perceived difficulty and cognitive demands of tasks within the MR environment. Influences user engagement and cognitive load management.

Distraction. The presence of elements that can divert the user's attention from primary tasks. It affects cognitive load and the quality of user interactions.

Control factors. The intuitiveness and responsiveness of the control mechanisms within the MR environment are crucial for usability and effective navigation.

Interaction fidelity. The accuracy and responsiveness of the system's interactions. It enhances user satisfaction and reduces frustration by providing precise feedback on user actions.

Involvement. The level of user engagement and absorption in the content of the MR environment. High involvement leads to deeper cognitive and emotional engagement.

Usability. The ease with which users can interact with and navigate the MR environment is useful for a smooth and frustration-free user experience.

User comfort. The physical ease and comfort experienced by users during interaction with the MR environment. It helps reduce physical strain and discomfort, which is important for extended use.

A.3 Safety Concerns

A.3.1 Cognitive

Disorientation. Occurs when users have difficulty orienting themselves within the MR environment, leading to confusion and impaired navigation.

Stress. Arises from highly realistic or intense virtual scenarios can cause emotional strain and mental pressure.

Overload. It happens when the cognitive demands of the MR environment exceed the user's capacity, leading to mental fatigue and decreased performance.

Frustration. Results from poorly designed interactions or controls lead to a negative user experience characterized by annoyance and dissatisfaction.

Errors. Occur when users make mistakes due to cognitive overload or poor interaction design, resulting in incorrect actions or decisions.

Distraction. It involves secondary environmental elements that divert attention from primary tasks, reducing focus and performance.

A.3.2 Physical

Reduced awareness. Manifests as a decreased awareness of the physical surroundings, increasing the risk of accidents.

Collisions. Results from users moving into real-world objects due to a lack of awareness of their physical environment.

Physical discomfort and strain. Refers to the physical unease and exertion experienced by users due to prolonged interaction with MR devices, including sensations of fatigue, muscle strain, and general physical discomfort.

MR Element	Presence Subscales	Safety concerns		Presence requirement	Worse with low presence
		Cognitive	Physical		
Immersive quality and spatial cues	Place Illusion	disorientation (✓)	reduced awareness, collisions (✓)	High	immersion, engagement
Sensory realism	Perceived Realism	stress, disorientation (✓)	reduced awareness (✓)	High	engagement, focus
Coherence	Plausibility Illusion	emotional stress (✓)	reduced awareness (✓)	High	realism, immersion
Scene setting	Environmental context	distraction, reduced performance (✓)		High	engagement, realism
Task	Task complexity	overload		High	control, engagement
Background elements	distraction	overload, reduced focus and attention		High	interaction quality
Interactive elements	Control factors	frustration		High	usability, navigation
Interaction responsiveness	Interaction fidelity	frustration, errors, fatigue	strain	High	comfort
Content	Involvement	overload, distraction, reduced focus and attention (✓)	reduced awareness (✓)	Low	None
User interface and navigation	Usability	frustration, errors (✓)	strain (✓)	Low	None
Ergonomics	User comfort	reduced performance, fatigue (✓)	discomfort, strain (✓)	Low	None

Table 1: Overview of MR elements, their corresponding presence subscales, associated safety concerns, presence requirements, and the impact of low presence on user experience. (✓) indicates that the factor can improve with a lower presence.(✓) shows that this factor can get better with low presence.