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Review Article

Immersive virtual reality for older adults: Challenges and solutions in basic research and clinical applications

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ABSTRACT

Immersive virtual reality (IVR) offers significant potential for aging research, providing a controlled yet ecologically valid platform for studying cognitive, emotional, and motor processes, as well as supporting interventions and diagnostic assessments in older adults. However, its usability can be hindered by age-related sensory, motor, and cognitive changes, which may contribute to anxiety, disorientation, and reduced task engagement. In this narrative review, we examine the challenges older adults face with IVR and explore strategies to optimize its design for this population. These challenges include negative attitudes, sensory and motor limitations, and cognitive decline, all of which influence interaction with virtual environments. Based on these insights, we discuss design considerations such as self-paced interactions, simplified control mechanisms, task-relevant visual and auditory adjustments, and structured training protocols to enhance engagement. Additionally, we highlight strategies to minimize cognitive load and physical discomfort, supporting the development of IVR applications that are both effective and accessible for aging populations.

1. Introduction

Immersive virtual reality (IVR) is transforming experimental and clinical practices across diverse fields, including neuroscience, psychology, physical rehabilitation, and mental health, by enabling the study and application of complex processes in controlled, interactive, and naturalistic environments. Recent advancements, including the development of affordable, stand-alone IVR systems, have made these technologies increasingly accessible. IVR enables researchers to create realistic experiences that closely mimic real-world interactions. In addition, IVR allows for innovative experimental manipulations—such as teleportation (Shahbaz Badr and De Amicis, 2023) or multisensory stimulation (Melo et al., 2022)—that are otherwise impossible in the real world. This provides a powerful tool for investigating complex behaviors and sensory integration in ways that traditional methods, including desktop-based virtual reality, cannot achieve (e.g. Howett et al., 2019).

For older adults (Ageing, 2020; Ke et al., 2025), IVR has numerous promising applications. It serves as a valuable platform for experimental research to study age-related changes in cognition, emotion, and motor function. For example, the use of IVR has transformed the study of spatial navigation, allowing the characterization of navigation behavior in more naturalistic, yet, highly controlled environments (e.g. Hill et al., 2024; Stangl et al., 2020). IVR also holds significant clinical potential in the context of aging, because it can serve as diagnostic tools or therapeutic interventions. This potential is highlighted by use cases such as improved detection of Alzheimer's disease (AD) by enabling novel assessments of cognitive abilities. For example, Howett et al. (2019) used an IVR path integration task to detect early AD-related deficits. Performance on the task predicted biomarker status and outperformed standard cognitive tests. Similarly, IVR-based assessments have shown promise in detecting unilateral spatial neglect—a common post-stroke condition that disproportionately affects older adults (Gottesman et al., 2008). Traditional paper-and-pencil tests often lack the sensitivity to detect subtle symptoms, whereas IVR tasks offer a more sensitive and ecologically valid alternative, capturing real-world spatial challenges

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more effectively (Perez-Marcos et al., 2023; Thomasson et al., 2024). Beyond these examples, IVR has also been used to assess a broad range of cognitive and physical functions in older adults—including memory (Corriveau Lecavalier et al., 2020), executive function (Davison et al., 2018), and motor performance (Everard et al., 2022, 2024)—further highlighting its versatility and diagnostic value.

Beyond assessment, IVR offers innovative interventions to enhance abilities like cognitive functions (e.g., memory and executive processing; Wais et al., 2021), motor skills (e.g. balance and coordination; Campo-Prieto et al., 2022), and emotional well-being (e.g., reducing anxiety, loneliness, or depressive symptoms; Lin et al., 2018). For instance, IVR-based reminiscence therapy—where older adults engage with immersive scenarios reminiscent of their past—has shown promise in fostering emotional connections and improving mood (Barsasella et al., 2021; Ng et al., 2024). Furthermore, a recent meta analysis shows that IVR is more efficient at reducing depression, anxiety and overall improving psychological well-being in older adults compared to non-IVR control conditions (Ke et al., 2025). Importantly, IVR's potential even extends beyond these areas, with ongoing research exploring its broader applications, such as enhancing the quality of life, promoting social interaction, and developing personalized interventions for aging populations.

One important aspect that is often overlooked are age-related physiological and cognitive changes, which may significantly affect how older adults engage with virtual environments (VE, Arlati et al., 2021; Healy et al., 2022; Plechatá et al., 2019). Declines in visual, vestibular, and proprioceptive systems, along with multifaceted changes in cognition, can all introduce challenges for both research and clinical applications. Therefore, it is crucial to get a deeper understanding of these age-related changes and consider strategies to mitigate their effects on IVR engagement. Here we present a narrative review aimed at providing an overview of the key challenges and potential solutions related to the use of IVR in older adults. While several systematic reviews and meta-analyses have addressed specific applications of IVR in older adults—such as its use in cognitive (Tortora et al., 2024; Yu et al., 2023) and physical training (Zhu et al., 2021), as well as those promoting wellbeing (Ke et al., 2025) and care (Diniz et al., 2024). These reviews often focus on more specific and narrow context or isolated outcomes (i.e. effectiveness of IVR in cognitive or functional training). In contrast, this narrative review examines a broad range of age-related changes—spanning cognitive, functional, sensory, and emotional domains—that may affect how older users interact with IVR systems. By identifying how these changes intersect with the specific demands of IVR we outline strategies to support usability, engagement, and safety. Through this approach, we aim to provide practical and actionable recommendations that can inform the development and implementation of IVR applications across research and clinical settings involving older adults.

2. Methodology

We conducted a targeted literature search using PubMed and Google Scholar covering articles published until April 2025. We use exemplar Boolean strings such as ("immersive virtual reality" OR "head-mounted display") AND ("older adult*" OR "aging" OR "elderly"). Additional articles were identified by citation chaining (reference lists of key papers) and expert recommendation. Our scope boundaries were:

- **Population:** older adults, defined according to the World Health Organization (WHO) as individuals aged 60 years and above
- **Language:** English, peer-reviewed publications
- **Technology:** fully immersive VR systems. IVR refers to technology that fully immerses users in a computer-generated environment, replacing real-world surroundings with a digitally constructed space. IVR typically involves head-mounted displays (HMDs) that support stereoscopic vision responsive to the user's position and orientation, along with motion-tracking systems to create a strong sense of presence (see **Section 2.4**). Core features include realistic 3D visuals, spatialized audio, and interactive elements that respond to user movement. This level of sensory immersion distinguishes IVR from non-immersive (e.g., desktop-based) or semi-immersive systems (e.g., CAVE environments, fish tank VR systems; Mandal, 2013), supporting its application in research, clinical interventions, and training simulations via HMDs.

We purposively sampled quantitative, qualitative, and mixed-method studies until no new themes emerged (conceptual saturation). Critically, we also consulted systematic reviews and meta-analyses to identify broader trends and synthesize established recommendations.

3. Challenges

Despite its benefits, IVR can place additional cognitive and physical demands on users compared to real-world environments. In daily life, older adults often rely on well-established cognitive, sensory, and motor strategies to interact with their surroundings. However, the novelty of VEs—combined with the absence of familiar spatial cues and contextual anchors—can disrupt these strategies. This mismatch may increase cognitive load and physical effort, potentially leading to difficulties in navigating and interacting with IVR systems. We therefore begin this review by examining the key age-related changes that may contribute to these challenges (Fig. 1), focusing specifically on sensory decline, reduced physical agility, executive and attentional deficits, memory loss, affective changes, limited tech expertise, and technology skepticism.

3.1. *Psychological and emotional factors*

Older adults often approach new technologies with skepticism, typically driven by anxiety, fear of ineffective interaction, and lack of familiarity (Hauk et al., 2018; Healy et al., 2022). These negative attitudes can reduce motivation, increase frustration, and negatively affect task performance (Wetherell et al., 2002). However, prior experience with computer-based technologies fosters more positive perceptions, and attitudes often improve after initial exposure (Abeele et al., 2021; Healy et al., 2022; Huygelier et al., 2019; Kalantari et al., 2022).

One useful framework for understanding the psychological drivers of older adults' engagement with new technologies such as IVR is Self-Determination Theory (SDT, Deci and Ryan, 2002). SDT posits that well-being is supported by the fulfillment of three basic psychological needs: autonomy (a sense of control over one's actions), competence (feeling effective and capable), and relatedness (feeling socially connected). When applied to aging, unmet needs—particularly autonomy and competence—can negatively affect motivation and well-being (Ng and Abbas, 2020). This is particularly relevant in IVR, where unfamiliar interfaces or overly complex interactions may undermine an older adult's sense of competence or autonomy. We refer back to this framework throughout the review when discussing how to optimize IVR design to better support psychological needs in older adults.

Affective changes such as generalized anxiety disorder and geriatric depression (Blazer, 2003) may further influence IVR engagement (Rmadi et al., 2023). Symptoms like excessive worry, fatigue, attentional deficits, and sleep disturbances can impact focus, information processing, and memory (Butters et al., 2011). As a consequence, some older adults prefer simpler, familiar tasks that feel less cognitively demanding and visually straining (Al-Sharman et al., 2021; Manera et al., 2016; Rashid Izullah et al., 2021; Zeuwts et al., 2021).

3.2. *Sensory-motor changes in aging*

Aging affects multiple sensory and motor systems, influencing how older adults engage with VEs. As a detailed review of these changes is

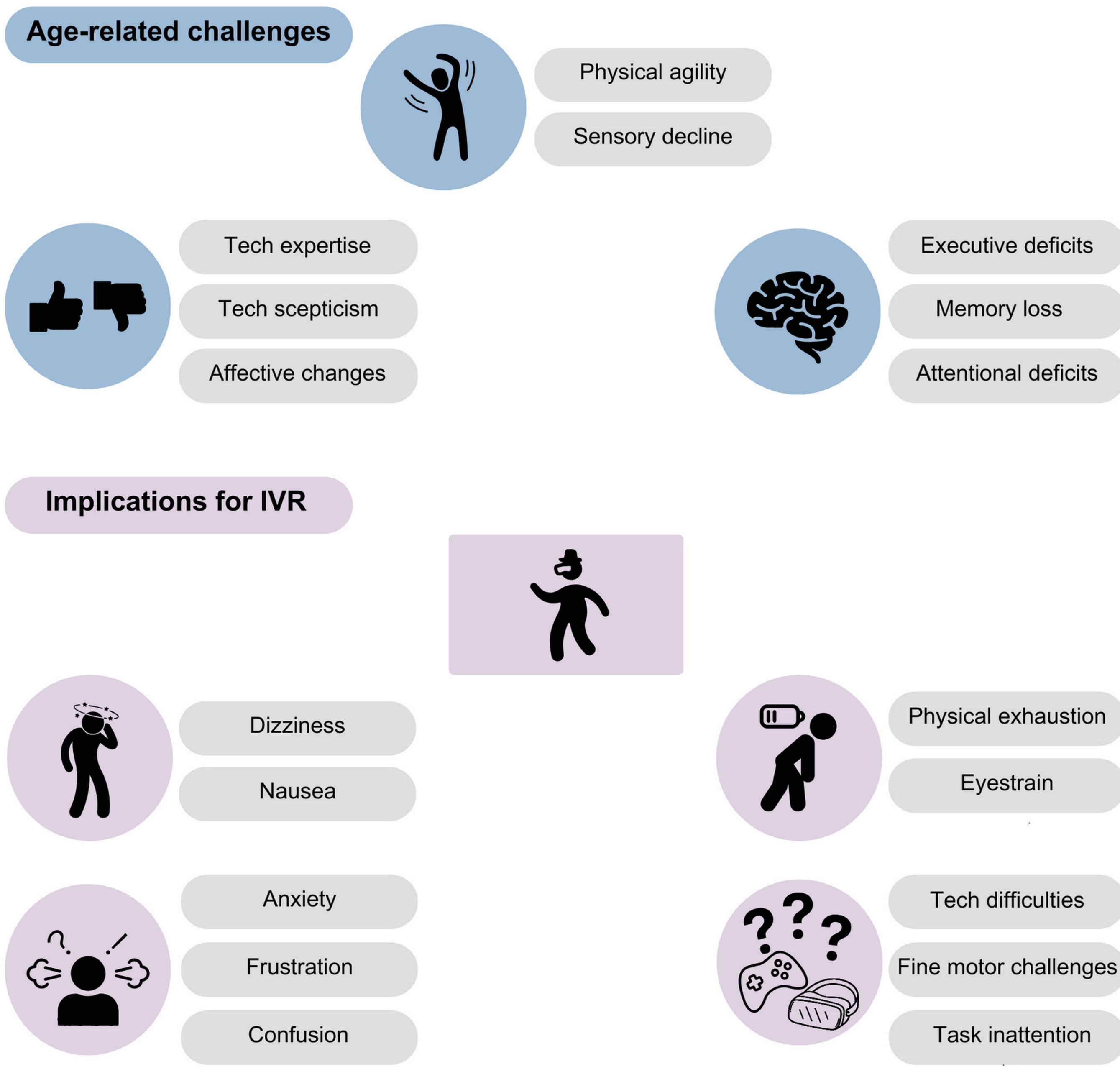

Fig. 1. Overview of age-related challenges and their implications for IVR use. The top section of the figure highlights age-related challenges that can affect older adults, including sensory decline, reduced physical agility, executive deficits, memory loss, attentional deficits, limited familiarity with technology, technology scepticism and affective changes. The lower section illustrates the implications of these challenges in the context of IVR use. For example, older adults may experience physical discomfort such as dizziness and nausea, along with physical exhaustion and eyestrain. It can also result in anxiety, frustration and confusion, difficulties in controller handling, fine motor challenges and task inattention. These factors can reduce task performance, engagement, and overall usability in IVR.

beyond the scope of this paper, we instead provide brief summaries of the most relevant age-related changes that could impact IVR use.

Hearing impairment: Age-related hearing loss affects speech perception and spatial audio localization, which may diminish the feeling of presence. Over half of individuals in their seventh decade experience hearing loss severe enough to affect communication (Agrawal et al., 2008), particularly in detecting high-pitched sounds (Davis et al., 2016). Importantly, hearing impairment has also been associated with declines in cognitive function—a relationship supported by meta-analytic evidence (Loughrey et al., 2018)—suggesting that hearing loss may not only affect sensory processing but also broader aspects of attention and memory relevant to IVR engagement. Furthermore hearing aid users may struggle with inappropriate volume levels and reduced effectiveness of ambient sound (Healy et al., 2022), preventing them from using auditory cues in the IVR environment as well as from benefiting from ambient sound to increase presence (Kern and Ellermeier, 2020; Pontus et al., 2002). Moreover, hearing aids can sometimes introduce audio feedback or distortion when used with over-ear headphones or integrated audio systems, leading to discomfort or distraction. Additionally, reduced ability to localize sounds could affect tasks that rely on spatial audio cues (Dobreva et al., 2011).

Visual system changes: Aging is associated with progressive degeneration of the visual system, including conditions such as age-related macular degeneration, which affects over 25 % of older adults (Li et al., 2020). Common age-related alterations such as reduced visual acuity and decreased contrast sensitivity make it harder for older adults to focus on objects or adapt to varying light levels within VEs (Owsley, 2016). These difficulties can cause eye strain, fatigue, or headaches, reducing the comfort and enjoyment of IVR experiences. Additionally, many older adults require glasses, which can cause discomfort when worn with IVR headsets—particularly due to issues like fogging, especially when used in combination with a face mask (Kalantari et al., 2022; Roberts et al., 2019). Increased light scattering within the eye also makes older adults more sensitive to glare (Fisk, Rogers and Charness, 2009), which may interfere with visual clarity in high-contrast or brightly lit VEs.

Tactile and motor decline: Although the tactile system remains relatively intact compared to the visual and auditory systems, age-related declines in tactile perception (for review, see (Decorps et al., 2014) can reduce the effectiveness of haptic feedback in IVR. These changes include a reduction in skin receptors and nerve function, which not only affect the ability to perceive tactile feedback but also impact motor control. Additionally, fine motor skills deteriorate with age (Seidler et al., 2010), leading to decreased hand-eye coordination, slower reaction times, and reduced muscle strength and dexterity (Murata et al., 2010). Collectively, these factors impair the timing and execution of motor behaviors, such as gripping, grasping, and manipulating small objects. These changes are particularly relevant for hand-object interaction in IVR, where older adults may experience difficulties using standard controllers or gesture-based interfaces. Reduced tactile acuity and motor precision can compromise their ability to press buttons accurately, maintain a stable grip on controllers, or interact reliably with virtual objects via hand-tracking technology. Furthermore, the physical demands of IVR, such as wearing HMDs, can contribute to discomfort, with many older adults—particularly those with arthritis—reporting neck strain or fatigue (Kalantari et al., 2022).

Vestibular changes: The vestibular system, which supports balance and spatial orientation, deteriorates with age, affecting about 60 % of adults over 60 (Zalewski, 2015). Loss of vestibular sensory cells and inner ear microvascular changes contribute to dizziness, vertigo, and instability. Such sensory degradation can impair postural control: older adults often exhibit greater postural sway and delayed adaptation when exposed to moving visual stimuli (Toledo and Barela, 2014), indicating increased susceptibility to environmental input. This can be particularly problematic in dynamic VEs and could lead to difficulties with maintaining balance and posture in IVR. Age-related declines in the vestibulo-ocular reflex may further hinder the ability to stabilize gaze during head movements, potentially complicating gaze-based interactions in IVR (Iwasaki and Yamasoba, 2015). These impairments not only make interaction more difficult but may also heighten sensitivity to visual-vestibular mismatches. As predicted by sensory conflict theory, such mismatches—particularly in dynamic VEs—can exacerbate discomfort and disorientation.

Proprioceptive changes: Proprioception—the sense of the relative position, movement, and force of body parts—is essential for meaningful interaction with the environment, as it enables coordinated movement and balance. With increasing age, proprioceptive function declines (Lee et al., 2013), contributing to a range of age-related syndromes, most notably an increased risk of falls (Lord et al., 1991) as well as delayed limb position sensing, and hesitancy in movement (Henry and Baudry, 2019). In the context of IVR, proprioception plays an even more critical role due to the frequent absence of visual feedback about the user's own body. Many IVR applications do not provide visual representations of the limbs or body, potentially reducing spatial awareness and increasing uncertainty during movement. This lack of visual-proprioceptive integration may elevate fear of falling and, in some cases, contribute to unsafe behavior or errors. For instance, older users may be unaware of the extent or orientation of their body movements—such as how much they have turned or shifted position—due to reduced proprioceptive sensitivity. Similarly, if they are required to perform certain actions they may not be able to perform without seeing direct visual feedback. As such, age-related proprioceptive decline could compromise both the safety and effectiveness of IVR interactions in older adults.

3.3. Cognitive changes

Cognitive decline begins in middle adulthood and affects processing speed, visuospatial abilities, episodic memory, and executive functions, including working memory, cognitive flexibility, and attentional control (Salthouse, 2009). These deficits make it harder to filter distractions, multitask, and adapt quickly to new tasks. Several theories of cognitive aging help explain these changes, including the Speed of Processing Theory (Salthouse, 1996), which posits that slower mental processing speed underlies broader performance declines; the Limited Resources Theory (Craik and Byrd, 1982) suggests a reduction in available attentional capacity with age; and the Inhibitory Control Theory (Hasher and Zacks, 1988), emphasizes age-related difficulties in suppressing irrelevant information. Together, these frameworks account for common challenges experienced by older adults, such as increased difficulty with multitasking, slower reaction times—particularly when stimuli are presented in rapid succession—and reduced ability to focus on relevant cues in complex or visually cluttered VEs. These changes have direct implications for the design and pacing of IVR tasks for aging users. They may also contribute to comprehension difficulties in IVR—such as understanding task instructions, navigating menus, or grasping the purpose of the virtual task—particularly when information is presented too quickly or without sufficient guidance or structure.

Operating IVR controllers also places demands on working memory and executive control. Older adults can struggle to remember button functions, leading to slower responses and increased errors. Additionally, even when controllers are visually represented in IVR, the mapping of hand positions may be unclear, requiring trial-and-error learning and further taxing cognitive resources. Uncertainty about button functions can compromise both response precision and speed (Cook et al., 2019). The lack of visual feedback on button positioning may also cause errors, imprecise pointing, or unintentional actions (Ijaz et al., 2022). Furthermore, the overall pace of IVR interactions (i.e. too quick) is a particular concern for some older adults, especially those with limited proficiency or prior experience with the technology (Hosseini et al., 2024). Some IVR systems also support interactions via hand-tracking, and although such interactions eliminate the need to remember button mappings, they introduce other cognitive demands. For example, the absence of haptic feedback and occasional tracking inconsistencies may reduce input reliability and require greater visual monitoring of one's hand movements, potentially increasing attentional load. This can be particularly challenging for older adults who already experience declines in visuomotor integration (Lee et al., 2013) and selective attention (Craik and Byrd, 1982).

3.4. Immersion and presence

Two central concepts that determine how a user experiences IVR scenarios are immersion and presence. Immersion refers to the technological characteristics of a VR setup, including the extent to which stimulation is panoramic/occludes the physical environment, the range of stimulated sensory modalities (e.g. visual, auditory, haptic), the quality of the simulated stimuli (e.g. display resolution, framerate), etc. Many of these dimensions can be controlled by the choice of hardware, and the degree of immersion is a key determinant of presence (Cummings and Bailenson, 2016). Presence refers to the subjective feeling of "being there" in a VE. In other words, the individual perceives and interacts with the virtual space and its elements as if they were truly part of it. Presence is often thought to be composed of spatial presence, where the user feels physically located within the virtual space and perceives it as their primary egocentric reference frame, instead of their actual physical surroundings (Wirth et al., 2007). In addition, in scenarios that include other beings (i.e. avatars), users also experience social presence or co-presence, the sense of "being together" with others in a VE (Biocca et al., 2003). Social presence is characterized by the awareness of, connection to, and interaction with other individuals, creating a feeling of mutual involvement and emotional engagement.

Given that presence can influence performance in cognitive tasks (Corriveau Lecavalier et al., 2020; Parong et al., 2020), it is important to consider whether—and under what conditions—older adults might experience presence differently. A systematic review of 13 qualitative studies (Healy et al., 2022) found that older adults consistently report both spatial and social presence in IVR environments. They also tend to experience stronger presence than in less-immersive control conditions (Xu et al., 2025) and at levels comparable to younger users (Corriveau Lecavalier et al., 2020; Mitzner et al., 2021). Interestingly, while there are no significant age differences in the speed at which spatial presence is established or in recovery from breaks in presence, older adults appear to experience fewer breaks overall (Mitzner et al., 2021). This effect is likely related to the age-related reduction in attentional capacity: with fewer attentional resources available, older adults may be less able to divide attention between the virtual and physical world, thereby reducing the likelihood of experiencing breaks in presence.

Despite the overall equivalence of presence experience across age groups, there appear to be particular situations that can have detrimental effects on presence particularly for older adults. For example, in a review, Abeele et al. (2021) propose that presence in older adults may be disrupted if virtual events or situations conflict with realistic expectations (e.g. walking through objects).

Finally, one additional aspect that is related to presence is embodiment—the sense that a virtual limb or body is one's own. Research suggests that healthy older adults can experience embodiment illusions as robustly as younger adults, particularly when multisensory cues such as vision and touch are congruent. For instance, Campos et al. (2021) demonstrated that both younger and older participants experienced comparable levels of body ownership and proprioceptive drift during a *virtual hand illusion* task, indicating that the basic mechanisms supporting embodiment remain largely intact with age. However, while upper-limb embodiment has been studied to some extent, there is limited research on embodiment of other body parts (e.g., lower limbs or full-body avatars) in aging populations. Given its central role in user engagement and sensorimotor realism (Groten, 2012), embodiment remains an important but underexplored dimension in IVR research with older adults.

4. Strategies for addressing age-related challenges in IVR

This section covers experimental paradigms and technical considerations to create accessible, intuitive VEs aligned with the preferences and capabilities of older adults. Following age-friendly design principles emphasizing clarity and simplicity (Kruse et al., 2024), we first discuss experimental design, focusing on active interactions, self-paced transitions, and task structures that reduce sensory mismatches. We then address interaction methods, emphasizing simplified controllers, visual feedback, and comfortable target placement. Finally, we outline hardware adaptations for HMDs, controllers, and peripherals, along with strategies to optimize IVR setups for a safer, more comfortable experience for older adults. Table 1 provides an overview of the recommendations.

Table 1
Overview of key recommendations for the use of IVR with older adults.

Recommendations	
A. **Software and interaction design**	
A.1 Experimental paradigm design	
Section	**Guideline**
4.1.1	Use active interactions (e.g., object manipulation, walking) rather than passive movement to enhance engagement and reduce cybersickness, including symptoms like dizziness and nausea
4.1.1	Align virtual transitions and movement speeds with natural walking paces for older adults to minimize sensory mismatches
4.1.2	Incorporate nature-inspired environments to enhance usability, relaxation, and presence and reduce anxiety
4.1.2	Avoid unrealistic virtual interactions (e.g., passing through objects) to align with real-world expectations and reduce confusion
4.2.2 and Fig. 2	Start with simpler tasks and gradually increase complexity to avoid overwhelming older participants.
4.1.2	Design tasks that are contextually relevant to participants' daily experiences to improve engagement and support task attention
4.1.4.	Limit IVR sessions to 20–30 minutes with regular breaks to prevent physical exhaustion, eyestrain and cybersickness
A.2 Interaction methods	
4.1.3	Design tasks that allow single-hand interactions to avoid bi-manual interaction which may be impacted by fine motor challenges
4.1.3	Position interactive targets within a comfortable range (−30° to 30° horizontally) to reduce physical exhaustion
4.1.3	Minimize the number of required buttons for task completion to simplify controller interactions to reduce tech difficulties, fine motor challenges, anxiety, frustration, confusion and error rates
4.2.2	Display a virtual 3D model of the controller within the VE, highlighting the required buttons (e.g. glowing or pulsating effects) to address tech difficulties and reduce confusion
4.1.1	Enhance autonomy by implementing self-paced task progression (e.g. allow participants to control when they move on to the next phase of a task)
A.3 Training and UI elements	
4.2.1	Provide pre-study familiarization materials (e.g., videos or guides) to build confidence, reduce anxiety and tech scepticism
4.2.2	Use step-by-step instructions and clear visual/audio aids during IVR tasks to reduce cognitive load
4.2.2	Employ intuitive UI elements like large icons, color-coded prompts, and 3D models of controllers to reduce tech difficulties and confusion
4.2.2 / 4.2.3	Offer real-time visual feedback (e.g., avatars) to enhance task accuracy and posture control
4.2.2	Use smooth transitions (e.g., fade-ins/outs) between training and testing phases to reduce disorientation and confusion
B. **Hardware and ergonomics**	
B.1 Visual and display considerations	
4.3.1	Ensure visual displays have high resolution and refresh rates to minimize visual fatigue, eyestrain and cybersickness
4.3.1	Provide compatibility with glasses or include diopter adjustments for users with vision impairment
B.2 Auditory design	
4.3.2	Use integrated or lightweight over-ear headphones with adjustable volume and noise-cancellation features
4.3.2	Ensure balance between ambient sound and task-relevant audio cues to prevent cognitive overload
4.3.2	Avoid high-pitched sounds, which can be uncomfortable for older adults with hearing aids

4.1. *How to optimize paradigm design*

4.1.1. *The importance of active interactions*

Older adults typically prefer IVR paradigms where they have more active control and a greater sense of agency (Gomez-Hernandez et al., 2023), with fewer unexpected transitions or interactions, enabling them to proceed at their own speed. This preference aligns with self-paced instructions and training, as well as active transitions into and out of VEs. For instance, older users often favor button presses to progress to the next stages of a task/instruction as well as button presses that initiate a countdown before transitioning out of IVR, providing them with time to prepare and reduce disorientation (Kruse et al., 2024). Similarly, active interactions within the VEs—such as physically moving or manipulating objects—are often preferred over passive interactions like automated movements or fixed animations. Active vs passive exploration, in general and not limited to IVR, results in better performance in older adults (Chrastil and Warren, 2012; Meade et al., 2019; Wallet et al., 2008). These preferences are in line with SDT (Deci and Ryan, 2002), because interactions that allow older adults to make choices, control pacing, and influence outcomes directly support the need for autonomy. Likewise, intuitive, goal-directed, and responsive interactions help foster a sense of competence. This in turn is likely to increase motivation, possibly leading to improved performance and satisfaction. Nonetheless, it is important to note this approach may not be suitable for all older adults, given the wide interindividual variability in physical and cognitive abilities as well as emotional needs. Moreover, in certain contexts—such as brief clinical assessments or therapeutic applications—simpler, less interactive designs may be more appropriate and better tolerated Fig. 2.

In addition to fostering engagement, active movement in IVR can reduce the risk of cybersickness (Text box 1 provides additional information on cybersickness). By aligning sensory inputs—such as visual and vestibular feedback—active movement helps minimize the sensory mismatches central to **Sensory Conflict Theory**, a widely accepted explanation for cybersickness (Reason and Brand, 1975). This alignment is thought to reduce the likelihood of conflict-triggered symptoms such as nausea or disorientation (Caserman et al., 2021; Laessoe et al., 2023). In this context, it is important to distinguish between the type of user interaction and the dynamics of the VE, as these factors can independently influence the risk of cybersickness. For example, an older user may be actively interacting with stationary virtual objects (active interaction in a passive environment), or passively observing a highly dynamic scene (passive interaction in an active environment). Research suggests that dynamic environments—particularly those simulating motion, acceleration, or rapid visual transitions—are more likely to provoke cybersickness (see Davis et al., 2015; Rebenitsch and Owen, 2016) for meta-analysis), especially when not accompanied by congruent vestibular or proprioceptive feedback (Reason and Brand, 1975). In contrast, passive environments (e.g., calm nature scenes with limited VE motion) are generally less likely to induce such symptoms, even when users are not actively engaging with the VE. Therefore, minimizing unnecessary visual motion in the environment may be just as important as supporting meaningful, active interaction.

Active movement can also facilitate performance by leveraging multisensory integration (Adamo et al., 2012; Bates and Wolbers, 2014; Hill et al., 2024; Segen et al., 2022), whilst enabling older users to interact with the VE in a way that feels natural and intuitive. In contrast, passive movement modes, such as flying, driving, or joystick-based navigation, are more likely to hinder performance and induce cybersickness and should be avoided when possible. Although there are no systematic comparisons between the different types of movement in IVR in older adults, more older adults dropped out in a driving simulator study compared to younger adults due to cybersickness, and overall took longer to recover from "driving" when only visual cues were available (Keshavarz et al., 2018).

Implementing active movement necessitates access to adequately sized rooms that permit walking, which may not always be feasible. When movement in the absence of body-based cues is necessary, it is crucial to adapt the rotation and translation speed (Terenzi and Zaal, 2020) to align with the typical walking speed of older adults, as higher speeds are more likely to elicit cybersickness symptoms (Davis et al., 2015; Porcino et al., 2017). Nevertheless, even with spatial constraints, it is possible to implement some self-motion information. For example, using a swivel chair that is synced with IVR—thus offering seamless rotation initiated by head rotations—or a simple swivel stool allows participants to rotate freely without the risk of falling. Such setups provide vestibular inputs about the rotational movements that match the visual feedback experienced in IVR, which may be sufficient to reduce cybersickness and to provide richer self-motion information that facilitates encoding. Finally, an alternative to completely passive translation is teleportation, where participants are instantly relocated within the VE. In younger adults, this is preferred for movements in IVR compared to joystick-based navigation (with regard to simulator sickness, presence, and ease of use; Buttussi and Chittaro, 2021; Clifton and Palmisano, 2020). It should be noted that the effectiveness and usability of teleportation for older adults have not been systematically evaluated, and it remains unclear whether this method would reduce cybersickness or potentially cause confusion in this population.

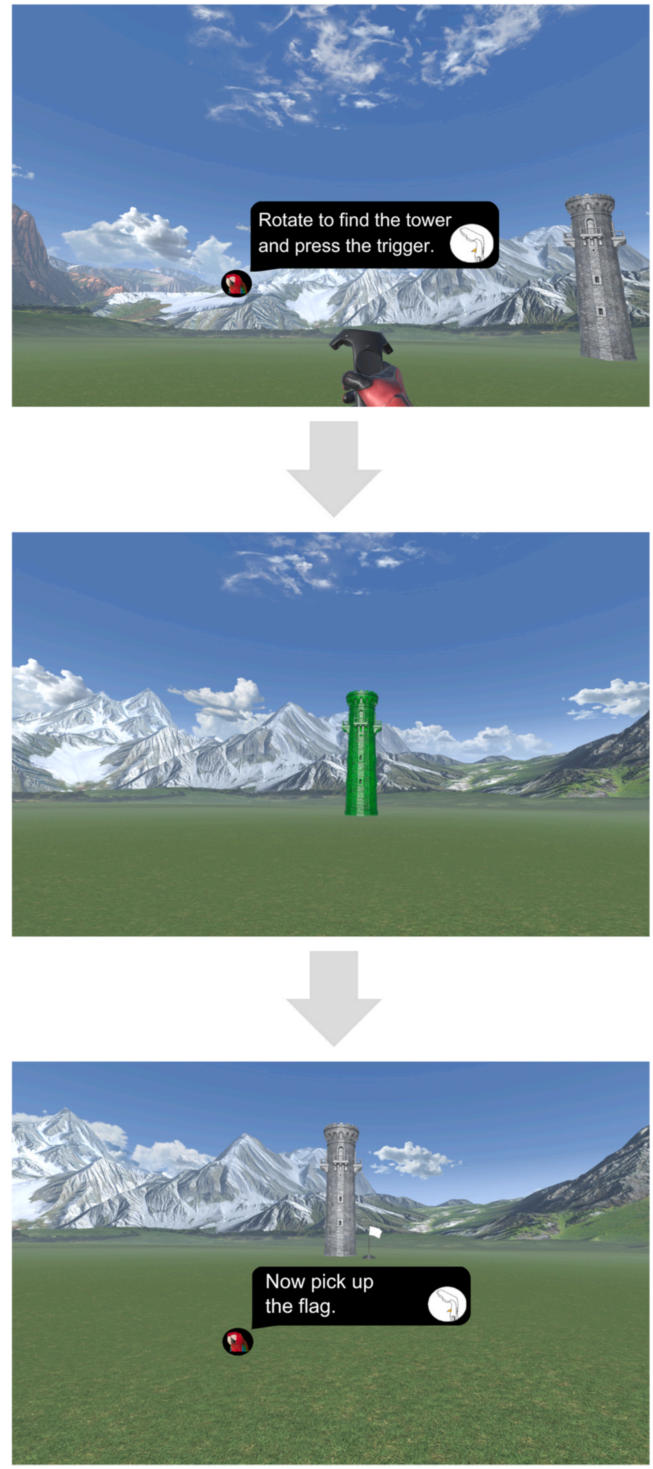

Fig. 2. Example of step-by-step guiding of participants in a virtual environment. In this example, when participants are tasked with locating a landmark (i.e. the tower), the instructions first prompt them to rotate in place until they face the tower (upper). Visual cues or markers, such as a temporary highlight on the tower, confirm they are facing the correct direction (middle). This can also be paired with audio cues, such as a chime when the correct orientation is achieved. Once the tower is located, a new instruction appears, asking participants to walk toward a clearly marked location, such as a glowing circle or a flag, positioned near the tower (lower).

Text Box 1
Aging and cybersickness.

A common concern for using IVR in aging research is whether older adults are more susceptible to cybersickness, which manifests as dizziness, nausea, and discomfort during IVR exposure (Caserman et al., 2021). A widely accepted explanation for cybersickness is the **Sensory Conflict Theory** (Reason and Brand, 1975), which posits that cybersickness arises when there is a mismatch between incoming sensory signals—particularly visual, vestibular, and proprioceptive inputs—and the brain's expectations based on prior experience. For instance, optic flow may suggest movement, while the vestibular system does not detect corresponding acceleration, creating a conflict that the brain interprets as an error signal, often triggering discomfort. This mechanism may be particularly relevant for older adults: **age-related sensory degradation**—such as declines in vestibular function, proprioception, and multisensory integration—may introduce more noise into sensory processing, thereby increasing the likelihood of such conflicts. Surprisingly, studies that directly compare young and older adults' experience of cybersickness suggest that older adults experience similar or even fewer cybersickness symptoms. For example, Dilanchian et al. (2021) tested 20 younger and 20 older adults in a naturalistic IVR task and found no significant age-related differences in reported cybersickness. Participants experienced four varied IVR environments—including exploratory, relaxing, and fast-paced game settings—designed to elicit different levels of sensory and interaction demands, with exposure durations ranging from 3 to 5 minutes. These results echo a review of 39 studies with older adults by Drazich et al. (2023). Six studies have reported no cybersickness among older participants while most described symptoms as minor or negligible when they occurred. However, in 13 studies (out of 39), some older adults did experience symptoms severe enough to prompt withdrawal from the intervention. Notably, these more extreme reactions often occurred in studies with technical difficulties—such as unstable visuals or poorly calibrated sensory input—conditions likely to exacerbate sensory conflicts. Despite this, the overall dropout rate due to cybersickness was generally ≤ 10 % in all but two studies.

While current findings are encouraging, the evidence on cybersickness in aging remains limited and difficult to interpret. Most studies are constrained by small sample sizes, lack of control conditions or baseline assessments, and use of heterogeneous methods—ranging from active navigation to passive observation or 360° video viewing. The variability in IVR environments, including differences in visual complexity, exposure duration, and interaction type, further complicates cross-study comparisons and limits generalizability.

Moreover, it remains unclear whether cybersickness manifests differently across age groups. Some evidence suggests that older adults may be more susceptible to disorientation, whereas younger adults more often report nausea, dizziness, or visual discomfort (Saredakis et al., 2020). This meta-analysis also identified key factors contributing to cybersickness, such as the type of locomotion and level of visual realism. Active locomotion, which provides congruent visual and bodily cues, is generally associated with reduced cybersickness, likely due to minimized sensory conflict. In contrast, highly immersive environments with rapid visual motion may increase symptom severity, particularly when visual input is not matched by corresponding vestibular or proprioceptive feedback (Davis et al., 2015; Lee et al., 2017).

Although the literature does not yet provide a definitive answer as to whether older adults are more or less susceptible to cybersickness, the issue remains critical due to its potential to undermine comfort, engagement, and retention. As such, efforts to reduce cybersickness—through thoughtful design, adaptive interaction strategies, and gradual familiarization—should be prioritized, especially when developing IVR systems for older populations.

4.1.2. Optimising environmental design

Research suggests that older adults have a preference for realistic nature-inspired environments, leading to improved relaxation, mood, and alertness during and after IVR sessions (Anderson et al., 2017; Moyle et al., 2018), thereby enhancing overall comfort and usability (Kalantari et al., 2022). Additionally, ambient nature sounds in IVR can have further positive effects including enhanced mood, attention, and perceived restorativeness among older adults (Long et al., 2023). However, researchers should balance realism with simplicity to prevent cognitive overload among older adults (Healy et al., 2022)—as high-fidelity VEs can overwhelm older adults, causing attentional lapses and memory difficulties. For example, high-fidelity lighting was found to negatively impact free recall performance in younger adults (Smith and Mulligan, 2021). Although older adults were not included in this study, their reduced cognitive resources may amplify these effects.

When tasks involve less realistic or unfamiliar settings, integrating familiar and relatable elements can help to bridge the gap between the virtual and real worlds, ensuring the environment remains intuitive, accessible, and effective for older users. These recommendations are consistent with prior design guidance offered by Abeele et al. (2021), who emphasize the importance of ecological validity, familiarity, and emotional comfort in VEs for older adults.

4.1.3. Means of interacting with the IVR

Interaction with the VE—whether through gestures, haptic controllers that mimic the "controllers" used in the VE, or standard controllers—shows no significant differences in usability, presence, or performance ratings across age groups (Dresel et al., 2023). For instance, while haptic controllers designed to mimic real-life objects (e.g., a controller shaped like a tablet for interacting with a virtual tablet) may enhance realism, they do not necessarily improve the overall user experience. Therefore, there may be little need to invest in or prioritize such elaborate designs if simpler controllers can effectively fulfill the task's requirements.

Interestingly, in younger adults, interacting with IVR using gestures resulted in higher cognitive load compared to using controllers. Despite being perceived as a more "natural" interaction method, gesture based interactions 'suffer' from the absence of haptic feedback and from technical shortcomings like inaccurate hand tracking (Galais et al., 2019). Yet, emerging evidence from clinical populations, such as post-stroke older adults, suggests that hand-tracking interfaces may offer higher usability than controllers in tasks involving fine motor control (Everard et al., 2024). This may reflect greater comfort or intuitiveness in specific rehabilitative contexts. Nonetheless, most comparative studies in younger adults report superior performance and handling with standard controllers, even in setups using high-precision systems (Luong et al., 2023), primarily due to limitations in hand-tracking accuracy. Hence, until tracking technologies improve, controllers are likely to remain the more practical and efficient option—particularly for older adults without significant impairments in manual dexterity.

Although the type of interaction may be less relevant for improving an IVR experience, it should be noted that older adults tend to experience challenges with bi-manual interactions, particularly when tasks require simultaneous use of both hands to manipulate objects (Wu et al., 2024). These findings come from a controlled lab-based IVR study comparing 18 younger and 18 older adults during object manipulation tasks involving varying hand use and target locations. Additionally, older adults prefer to use the dominant hand when interacting with objects, highlighting the need to design interactions that minimize reliance on two controllers and instead prioritize tasks that can be performed with one hand (Wu et al., 2024). In that study, they also showed that although elevated or distant object interactions in IVR were uncomfortable for individuals of all ages, older adults reported significantly greater difficulty and discomfort—particularly during hand movements that require raised arms or reaching beyond comfortable limits.

Finally, older adults often experience confusion and a sense of disorientation due to accidental button presses that transition between phases in the VE (Hosseini et al., 2024). Accidental responses can disrupt the flow of tasks and create psychological frustration, particularly when older participants are unfamiliar with the controller or its functionality. To address this, increasing the time required to register a response, such as holding a button for a few seconds, can help prevent unintended inputs. Additionally, providing visual feedback on the screen ensures that older adults understand when their response has been accepted and that the next phase of a task has been initiated (Colombo et al., 2024). To further reduce cognitive load and confusion, it is best to keep the number of required buttons to a minimum (Gluck et al., 2022).

4.1.4. Duration of IVR exposure

The duration of IVR sessions is a critical factor in ensuring comfort and minimizing adverse effects, particularly for older adults. Prolonged use of HMDs is associated with increased risks of cybersickness and general physical discomfort (Clifton and Palmisano, 2020; Petri et al., 2020). For example, in one study, older adults were found to have higher levels of cybersickness following a 20 vs 10-minute IVR session (Petri et al., 2020). However, longer uninterrupted sessions of 20–30 minutes should also be feasible with the majority of older adults. This is supported by studies that used single and multiple 20–30 minute sessions without observing a significant number of dropouts or discomfort experienced by older adults (e.g. Hill et al., 2024; Howett et al., 2019).

For sessions requiring longer engagement, implementing regular breaks is strongly recommended. Major HMD manufacturers suggest taking 10–15 minute breaks between exposures, especially for sessions exceeding 30–60 minutes. For older adults, breaks are particularly important not only to mitigate cybersickness but also to help to reduce physical fatigue and discomfort, such as eye and neck strain as well as musculoskeletal fatigue.

4.2. Guided IVR experience with UI support

Older adults often require more extensive training with new technologies and are less inclined to learn through trial and error. Research shows they may need 50–100 % more time when engaging with new technology than younger participants, highlighting the importance of clear, structured, and engaging instructions (Gomez-Hernandez et al., 2023). Practical demonstrations and consistent guidance are essential for building confidence, enhancing interactions, and improving performance in VEs (Healy et al., 2022). For the purposes of this review, we organize our discussion of user guidance in IVR into three general phases that are likely relevant across most IVR experiences: before IVR, during IVR, and after IVR. In addition, a discussion on the use of narrative and gamification is provided in Text box 2.

4.2.1. Preparing older adults for IVR: Familiarization and instruction

Before beginning the IVR task, it is helpful to provide an overview of the experiment—through a detailed leaflet/printout or a demonstration video/animation—which can help participants familiarize themselves with the task and understand its objectives. This preparatory step is especially beneficial for naïve participants, as it offers an opportunity to introduce the equipment and experimental setup, helping to set realistic expectations and reduce apprehension. Such efforts are effective in addressing older adults' negative attitudes towards IVR, such as concerns about complexity, fear of failure, or skepticism about the technology's relevance. This is consistent with findings by Medhi and Toyama (2007), who showed that visual, context-setting materials can support users with low technology familiarity by enhancing

Text box 2
Gamification and narrative.

Gamification is a powerful tool for increasing engagement, motivation, and comprehension, particularly in experimental and therapeutic contexts (Deterding et al., 2011). By integrating game elements into non-gaming settings, such as education, healthcare, and cognitive research, gamification creates structured, rewarding, and enjoyable experiences. Common gamification elements include points, badges, leaderboards, performance feedback, levels of difficulty, meaningful stories (narratives), avatars, and social elements like teammates (Sailer et al., 2017). These elements appeal to different psychological needs: points and performance feedback foster competence, while avatars, teammates, and narratives enhance social relatedness. Designing gamification experiences that align with the psychological needs of older adults ensures their effectiveness and relevance.

Older adults derive satisfaction from accomplishing goals but often prefer minimizing competitive elements, such as public leaderboards, to avoid frustration (Salazar-Cardona et al., 2023). Instead, focusing on personal progress through tangible feedback, such as visualizations of improvement, fosters autonomy and motivation. Collaboration and social interaction are also highly valued (Salazar-Cardona et al., 2023), making cooperative tasks and shared experiences with teammates especially effective.

While gamification provides structure and rewards, narrative can act as a complementary and vital component to enhance comprehension and reduce cognitive barriers for older adults. Relatable, real-world storylines offer context, foster presence, and make complex tasks more accessible. Older adults, who often prioritize the logical structure of a narrative (Chu Yew Yee et al., 2010) benefit from coherent and meaningful storylines that resonate with their life experiences. By adding emotional depth and a sense of purpose, narratives enrich gamified systems, enhancing user engagement and improving retention.

For example, in Sea Hero Quest, a mobile game designed to study spatial navigation, researchers embedded the study within a compelling story (Coutrot et al., 2018). Players took on the role of a sailor on a quest to recover their father's lost memories, guided by fragments of his navigational journals. The narrative was presented through small elements, using text and visuals to balance storytelling, gameplay, and study clarity. This thoughtful integration of narrative not only provided purpose and context but also increased motivation and engagement, demonstrating the powerful synergy between gamification and storytelling.

By combining gamification with meaningful narratives, VEs can cater to older adults' specific needs, including autonomy, social relatedness, competence, and a sense of purpose. These approaches not only enhance motivation and comprehension but also create enjoyable and meaningful experiences, ultimately improving outcomes in experimental, therapeutic, and training contexts.

comprehension and building confidence—principles that are likely to benefit older adult users of IVR as well. A potential mechanism through which this familiarization improves older adults IVR use is by fostering a sense of competence—one of the core psychological needs identified by SDT (Deci and Ryan, 2002)—which may improve confidence and willingness to engage.

If relevant to the task, it is essential to also introduce the IVR controllers and demonstrate how to use them, with particular emphasis on the buttons required for the task. A simple, yet effective way to do so is to demonstrate the required buttons and assign them clear names.

4.2.2. Enhancing accessibility and engagement during IVR interaction

A step-by-step approach should then be adopted to introduce the task (Ijaz et al., 2022), supported by user interface (UI) elements within the VE to explain ongoing or upcoming actions (for an example see Fig. 2). UI is defined by the way humans interact with the information system (Deshmukh and Chalmeta, 2024). It allows users to intuitively engage with the VE including hand gestures, gaze input, voice commands and controller-based interactions (Yeo et al., 2024). The introduction of the task can be complemented with a brief animation or video that can demonstrate, for example, an avatar performing the task—such as walking to a marked location, or performing a specific exercise (Fig. 3). This provides participants with a clear and relatable example before they attempt the action themselves, contributing to lower disorientation and confusion.

Presenting an avatar in the IVR setting offers an additional layer of clarity by giving participants the opportunity to observe the task in context, which can reduce cognitive load when they eventually perform it themselves. Although there are no direct studies in IVR and aging specifically examining this, research in related domains suggests that avatars can capture users' attention (Hongpaisanwiwat and Lewis, 2003), enhance engagement, and support task comprehension—particularly in learning environments, where virtual characters may positively influence performance. In one non-IVR study with older adults, participants who received instructions from an avatar were more likely to perform the requested task correctly compared to those who received only text-based instructions (Ortiz et al., 2007). Similarly, a review on agent-based tutoring systems found that the inclusion of virtual agents improved users' understanding of the material (Dehn and Van Mulken, 2000). Notably, a study involving individuals with AD (Tran et al., 2016) showed that having an avatar explain the task was especially beneficial for participants with AD, highlighting the potential of avatar-based guidance for cognitively impaired populations.

During testing, it is crucial to provide ongoing aids to support participants in using the IVR system effectively. For example, intuitive UI elements like icons or color codes can prompt participants to press a specific button, while subtle animations can guide them toward the next step. Additionally, icons can remind participants of their current phase within the task, reducing uncertainty and helping them track their progress. To simplify controller interactions, a virtual 3D model of the controller can be displayed within the VE. Highlighting the relevant buttons directly on the model helps participants visually confirm their actions, and it provides a visual reminder of the spatial arrangement of the buttons. Enhancing this with additional visual cues, such as glowing or pulsating effects on the buttons, can serve as real-time reminders, which reduce working memory load and allow participants to concentrate more fully on the task itself (Colombo et al., 2024). These ongoing aids are particularly helpful for tasks requiring multiple steps or complex interactions. Overall, this approach not only improves task performance and user experience but also makes IVR more intuitive and accessible, especially for older adults or those less familiar with technology (Machado et al., 2018).

Continuous feedback is essential during both training and testing to reinforce correct actions, support task progression, and reduce uncertainty (Machado et al., 2018). Visual and auditory cues—such as confirmation messages, chimes for task completion, or click sounds for button presses—can enhance usability and motivate participants. Narrated instructions may also improve task navigation for older adults. These recommendations confer with the previous work providing evidence based recommendations on IVR use in aging (Abeele et al., 2021). However, given that many older users experience hearing difficulties, auditory cues should always be paired with clear visual indicators to ensure accessibility and comprehension. Additionally, incorporating haptic feedback—such as vibrations to confirm actions or guide attention (McGlynn and Rogers, 2017)—can further support older users by compensating for age-related declines in auditory and visual processing, as tactile perception tends to be relatively well preserved. Nonetheless, due to subtle reductions in tactile sensitivity with age (Decorps et al., 2014), it may be necessary to increase the intensity or duration of vibration signals to ensure they are perceived effectively.

Summary feedback at the end of a phase or task can enhance clarity, help participants track their progress, and manage expectations around task duration (Fig. 3). Such feedback also supports the debriefing process by reinforcing a sense of accomplishment. Displaying achievements—like badges earned, trials completed, or items collected—can provide closure and motivate continued engagement. Simple rewards, including congratulatory messages, animations, or icons, can further boost positive reinforcement and overall user satisfaction (Colombo et al., 2024). However, feedback related to performance on primary research outcomes should align with the specific objectives of the study and be implemented as needed. See Text box 3 for a discussion on use of motion tracking for feedback about own body location in IVR.

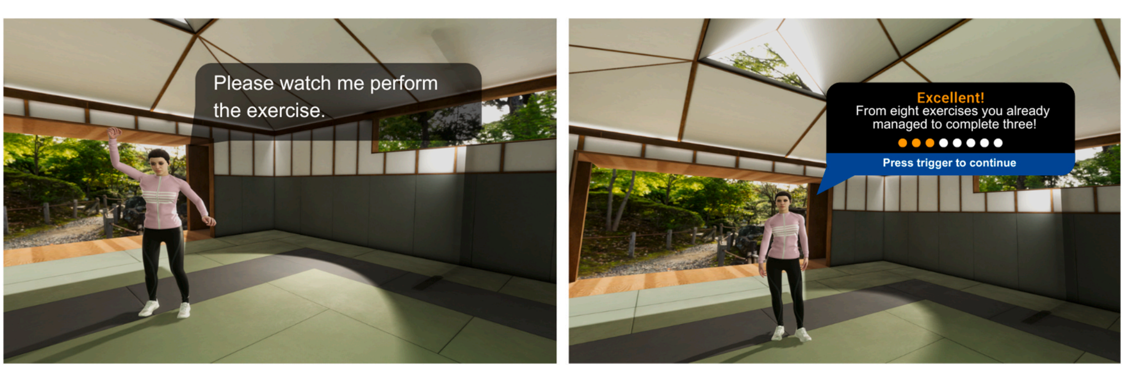

Fig. 3. Example of instructional and feedback elements in IVR. The left panel shows an instructional prompt where a virtual avatar demonstrates a movement exercise, providing a visual guide for participants before task execution. The right panel displays a progress indicator with positive reinforcement ("Well done!") which aims to help participants track their achievements. Such instructional prompts and feedback elements aim to reduce cognitive load, increase clarity, and maintain participant motivation during IVR sessions.

Text box 3
Optimizing visual alignment and visual feedback.

Optimizing vision through proper lens alignment

Interpupillary distance (IPD) refers to the distance between the centers of the pupils, typically measured in millimeters. It varies among individuals, with average adult values ranging from 54 mm to 72 mm although some outliers exist. Appropriate IPD adjustment is critical because IVR headsets need to align the display's virtual lenses with the user's eyes to ensure clear and comfortable viewing.

Improper IPD settings can exacerbate eye strain and discomfort. As people age, the eye muscles become less flexible, making it harder to accommodate poorly aligned visuals. If the IPD is not accurately set, older adults may experience greater eye strain or discomfort. Pre-existing vision problems, such as presbyopia, cataracts, or glaucoma can also be worsened by an incorrect IPD setting, making it even more difficult to focus or feel comfortable in IVR. Furthermore, incorrect IPD can negatively affect depth perception (Hibbard et al., 2020), which can, for example, influence performance in tasks that require accurate space perception. In addition, it may lead to feelings of unsteadiness or disorientation in VE, potentially increasing the risk of falls, particularly in these individuals who already face balance or mobility challenges. Properly adjusting IPD for each user can therefore help reduce disorientation, improve depth perception, and ultimately lower the risk of falls and discomfort in older adults.

Accurate motion tracking for effective feedback

Older adults often encounter challenges in posture and movement control due to age-related sensory decline and physiological changes, such as diminished proprioception (Lee et al., 2013). Visual feedback can compensate for these deficits, offering critical support for maintaining balance and executing tasks with greater precision. This is especially relevant for studies requiring specific physical movements, such as exercises or particular stances. Such visual feedback could be included by simulating participants' bodies (or critical parts i.e. hands) or with a virtual mirror that displays the participant's body. This allows users to see if they are performing a given task correctly and make adjustments to their posture or movements as needed, enhancing accuracy and confidence in task execution (Everard et al., 2023) as well as decreasing fall risk. However, providing accurate feedback about the position and orientation of body parts requires additional tracking hardware. Ensuring the accuracy of motion tracking is crucial, as discrepancies between the virtual representation and the actual body position can lead to confusion and, more importantly, potentially increase the risk of falls. Careful calibration and system optimization are essential to minimize such risks and maintain user safety. Reliable tracking is achieved with specific adjustments to lighting conditions and by ensuring an unobstructed line of sight between trackers and sensors.

4.2.3. Post-session support: Debriefing, feedback, and cybersickness monitoring

Following task completion, debriefing older adults is a vital phase that ensures any questions or concerns that arose during the session are clarified, addressing uncertainties and reducing anxiety for future interactions. Debriefing can also help identify participants who may have misunderstood the task or experienced cybersickness, allowing researchers to account for these factors during data analysis.

To assess cybersickness we recommend systematically measuring symptoms both before and after IVR exposure using validated questionnaires (Kennedy et al., 1993). However, it should be noted that assessing cybersickness symptoms prior to IVR exposure may predispose participants to higher levels of cybersickness (Young et al., 2006), one way to avoid this is to obtain the pre and post measures both after IVR exposure (Starrett, 2021).

4.2.4. General use of UI in IVR experiments

Throughout all phases of IVR interactions, UI elements can be highly effective in achieving the goals of clarity and simplicity, which are essential for supporting accessibility and ease of use for older adults. Large, high-contrast icons accommodate reduced visual acuity, while dynamic elements such as zooming, jiggling, or highlighting can draw attention to critical instructions (Havukainen et al., 2020; Ijsselsteijn et al., 2007). These bottom-up attentional cues are particularly valuable, as older adults often show preserved sensitivity to salient visual features, which can help compensate for age-related declines in top-down attentional control (Craik and Byrd, 1982; Hasher and Zacks, 1988; Salthouse, 1996, 2009). As such, jiggling or highlighting not only attracts attention but ensures it is directed where it is most needed. Text-based prompts should be minimized and replaced with sequential instructions delivered through visual (including icons) or audio cues to reduce screen clutter (Farage et al., 2012). Such decluttering strategies are especially important given reduced attentional capacity, inhibitory control deficits, and increased distractibility, all of which make it more difficult to process information in visually complex environments (Abeele et al., 2021; Van Schaik et al., 2008). However, care should be taken to ensure that icons or other elements are intuitive and easy to understand, avoiding ambiguity that might confuse participants (Colombo et al., 2024). Overall, when using UI prompts (i.e. pop-ups) it is important that they remain visible until participants acknowledge them, accommodating slower response times and reducing cognitive strain. By implementing these UI recommendations, IVR systems can become more intuitive and engaging for older adults.

4.3. Optimizing overall characteristics of the IVR setup

In addition to experimental design considerations, designing IVR experiences for older adults should also involve careful consideration of the hardware involved. This pertains to the design and functionality of HMDs, interaction devices, and headphones, as well as the overall setup.

4.3.1. Visual display characteristics

Even though IVR is a multisensory technology, visual information is of particular importance because it typically provides much richer and more detailed information about the environment and events happening therein. Therefore, optimizing visual quality enhances older adults' experience and interaction. High-resolution displays with fast refresh rates and a wide field-of-view improve immersion, reduce fatigue, and minimize motion sickness (Caserman et al., 2021; Zheleva et al., 2020).

Care also needs to be taken to ensure that age-related vision impairments such as myopia are properly accommodated (see Text box 3 on IPD adjustments). Even though the screens inside an HMD are physically very close to the eyes, built-in lenses mimic natural viewing conditions by projecting the image as if it were far away, typically at a distance of 1–2 m or more. As a consequence, the eyes must focus as if looking at objects in the distance and not close-up, which can create problems for users suffering from myopia. While some HMDs provide enough space for users to wear glasses during IVR exposure, it is important to ensure that they accommodate glasses (Abeele et al., 2021) in such a way that (i) they do not interfere with IPD adjustment and potential eye tracking, and (ii) they do not cause discomfort for users (Roberts et al., 2019), for example due to the frame of the glasses being pressed on the face or fogging. These issues can be mitigated by using face cushions or covers that promote airflow between the eyes and lenses, as well as by adding accessories that create protective spacing between the glasses and headset optics. As an alternative to glasses, several HMDs include diopter adjustments or compatibility with prescription lenses. Finally, glare should be minimized to enhance visibility and prevent discomfort. This can be achieved by using anti-reflective lens coatings, reducing excessive brightness, and avoiding high-contrast lighting conditions in the VE.

4.3.2. Auditory stimulation

The hearing and cognitive changes associated with aging necessitate careful consideration of audio system design to enhance both presence and accessibility without overwhelming the user. Integrated headphones in HMDs reduce the need for additional equipment and simplify the setup. Alternatively, lightweight over-ear headphones with soft padding can provide high-quality sound while ensuring comfort during extended use.

While ambient sound can enhance the immersion and realism of the VE (Smith and Mulligan, 2021), excessive use of ambient sounds might increase cognitive load and distract older adults (Janse, 2012; Stevens et al., 2008), who may already face challenges in processing multiple sources of auditory information (see **Section 3.2**). Additionally, ambient sounds should not be competing with essential audio cues. Audio instructions, specifically when implemented together with visual instructions and/or cues, can provide valuable guidance for navigating tasks (Cooper et al., 2015; Wu et al., 2020). If spatial sound is used to guide participants in the VE, it should be paired with visual cues, as older adults may have greater difficulties in localising spatial sound alone (Adel Ghahraman et al., 2020).

Adjusting volume levels individually for each session, before beginning tasks, is strongly recommended to ensure optimal clarity without overloading the user. Noise-cancellation features can further enhance focus by minimizing external distractions, making them especially beneficial for older users (Janse, 2012; Stevens et al., 2008). For those using hearing aids, compatibility with audio systems—or alternatives such as bone-conduction headphones—can mitigate interference, thus, as highlighted in an earlier review on use of IVR in aging, it is essential to ensure that HMD set ups accommodate hearing aids (Abeele et al., 2021). Additionally, high-pitched sounds should be avoided, as they are often difficult for older adults to perceive (Davis et al., 2016) and may cause discomfort, particularly when wearing hearing aids (McGlynn and Rogers, 2017; Reis et al., 2013).

5. Clinical implications

IVR offers significant potential in clinical settings, particularly for older adults (Wrzus et al., 2024). One promising use case is the detection of preclinical signs of AD, because currently used neuropsychological assessments are insensitive to the earliest disease stages. Given that the first neuropathological changes in AD affect key structures of the brain's navigation network, researchers have developed IVR-based assessments of spatial orientation deficits (Clay et al., 2020). In this approach, patients have to solve simple navigation tasks in virtual worlds, and the accuracy of their answers is measured by tracking position and orientation. Multiple studies have shown that patients exhibit subtle orientation deficits in the early stages of AD (Castegnaro et al., 2022; Howett et al., 2019), while performance in traditional neuropsychological assessments is unaffected. In addition, navigational deficits have even been reported in people with increased genetic risk of developing AD (Bierbrauer et al., 2020; Newton et al., 2024). As a consequence, a standardised IVR assessment in clinical practice could be a sensitive approach to identify patients at risk of developing AD early on and to initiate disease-modifying therapies before substantial neuropathological changes have developed (Coughlan et al., 2018).

Beyond assessment, meta-analyses have shown that IVR-based interventions can improve cognitive function, physical performance (Ortiz-Mallasén et al., 2024), and emotional well-being (Ke et al., 2025) across a range of clinical populations. For instance, Kim et al. (2019) and Zhu et al. (2021) reported cognitive gains in older adults following IVR training, while Ogourtsova et al. (2017) and Maier et al. (2019) demonstrated positive outcomes in post-stroke rehabilitation. Although performance benefits are not always superior to conventional methods (Ng et al., 2024; Rosiak et al., 2018), the immersive nature of IVR may help overcome common barriers to adherence (Beard et al., 2012; Ricci et al., 2015), which could exceed over 25 % (Jaeggi et al., 2013), particularly by increasing engagement and enjoyment. To further support adherence IVR can be augmented with gamification elements (Text box 2). Repetitive or monotonous tasks, common in both cognitive and physical training, can be made more engaging through progress tracking, rewards, adaptive difficulty, and real-time feedback. For example, a meta-analysis on the effects of gamification on computerized cognitive training showed that gamified training tasks were more motivating/engaging (Vermeir et al., 2020). These design strategies align with SDT by supporting both intrinsic (e.g., curiosity, enjoyment) and extrinsic motivation (e.g., completing goals, earning feedback), which are essential for both initial uptake and sustained adherence.

As with any clinical intervention, the success of IVR-based interventions depends on careful alignment between design and therapeutic goals (Constantin et al., 2022; Sanjuán et al., 2020; Zubala et al., 2017). IVR programs should be tailored to users' needs, incorporating factors such as pacing, feedback, task relevance, and usability, just as one would in non-immersive formats. Crucially, IVR also enables self-adaptive interventions and high-resolution performance monitoring, using HMDs and motion sensors to track body posture, range of motion, and exercise quality. These features are often lacking in traditional delivery formats, but they remain underutilized and under-evaluated in IVR interventions with older adult populations.

One major advantage of IVR is that it offers a tool for personalised, home-based interventions. However, as it expands into home-based settings, safety becomes a critical consideration—particularly for older adults who may face increased risk of falls, disorientation, or other adverse effects during unsupervised use. To mitigate these risks, IVR systems should be designed to minimize physical demands, include virtual boundary indicators, and offer gradual familiarization protocols or pre-session training. The growing availability of wireless headsets, especially those with inside-out tracking, has made home-based interventions more feasible. This development is particularly important given that wired setups are among the most frequently cited concerns among older users (Healy et al., 2022), due to mobility constraints and tripping hazards. One promising example is the use of IVR in home-based vestibular rehabilitation (García-Muñoz et al., 2022), which has shown potential for improving balance and reducing symptoms. However, further research is needed to evaluate the safety, usability, and clinical effectiveness of home-based IVR systems in aging populations and to develop evidence-based guidelines for safe implementation.

Finally, while much attention has been given to UI design for older adults, clinical applications also require interfaces tailored to clinicians. These interfaces should be intuitive, easy to set up, and capable of providing clear access to relevant data—for example, to monitor user progress, adjust task difficulty, or support diagnostic decision-making. Streamlining clinician-facing UIs is essential for ensuring that IVR systems can be effectively integrated into real-world clinical workflows. Importantly, engaging clinicians early in the design process—particularly when interfaces are intended to support performance monitoring or clinical decision-making—can significantly improve workflow compatibility, enhance trust in the technology, and facilitate early adoption (Helman et al., 2022). While this has been demonstrated in the context of AI-based decision support systems, it is directly relevant to IVR applications in healthcare, where clinician-facing tools remain an understudied but essential component of successful implementation.

6. Discussion

This review synthesizes key age-related challenges and design strategies for IVR, offering a cross-disciplinary perspective that spans cognitive, sensory, emotional, and physical domains. By integrating findings from empirical studies, systematic reviews, and theoretical models, we highlight the multifaceted barriers that may hinder older adults' engagement with IVR, while identifying actionable design principles to improve usability, safety, and overall experience. Our conclusions build on earlier work (e.g., Abeele et al., 2021; Healy et al., 2022), while extending these efforts by incorporating recent evidence, broader clinical applications, and a deeper theoretical framing to support the development of age-inclusive IVR systems.

Importantly, IVR holds significant promise for advancing our understanding of aging. It enables the study of cognitive, emotional, and motor changes in immersive yet experimentally controlled environments and supports the development of more accurate diagnostic tools and engaging therapeutic interventions. Realizing this potential, however, requires careful consideration of the cognitive and functional diversity of older adults. Our review emphasizes the importance of adaptable, flexible design strategies that accommodate a wide range of user abilities and preferences.

Specifically, in this review we emphasized the importance of age-friendly design principles, including self-paced interactions, simplified IVR controllers, and nature-inspired environments to foster comfort and immersion. Ergonomic hardware adjustments, tailored visual and audio aids, and intuitive narrative elements are proposed to enhance accessibility. Structured training and phased introductions to IVR tasks are also key to reducing anxiety and building confidence. Importantly, these recommendations are grounded in theoretical frameworks that help explain why certain design features may be particularly effective for older adults. For example, we draw on SDT to suggest that allowing users to proceed at their own pace and control their transitions can enhance feelings of autonomy and competence—core psychological needs that are closely tied to motivation and engagement. By integrating such frameworks, we provide not only practical guidance but also a deeper conceptual rationale for why these design adaptations are likely to support better outcomes. By incorporating these strategies, researchers and clinicians can better design IVR studies and interventions suited to the unique needs of older adults, enabling a more nuanced understanding of aging.

6.1. Methodological and sampling limitations

Despite the wealth of research discussed in this review, several important questions remain to be thoroughly addressed. A persistent challenge in the IVR literature—particularly in studies involving older populations—is the lack of methodological consistency and rigor. Many studies are limited by small sample sizes, absence of control conditions, or idiosyncratic task setups that hinder replication and generalization. Additionally, comparative studies often use different hardware, software platforms, or interaction paradigms, making it difficult to draw coherent conclusions about best practices. More high-quality studies with larger, well-characterized samples and adequately powered, controlled designs are needed to generate stronger and more generalizable conclusions about IVR use in aging.

Another important concern is sampling bias. Much of the literature focuses on older adults in care settings or those with cognitive impairments, underrepresenting more independent, tech-savvy individuals. This is significant, as studies have shown that prior experience with computer-based technologies strongly influences IVR attitudes and engagement (Healy et al., 2022; Hauk et al., 2018; Abeele et al., 2021). As new cohorts of older adults increasingly enter this demographic with decades of experience using smartphones, computers, and digital technologies, they may require fewer accommodations than previous generations.

This trend underscores the importance of regularly reassessing user profiles, as digital familiarity, mobility, and cognitive health vary widely and evolve over time. Nonetheless, many of the design strategies presented in this review—such as simplified navigation, customizable pacing, and multimodal feedback—represent universal design principles that can enhance usability for users of all ages. Improving accessibility in IVR benefits not only older adults but also younger, less experienced users by reducing unnecessary complexity and cognitive load.

6.2. Future research directions

While this review provides a comprehensive synthesis, several key areas warrant further investigation. For instance, future studies should systematically investigate age-related differences in cybersickness using matched paradigms, ideally incorporating both subjective ratings and physiological measures (e.g., heart rate variability, skin conductance) to better understand the underlying mechanisms. Investigating the effectiveness of breaks or pacing strategies to mitigate cybersickness during prolonged IVR use is also a critical area of need. A few novel approaches—primarily studied in younger adults—may also hold promise for enhancing IVR experiences in older users. For example, walking-in-place locomotion has been associated with greater immersion and satisfaction compared to joystick controls, with minimal cybersickness reported in younger adults (Lee et al., 2017; Tan et al., 2022). However, the tolerability of this method among older adults, particularly those with mobility limitations, remains unclear. Similarly, chewing gum has been shown to reduce cybersickness in younger users—possibly by modulating vestibular input through mastoid stimulation (Kaufeld et al., 2022)—but its effectiveness in older adults with diminished vestibular sensitivity is still unknown. These techniques warrant further investigation, especially in light of known sensory changes associated with aging.

Future research should also explore how interacting with real-world objects within IVR environments affects older adults, as this remains a largely unexamined area. While promising for enhancing realism and engagement, such interactions may introduce unique age-related challenges, particularly related to motor coordination, sensory feedback, and breaks in presence. Similarly, although many reviews on usability of IVR in aging advocate for the use of auditory cues and ambient sounds (Abeele et al., 2021; McGlynn and Rogers, 2017; Reis et al., 2013) their role in supporting older users remains largely unstudied and deserves further empirical attention. Investigating these emerging strategies could inform more effective and inclusive design, ultimately improving the accessibility and utility of IVR for a growing aging population.

7. Conclusion

As IVR technologies continue to evolve, their successful integration into aging research and clinical practice will depend on thoughtful, inclusive, and evidence-based design. The findings and recommendations in this review highlight both the challenges and opportunities in making IVR more accessible and effective for older adults. By grounding design choices in both empirical evidence and theoretical models, and by accounting for the increasing diversity in aging user groups, researchers and developers can create VEs that are not only age-friendly, but universally beneficial.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

No data was used for the research described in the article.

References

Abeele, V.V., Schraepen, B., Huygelier, H., Gillebert, C., Gerling, K., Van Ee, R., 2021. Immersive virtual reality for older adults. ACM Trans. Access. Comput. 14 (3), 1–30.
Adamo, D.E., Briceño, E.M., Sindone, J.A., Alexander, N.B., Moffat, S.D., 2012. Age differences in virtual environment and real world path integration. Front. Aging Neurosci. 4, 26.
Adel Ghahraman, M., Ashrafi, M., Mohammadkhani, G., Jalaie, S., 2020. Effects of aging on spatial hearing. Aging Clin. Exp. Res. 32 (4), 733–739.
Ageing. 2020. World Health Organization: WHO. ⟨https://www.who.int/health-topics/ageing#tab=tab_1⟩.
Agrawal, Y., Platz, E.A., Niparko, J.K., 2008. Prevalence of hearing loss and differences by demographic characteristics among US adults: data from the National Health and Nutrition Examination Survey, 1999-2004. Arch. Intern. Med. 168 (14), 1522–1530.
Al-Sharman, A., Ismaiel, I.A., Khalil, H., El-Salem, K., 2021. Exploring the relationship between sleep quality, sleep-related biomarkers, and motor skill acquisition using virtual reality in people with Parkinson's disease: a pilot study. Front. Neurol. 12, 582611.
Anderson, A.P., Mayer, M.D., Fellows, A.M., Cowan, D.R., Hegel, M.T., Buckey, J.C., 2017. Relaxation with immersive natural scenes presented using virtual reality. Aerosp. Med. Hum. Perform. 88 (6), 520–526.
Arlati, S., Di Santo, S.G., Franchini, F., Mondellini, M., Filiputti, B., Luchi, M., Ratto, F., Ferrigno, G., Sacco, M., Greci, L., 2021. Acceptance and usability of immersive virtual reality in older adults with objective and subjective cognitive decline. J. Alzheimer'S. Dis.: JAD 80 (3), 1025–1038.
Barsasella, D., Liu, M.F., Malwade, S., Galvin, C.J., Dhar, E., Chang, C.-C., Li, Y.-C.J., Syed-Abdul, S., 2021. Effects of virtual reality sessions on the quality of life, happiness, and functional fitness among the older people: a randomized controlled trial from Taiwan. Comput. Methods Prog. Biomed. 200 (105892), 105892.
Bates, S.L., Wolbers, T., 2014. How cognitive aging affects multisensory integration of navigational cues. Neurobiol. Aging 35 (12), 2761–2769.
Beard, C., Weisberg, R.B., Primack, J., Kuckertz, J.M., Schofield, C.A., Clerkin, E.M., Primack, J., Boettcher, H., Weisberg, R.B., 2012. Socially anxious primary care patients' attitudes toward cognitive bias modification (CBM): qualitative study. Behav Cogn Psychother 2012 Oct;40(5):618-633. Behav. Cogn. Psychother. 40 (5), 16–38.
Bierbrauer, A., Kunz, L., Gomes, C.A., Luhmann, M., Deuker, L., Getzmann, S., Wascher, E., Gajewski, P.D., Hengstler, J.G., Fernandez-Alvarez, M., Atienza, M., Cammisuli, D.M., Bonatti, F., Pruneti, C., Percesepe, A., Bellaali, Y., Hanseeuw, B., Strange, B.A., Cantero, J.L., Axmacher, N., 2020. Unmasking selective path integration deficits in Alzheimer's disease risk carriers. Sci. Adv. 6 (35), eaba1394.
Biocca, F., Harms, C., Burgoon, J.K., 2003. Toward a more robust theory and measure of social presence: review and suggested criteria. Presence 12 (5), 456–480.
Blazer, D.G., 2003. Depression in late life: review and commentary. J. Gerontol. Ser. A Biol. Sci. Med. Sci. 58 (3), 249–265.
Butters, M.A., Bhalla, R.K., Andreescu, C., Wetherell, J.L., Mantella, R., Begley, A.E., Lenze, E.J., 2011. Changes in neuropsychological functioning following treatment for late-life generalised anxiety disorder. Br. J. Psychiatry J. Ment. Sci. 199 (3), 211–218.
Buttussi, F., Chittaro, L., 2021. Locomotion in place in virtual reality: a comparative evaluation of joystick, teleport, and leaning. IEEE Trans. Vis. Comput. Graph. 27 (1), 125–136.
Campo-Prieto, P., Cancela-Carral, J.M., Rodríguez-Fuentes, G., 2022. Feasibility and effects of an immersive virtual reality exergame program on physical functions in institutionalized older adults: a randomized clinical trial. Sensors 22 (18), 6742.
Campos, J.L., El-Khechen Richandi, G., Coahran, M., Fraser, L.E., Taati, B., Keshavarz, B., 2021. Virtual Hand Illusion in younger and older adults. J. Rehabil. Assist. Technol. Eng. 8, 20556683211059389.
Caserman, P., Garcia-Agundez, A., Gámez Zerban, A., Göbel, S., 2021. Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. Virtual Real. 25 (4), 1153–1170.
Castegnaro, A., Howett, D., Li, A., Harding, E., Chan, D., Burgess, N., King, J., 2022. Assessing mild cognitive impairment using object-location memory in immersive virtual environments. Hippocampus 32 (9), 660–678.
Chrastil, E.R., Warren, W.H., 2012. Active and passive contributions to spatial learning. Psychon. Bull. Rev. 19 (1), 1–23.
Chu Yew Yee, S.L., Duh, H.B.-L., & Quek, F. ,2010. Investigating narrative in mobile games for seniors. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. CHI '10: CHI Conference on Human Factors in Computing Systems, Atlanta Georgia USA. https://doi.org/10.1145/1753326.1753424.
Clay, F., Howett, D., FitzGerald, J., Fletcher, P., Chan, D., Price, A., 2020. Use of immersive virtual reality in the assessment and treatment of Alzheimer's disease: a systematic review. J. Alzheimer'S. Dis.: JAD 75 (1), 23–43.
Clifton, J., Palmisano, S., 2020. Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. Virtual Real. 24 (3), 453–468.
Colombo, G., Minta, K., Grübel, J., Tai, W.L.E., Hölscher, C., Schinazi, V.R., 2024. Detecting cognitive impairment through an age-friendly serious game: the development and usability of the Spatial Performance Assessment for Cognitive Evaluation (SPACE). Comput. Hum. Behav. 160 (108349), 108349.
Constantin, N., Edward, H., Ng, H., Radisic, A., Yule, A., D'Asti, A., D'Amore, C., Reid, J. C., Beauchamp, M., 2022. The use of co-design in developing physical activity interventions for older adults: a scoping review. BMC Geriatr. 22 (1), 647.
Cook, D.M., Dissanayake, D., & Kaur, K. ,2019. Virtual Reality and Older Hands. Proceedings of the 5th International ACM In-Cooperation HCI and UX Conference. CHIuXiD'19: The 5th International HCI and UX Conference, Jakarta Surabaya, Bali Indonesia. https://doi.org/10.1145/3328243.3328262.
Cooper, N., Milella, F., Cant, I., Pinto, C., White, M., & Meyer, G. ,2015. The effects of multisensory cues on the sense of presence and task performance in a virtual reality environment.
Corriveau Lecavalier, N., Ouellet, É., Boller, B., Belleville, S., 2020. Use of immersive virtual reality to assess episodic memory: a validation study in older adults. Neuropsychol. Rehabil. 30 (3), 462–480.
Coughlan, G., Laczó, J., Hort, J., Minihane, A.-M., Hornberger, M., 2018. Spatial navigation deficits - overlooked cognitive marker for preclinical Alzheimer disease? Nat. Rev. Neurol. 14 (8), 496–506.
Coutrot, A., Silva, R., Manley, E., de Cothi, W., Sami, S., Bohbot, V.D., Wiener, J.M., Hölscher, C., Dalton, R.C., Hornberger, M., Spiers, H.J., 2018. Global determinants of navigation ability. Curr. Biol.: CB 28 (17), 2861–2866 e4.
Craik, F.I.M., Byrd, M., 1982. Aging and Cognitive Deficits. Aging and Cognitive Processes. Springer US, pp. 191–211.
Cummings, J.J., Bailenson, J.N., 2016. How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. Media Psychol. 19 (2), 272–309.
Davis, A., McMahon, C.M., Pichora-Fuller, K.M., Russ, S., Lin, F., Olusanya, B.O., Chadha, S., Tremblay, K.L., 2016. Aging and hearing health: the life-course approach. Gerontologist 56 (2), S256–S267. *Suppl 2*.
Davis, S., Nesbitt, K., Nalivaiko, E., 2015. Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters. In: Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015), 27. Australian Computing Society.
Davison, S.M.C., Deeprose, C., Terbeck, S., 2018. A comparison of immersive virtual reality with traditional neuropsychological measures in the assessment of executive functions. Acta Neuropsychiatr. 30 (2), 79–89.
Deci, E.L., Ryan, R.M., 2002. Overview self-determination theory: organismic dialectical perspective. In: In E. L. M. Deci, R. (Ed.), Handbook Self-determination Research. University Rochester Press, pp. 3–33.
Decorps, J., Saumet, J.L., Sommer, P., Sigaudo-Roussel, D., Fromy, B., 2014. Effect of ageing on tactile transduction processes. Ageing Res. Rev. 13, 90–99.
Dehn, D.M., Van Mulken, S., 2000. The impact of animated interface agents: a review of empirical research. Int. J. Hum. -Comput. Stud. 52 (1), 1–22.
Deshmukh, A.M., Chalmeta, R., 2024. User experience and usability of voice user interfaces: a systematic literature review. Information 15 (9), 579.
Deterding, S., Dixon, D., Khaled, R., & Nacke, L. ,2011. From game design elements to gamefulness. Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments. MindTrek '11: Academic MindTrek 2011, Tampere Finland. https://doi.org/10.1145/2181037.2181040.
Dilanchian, A.T., Andringa, R., Boot, W.R., 2021. A pilot study exploring age differences in presence, workload, and cybersickness in the experience of immersive virtual reality environments. Front. Virtual Real. 2. https://doi.org/10.3389/frvir.2021.736793.
Diniz, J.L., Oliveira, N.M.C., Coutinho, J.F.V., Marques, M.B., Pillon, C.B., Araújo, Í.L. de, 2024. Purposes and characteristics of virtual reality technologies for the elderly in the community: a scoping review. Rev. Lat. Am. De. Enferm. 32, e4389.
Dobreva, M.S., O'Neill, W.E., Paige, G.D., 2011. Influence of aging on human sound localization. J. Neurophysiol. 105 (5), 2471–2486.
Drazich, B.F., McPherson, R., Gorman, E.F., Chan, T., Teleb, J., Galik, E., Resnick, B., 2023. In too deep? A systematic literature review of fully-immersive virtual reality and cybersickness among older adults. J. Am. Geriatr. Soc. 71 (12), 3906–3915.
Dresel, M., Plaumann, J., Jochems, N., 2023. Investigating age differences in passive haptic feedback for immersive virtual reality: a pilot study on configuration tasks. Lecture Notes in Computer Science. Springer Nature Switzerland, pp. 210–222.
Everard, G., Burton, Q., Van de Sype, V., Bibentyo, T.N., Auvinet, E., Edwards, M.G., Batcho, C.S., Lejeune, T., 2024. Extended reality to assess post-stroke manual dexterity: contrasts between the classic box and block test, immersive virtual reality with controllers, with hand-tracking, and mixed-reality tests. J. Neuroeng. Rehabil. 21 (1), 36.
Everard, G.J., Lejeune, T.M., Batcho, C.S., 2023. Visual feedback and age affect upper limb reaching accuracy and kinematics in immersive virtual reality among healthy adults. Int. J. Rehabil. Res. Int. Z. F. üR. Rehabil. Rev. Int. De. Rech. De. Readapt. 46 (3), 221–229.
Everard, G., Otmane-Tolba, Y., Rosselli, Z., Pellissier, T., Ajana, K., Dehem, S., Auvinet, E., Edwards, M.G., Lebleu, J., Lejeune, T., 2022. Concurrent validity of an immersive virtual reality version of the Box and Block Test to assess manual dexterity among patients with stroke. J. Neuroeng. Rehabil. 19 (1), 7.
Farage, M.A., Miller, K.W., Ajayi, F., Hutchins, D., 2012. Design principles to accommodate older adults. Glob. J. Health Sci. 4 (2), 2–25.

Fisk, A.D., Rogers, W.A., Charness, N., 2009. Involving older adults in research and usability studies (Ed.). In: Rogers, In.W.A., Fisk, A.D. (Eds.), Human Factors and Aging Series. CRC Press, pp. 171–178 (Ed.).

Galais, T., Delmas, A., & Alonso, R. ,2019. Natural interaction in virtual reality. Adjunct Proceedings of the 31st Conference on l'Interaction Homme-Machine. IHM "19: 31e Conférence Francophone sur l"Interaction Homme-Machine, Grenoble France. https://doi.org/10.1145/3366551.3370342.

García-Muñoz, C., Cortés-Vega, M.-D., Hernández-Rodríguez, J.-C., Fernández-Seguín, L. M., Escobio-Prieto, I., Casuso-Holgado, M.J., 2022. Immersive virtual reality and vestibular rehabilitation in multiple sclerosis: Case report. JMIR Serious Games 10 (1), e31020.

Gluck, A., Solini, H., Maiti, K., & Brinkley, J. ,2022. Evaluating 3D printed VR controller prototypes to increase VR accessibility for older adults. 2022 IEEE 3rd International Conference on Human-Machine Systems (ICHMS). 2022 IEEE 3rd International Conference on Human-Machine Systems (ICHMS), Orlando, FL, USA. https://doi.org/10.1109/ichms56717.2022.9980720.

Gomez-Hernandez, M., Ferre, X., Moral, C., Villalba-Mora, E., 2023. Design guidelines of mobile apps for older adults: systematic review and thematic analysis. JMIR mHealth uHealth 11, e43186.

Gottesman, R.F., Kleinman, J.T., Davis, C., Heidler-Gary, J., Newhart, M., Kannan, V., Hillis, A.E., 2008. Unilateral neglect is more severe and common in older patients with right hemispheric stroke. Neurology 71 (18), 1439–1444.

Groten, R. ,2012. The sense of embodiment in. 〈https://diposit.ub.edu/dspace/bitstream/2445/53294/1/634024.pdf?ref=https://githubhelp.com〉.

Hasher, L., Zacks, R.T., 1988. Working memory, comprehension, and aging: A review and a new view. Psychology of Learning and Motivation. Elsevier, pp. 193–225.

Hauk, N., Hüffmeier, J., Krumm, S., 2018. Ready to be a silver surfer? A meta-analysis on the relationship between chronological age and technology acceptance. Comput. Hum. Behav. 84, 304–319.

Havukainen, M., Laine, T.H., Martikainen, T., Sutinen, E., 2020. A case study on co-designing digital games with older adults and children: game elements, assets, and challenges. Comput. Games J. 9 (2), 163–188.

Healy, D., Flynn, A., Conlan, O., McSharry, J., Walsh, J., 2022. Older adults' experiences and perceptions of immersive virtual reality: systematic review and thematic synthesis. JMIR Serious Games 10 (4), e35802.

Helman, S., Terry, M.A., Pellathy, T., Williams, A., Dubrawski, A., Clermont, G., Pinsky, M.R., Al-Zaiti, S., Hravnak, M., 2022. Engaging clinicians early during the development of a graphical user display of an intelligent alerting system at the bedside. Int. J. Med. Inform. 159 (104643), 104643.

Henry, M., Baudry, S., 2019. Age-related changes in leg proprioception: implications for postural control. J. Neurophysiol. 122 (2), 525–538.

Hibbard, P.B., van Dam, L.C.J., & Scarfe, P. ,2020. The implications of interpupillary distance variability for virtual reality. 2020 International Conference on 3D Immersion (IC3D). 2020 International Conference on 3D Immersion (IC3D), Brussels, Belgium. https://doi.org/10.1109/ic3d51119.2020.9376369.

Hill, P.F., Bermudez, S., McAvan, A.S., Garren, J.D., Grilli, M.D., Barnes, C.A., Ekstrom, A.D., 2024. Age differences in spatial memory are mitigated during naturalistic navigation. Neuropsychol., Dev., Cogn. Sect. B Aging, Neuropsychol. Cogn. 31 (6), 1106–1130.

Hongpaisanwiwat, C., & Lewis, M. ,2003. Attentional effect of animated character. IFIP TC13 International Conference on Human-Computer Interaction. 〈https://rauterberg.employee.id.tue.nl/conferences/INTERACT2003/INTERACT2003-p423.pdf〉.

Hosseini, M., Thomas, R., Pilutti, L., Fallavollita, P., Jutai, J.W., 2024. Acceptance of physical activity virtual reality games by residents of long-term care facilities: a qualitative study. PloS One 19 (6), e0305865.

Howett, D., Castegnaro, A., Krzywicka, K., Hagman, J., Marchment, D., Henson, R., Rio, M., King, J.A., Burgess, N., Chan, D., 2019. Differentiation of mild cognitive impairment using an entorhinal cortex-based test of virtual reality navigation. Brain A J. Neurol. 142 (6), 1751–1766.

Huygelier, H., Schraepen, B., van Ee, R., Vanden Abeele, V., Gillebert, C.R., 2019. Acceptance of immersive head-mounted virtual reality in older adults. Sci. Rep. 9 (1), 4519.

Ijaz, K., Tran, T.T.M., Kocaballi, A.B., Calvo, R.A., Berkovsky, S., Ahmadpour, N., 2022. Design considerations for immersive virtual reality applications for older adults: a scoping review. Multimodal Technol. Interact. 6 (7), 60.

Ijsselsteijn, W., Nap, H.H., de Kort, Y., & Poels, K. ,2007. Digital game design for elderly users. Proceedings of the 2007 Conference on Future Play - Future Play '07. the 2007 conference, Toronto, Canada. https://doi.org/10.1145/1328202.1328206.

Iwasaki, S., Yamasoba, T., 2015. Dizziness and imbalance in the elderly: age-related decline in the vestibular system. Aging Dis. 6 (1), 38–47.

Jaeggi, S.M., Buschkuehl, M., Shah, P., Jonides, J., Redick, T.S., Shipstead, Z., Harrison, T.L., Hicks, K.L., Fried, D.E., Hambrick, D.Z., 2013. evidence intelligence improvement after working memory training: randomized, placebo-controlled study. J. Exp. Psychol. Gen. 42 (3), 359–379.

Janse, E., 2012. A non-auditory measure of interference predicts distraction by competing speech in older adults. Neuropsychol., Dev., Cogn. Sect. B Aging Neuropsychol. Cogn. 19 (6), 741–758.

Kalantari, S., Bill Xu, T., Mostafavi, A., Lee, A., Barankevich, R., Boot, W.R., Czaja, S.J., 2022. Using a nature-based virtual reality environment for improving mood states and cognitive engagement in older adults: a mixed-method feasibility study. Innov. Aging 6 (3) igac015.

Kaufeld, M., De Coninck, K., Schmidt, J., Hecht, H., 2022. Chewing gum reduces visually induced motion sickness. Exp. Brain Res. 240 (2), 651–663.

Ke, Z., Wei, M., Yang, F., Qiu, Y., Zhu, X., Gao, X., Zhou, J., Qiao, G., 2025. The effectiveness of immersive virtual reality on the psychology of older adults: a systematic review and Meta-analysis of randomized controlled trials. Gen. Hosp. Psychiatry 94, 86–96.

Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G., 1993. Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int. J. Aviat. Psychol. 3 (3), 203–220.

Kern, A.C., Ellermeier, W., 2020. Audio in VR: Effects of a soundscape and movement-triggered step sounds on presence. Front. Robot. AI 7, 20.

Keshavarz, B., Ramkhalawansingh, R., Haycock, B., Shahab, S., Campos, J.L., 2018. Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions. Transp. Res. Part F. Traffic Psychol. Behav. 54, 47–62.

Kim, O., Pang, Y., Kim, J.H., 2019. The effectiveness of virtual reality for people with mild cognitive impairment or dementia: a meta-analysis. BMC Psychiatry 19, 219 (Article).

Kruse, L., Knaack, L., Steinicke, F., 2024. Back to (virtual) reality: preferences and effects of entry and exit transitions to virtual experiences for older adults. ACM Symp. . Spat. Use Interact. 4, 1–2.

Laessoe, U., Abrahamsen, S., Zepernick, S., Raunsbaek, A., Stensen, C., 2023. Motion sickness and cybersickness - sensory mismatch. Physiol. Behav. 258 (114015), 114015.

Lee, J., Kim, M., Kim, J., 2017. A study on immersion and VR sickness in walking interaction for immersive virtual reality applications. Symmetry 9 (5), 78.

Lee, N.K., Kwon, Y.H., Son, S.M., Nam, S.H., Kim, J.S., 2013. The effects of aging on visuomotor coordination and proprioceptive function in the upper limb. J. Phys. Ther. Sci. 25 (5), 627–629.

Li, J.Q., Welchowski, T., Schmid, M., Mauschitz, M.M., Holz, F.G., Finger, R.P., 2020. Prevalence and incidence of age-related macular degeneration in Europe: a systematic review and meta-analysis. Br. J. Ophthalmol. 104 (8), 1077–1084.

Lin, C.X., Lee, C., Lally, D., Coughlin, J.F., 2018. Impact of virtual reality (VR) experience on older adults' well-being. Human Aspects of IT for the Aged Population. Applications in Health, Assistance, and Entertainment. Springer International Publishing, pp. 89–100.

Long, X., Din, N.C., Mahyuddin, N., Lei, Y., Liu, L., 2023. Virtual reality reproducing outdoor audio-visual environments in nursing homes: exploring the restorative effects of soundscapes on the elderly. INTER-NOISE NOISE-CON Congr. Conf. Proc. 268 (8), 105–115.

Lord, S.R., Clark, R.D., Webster, I.W., 1991. Postural stability and associated physiological factors in a population of aged persons. J. Gerontol. 46 (3), M69–M76.

Loughrey, D.G., Kelly, M.E., Kelley, G.A., Brennan, S., Lawlor, B.A., 2018. Association of age-related hearing loss with cognitive function, cognitive impairment, and dementia: a systematic review and meta-analysis. JAMA Otolaryngol. – Head. Neck Surg. 144 (2), 115–126.

Luong, T., Cheng, Y.F., Mobus, M., Fender, A., Holz, C., 2023. Controllers or bare hands? A controlled evaluation of input techniques on interaction performance and exertion in virtual Reality. IEEE Trans. Vis. Comput. Graph. (11), 4633–4643 (PP).

Machado, M., da, C., Ferreira, R.L.R., Ishitani, L., 2018. Heuristics and recommendations for the design of mobile serious games for older adults. Int. J. Comput. Games Technol. 2018, 1–15.

Maier, M., Rubio Ballester, B., Duff, A., Duarte Oller, E., Verschure, P.F.M.J., 2019. Effect of specific over nonspecific VR-based rehabilitation on poststroke motor recovery: A systematic meta-analysis. Neurorehabil. Neural Repair 33 (2), 112–129.

Mandal, S. ,2013. Brief Introduction of Virtual Reality & its Challenges. International Journal of Scientific and Engineering Research. 〈https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b879c50ac2827e11575c589d5c199e30f83e97bc〉.

Manera, V., Chapoulie, E., Bourgeois, J., Guerchouche, R., David, R., Ondrej, J., Drettakis, G., Robert, P., 2016. A feasibility study with image-based rendered virtual Reality in patients with mild cognitive impairment and dementia. PloS One 11 (3), e0151487.

McGlynn, S.A., Rogers, W.A., 2017. Design recommendations to enhance virtual reality presence for older adults. Proc. Hum. Factors Ergon. Soc. Annu. Meet. Hum. Factors Ergon. Soc. Annu. Meet. 61 (1), 2077–2081.

Meade, M.E., Meade, J.G., Sauzeon, H., Fernandes, M.A., 2019. Active navigation in virtual environments benefits spatial memory in older adults. Brain Sci. 9 (3), 47.

Medhi, I., & Toyama, K. ,2007. Full-context videos for first-time, non-literate PC users. 2007 International Conference on Information and Communication Technologies and Development. 2007 International Conference on Information and Communication Technologies and Development (ICTD), Bangalore, India. https://doi.org/10.1109/ictd.2007.4937400.

Melo, M., Goncalves, G., Monteiro, P., Coelho, H., Vasconcelos-Raposo, J., Bessa, M., 2022. Do multisensory stimuli benefit the virtual reality experience? A systematic review. IEEE Trans. Vis. Comput. Graph. 28 (2), 1428–1442.

Mitzner, L., McGlynn, S, T.A., A. Rogers, W., 2021. Understanding spatial presence formation and maintenance in virtual reality for younger and older adults. Gerontechnology Int. J. Fundam. Asp. Technol. Serve Ageing Soc. 20 (2), 1–14.

Moyle, W., Jones, C., Dwan, T., Petrovich, T., 2018. Effectiveness of a virtual reality forest on people with dementia: a mixed methods pilot study. Gerontologist 58 (3), 478–487.

Murata, J., Murata, S., Hiroshige, J., Ohtao, H., Horie, J., Kai, Y., 2010. The influence of age-related changes in tactile sensibility and muscular strength on hand function in older adult females. Int. J. Gerontol. 4 (4), 180–183.

Newton, C., Pope, M., Rua, C., Henson, R., Ji, Z., Burgess, N., Rodgers, C.T., Stangl, M., Dounavi, M.-E., Castegnaro, A., Koychev, I., Malhotra, P., Wolbers, T., Ritchie, K., Ritchie, C.W., O'Brien, J., Su, L., Chan, D., Dementia Research Programme, P.R.E.V.E.N.T., 2024. Entorhinal-based path integration selectively predicts midlife risk of

Alzheimer's disease. Alzheimer'S. Dement. J. Alzheimer'S. Assoc. 20 (4), 2779–2793.
Ng, B., Abbas, D., 2020. Self-determination theory: Attributes of healthy aging. Self-Determination Theory and Healthy Aging. Springer, Singapore, pp. 19–30.
Ng, W.H.D., Ang, W.H.D., Fukahori, H., Goh, Y.S., Lim, W.S., Siah, C.J.R., Seah, B., Liaw, S.Y., 2024. Virtual reality-based reminiscence therapy for older adults to improve psychological well-being and cognition: a systematic review. J. Clin. Nurs. https://doi.org/10.1111/jocn.17375.
Ogourtsova, T., Souza Silva, W., Archambault, P.S., Lamontagne, A., 2017. Virtual reality treatment and assessments for post-stroke unilateral spatial neglect: a systematic literature review. Neuropsychol. Rehabil. 27 (3), 409–454.
Ortiz, A., del Puy Carretero, M., Oyarzun, D., Yanguas, J.J., Buiza, C., Gonzalez, M.F., Etxeberria, I., 2007. Elderly users in ambient intelligence: Does an avatar improve the interaction?. In: Universal Access in Ambient Intelligence Environments, 99 Springer, Berlin Heidelberg, pp. 99–114.
Ortiz-Mallasén, V., Claramonte-Gual, E., González-Chordá, V.M., Llagostera-Reverter, I., Valero-Chillerón, M.J., Cervera-Gasch, Á., 2024. Can virtual reality help improve motor and cognitive function in active aging in older adults? A scoping review. Healthcare 12 (3), 356.
Owsley, C., 2016. Vision and aging. Annu. Rev. Vis. Sci. 2 (1), 255–271.
Parong, J., Pollard, K.A., Files, B.T., Oiknine, A.H., Sinatra, A.M., Moss, J.D., Passaro, A., Khooshabeh, P., 2020. The mediating role of presence differs across types of spatial learning in immersive technologies. Comput. Hum. Behav. 107 (106290), 106290.
Perez-Marcos, D., Ronchi, R., Giroux, A., Brenet, F., Serino, A., Tadi, T., Blanke, O., 2023. An immersive virtual reality system for ecological assessment of peripersonal and extrapersonal unilateral spatial neglect. J. Neuroeng. Rehabil. 20 (1), 33.
Petri, K., Feuerstein, K., Folster, S., Bariszlovich, F., Witte, K., 2020. Effects of age, gender, familiarity with the content, and exposure time on cybersickness in immersive head-mounted display based virtual reality. Am. J. Biomed. Sci. 107–121.
Plechatá, A., Sahula, V., Fayette, D., Fajnerová, I., 2019. Age-related differences with immersive and non-immersive virtual reality in memory assessment. Front. Psychol. 10, 1330.
Pontus, L., Daniel, V., Mendel, K., 2002. better presence and performance in virtual environments by improved binaural sound rendering. J. Audio Eng. Soc. 000228.
Porcino, T.M., Clua, E., Trevisan, D., Vasconcelos, C.N., Valente, L., 2017. Minimizing cybersickness in head-mounted display systems: Design guidelines and applications. Proceedings of the 2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH). IEEE, pp. 1–6.
Rashid Izullah, F., Af Schulten, A., Koivisto, M., Nieminen, V., Luimula, M., HÄmÄlÄinen, H., 2021. Differential interactions of age and sleep deprivation in driving and spatial perception by male drivers in a virtual reality environment. Scand. J. Psychol. 62 (6), 787–797.
Reason, J.T., & Brand, J.J. ,1975. Motion sickness. Vii, 310. ⟨https://psycnet.apa.org/fulltext/1976-12574-000.pdf⟩.
Rebenitsch, L., Owen, C., 2016. Review on cybersickness in applications and visual displays. Virtual Real. 20 (2), 101–125.
Reis, L., Duarte, E., Rebelo, F., 2013. Main usability issues in using virtual environments for older population warning studies. Design, User Experience, and Usability. User Experience in Novel Technological Environments. Springer, Berlin Heidelberg, pp. 189–198.
Ricci, N.A., Aratani, M.C., Caovilla, H.H., Ganança, F.F., 2015. Challenges in conducting a randomized clinical trial of older people with chronic dizziness: before, during and after vestibular rehabilitation. Contemp. Clin. Trials 40, 26–34.
Rmadi, H., Maillot, P., Artico, R., Baudouin, E., Hanneton, S., Dietrich, G., Duron, E., 2023. Tolerance of immersive head-mounted virtual reality among older nursing home residents. Front. Public Health 11, 1163484.
Roberts, A.R., De Schutter, B., Franks, K., Radina, M.E., 2019. Older adults' experiences with audiovisual virtual reality: perceived usefulness and other factors influencing technology acceptance. Clin. Gerontol. 42 (1), 27–33.
Rosiak, O., Krajewski, K., Woszczak, M., Jozefowicz-Korczynska, M., 2018. Evaluation of the effectiveness of a virtual reality-based exercise program for unilateral peripheral vestibular deficit. J. Vestib. Res. Equilib. Orientat. 28 (5-6), 409–415.
Sailer, M., Hense, J.U., Mayr, S.K., Mandl, H., 2017. How gamification motivates: an experimental study of the effects of specific game design elements on psychological need satisfaction. Comput. Hum. Behav. 69, 371–380.
Salazar-Cardona, J., Gutiérrez Vela, F.L., Arango-Lopez, J., Moreira, F., 2023. Older adults' motivations in game based systems: heuristic definition and its connection with fun. Comput. Hum. Behav. Rep. 11 (100304), 100304.
Salthouse, T.A., 1996. The processing-speed theory of adult age differences in cognition. Psychol. Rev. 103 (3), 403–428.
Salthouse, T.A., 2009. When does age-related cognitive decline begin? Neurobiol. Aging 30 (4), 507–514.
Sanjuán, M., Navarro, E., Calero, M.D., 2020. Effectiveness of cognitive interventions in older adults: a review. Eur. J. Investig. Health Psychol. Educ. 10 (3), 876–898.
Saredakis, D., Szpak, A., Birckhead, B., Keage, H.A.D., Rizzo, A., Loetscher, T., 2020. Factors associated with virtual reality sickness in head-mounted displays: A systematic review and meta-analysis. Front. Hum. Neurosci. 14, 96.
Segen, V., Ying, J., Morgan, E., Brandon, M., Wolbers, T., 2022. Path integration in normal aging and Alzheimer's disease. Trends Cogn. Sci. 26 (2), 142–158.
Seidler, R.D., Bernard, J.A., Burutolu, T.B., Fling, B.W., Gordon, M.T., Gwin, J.T., Kwak, Y., Lipps, D.B., 2010. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. Neurosci. Biobehav. Rev. 34 (5), 721–733.
Shahbaz Badr, A., De Amicis, R., 2023. An empirical evaluation of enhanced teleportation for navigating large urban immersive virtual environments. Front. Virtual Real. 3. https://doi.org/10.3389/frvir.2022.1075811.
Smith, S.A., Mulligan, N.W., 2021. Immersion, presence, and episodic memory in virtual reality environments. Memory 29 (8), 983–1005.
Stangl, M., Kanitscheider, I., Riemer, M., Fiete, I., Wolbers, T., 2020. Sources of path integration error in young and aging humans. Nat. Commun. 11 (1), 2626.
Starrett, M.J. ,2021. Studying Human Spatial Cognition Large-Scale, Virtual Environments: Learning, Memory, Representational Flexibility. The University of Arizona ProQuest Dissertations & Theses.
Stevens, W.D., Hasher, L., Chiew, K.S., Grady, C.L., 2008. A neural mechanism underlying memory failure in older adults. J. Neurosci. Off. J. Soc. Neurosci. 28 (48), 12820–12824.
Tan, C.T., Foo, L.C., Yeo, A., Lee, J.S.A., Wan, E., Kok, X.-F.K., Rajendran, M., 2022. Understanding user experiences across VR walking-in-place locomotion methods. April 29 CHI Conference on Human Factors in Computing Systems (CHI '22) (New Orleans, LA, USA). Association for Computing Machinery.
Terenzi, L., & Zaal, P. ,2020. Rotational and translational velocity and acceleration thresholds for the onset of cybersickness in virtual reality. AIAA Scitech 2020 Forum. AIAA Scitech 2020 Forum, Orlando, FL. https://doi.org/10.2514/6.2020-0171.
Thomasson, M., Perez-Marcos, D., Crottaz-Herbette, S., Brenet, F., Saj, A., Bernati, T., Serino, A., Tadi, T., Blanke, O., Ronchi, R., 2024. An immersive virtual reality tool for assessing left and right unilateral spatial neglect. J. Neuropsychol. 18 (3), 349–376.
Toledo, D.R., Barela, J.A., 2014. Age-related differences in postural control: effects of the complexity of visual manipulation and sensorimotor contribution to postural performance. Exp. Brain Res. 232 (2), 493–502.
Tortora, C., Di Crosta, A., La Malva, P., Prete, G., Ceccato, I., Mammarella, N., Di Domenico, A., Palumbo, R., 2024. Virtual reality and cognitive rehabilitation for older adults with mild cognitive impairment: a systematic review. Ageing Res. Rev. 93, 102146.
Tran, M.K., Robert, P., & Brémond, F. ,2016. A Virtual Agent for enhancing performance and engagement of older people with dementia in Serious Games. ⟨https://hal.science/hal-01369878/document⟩.
Van Schaik, P., Martyr, A., Blackman, T., Robinson, J., 2008. Involving persons with dementia in the evaluation of outdoor environments. Cyber Behav.: Impact Internet, Multimed. Virtual Real. Behav. Soc. 11 (4), 415–424.
Vermeir, J.F., White, M.J., Johnson, D., Crombez, G., Van Ryckeghem, D.M.L., 2020. The effects of gamification on computerized cognitive training: systematic review and meta-analysis. JMIR Serious Games 8 (3), e18644.
Wais, P.E., Arioli, M., Anguera-Singla, R., Gazzaley, A., 2021. Virtual reality video game improves high-fidelity memory in older adults. Sci. Rep. 11 (1), 2552.
Wallet, G., Sauzéon, H., Rodrigues, J., & N'Kaoua, B. ,2008. Use of virtual reality for spatial knowledge transfer. Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology. VRST08: The ACM Symposium on Virtual Reality Software and Technology, Bordeaux France. https://doi.org/10.1145/1450579.1450616.
Wetherell, J.L., Reynolds, C.A., Gatz, M., Pedersen, N.L., 2002. Anxiety, cognitive performance, and cognitive decline in normal aging. J. Gerontol. Ser. B Psychol. Sci. Soc. Sci. 57 (3), 246–P255.
Wirth, W., Hartmann, T., Böcking, S., Vorderer, P., Klimmt, C., Schramm, H., Saari, T., Laarni, J., Ravaja, N., Gouveia, F.R., Biocca, F., Sacau, A., Jäncke, L., Baumgartner, T., Jäncke, P., 2007. A process model of the formation of spatial presence experiences. Media Psychol. 9 (3), 493–525.
Wrzus, C., Frenkel, M.O., Schöne, B., 2024. Current opportunities and challenges of immersive virtual reality for psychological research and application. Acta Psychol. 249 (104485), 104485.
Wu, F., Thomas, J., Chinnola, S., & Rosenberg, E.S. ,2020. Comparison of audio and visual cues to support remote guidance in immersive environments. The Eurographics Association. https://doi.org/10.2312/EGVE.20201266.
Wu, Z., Wang, D., Zhang, S., Huang, Y., Wang, Z., Fan, M., 2024. Toward making virtual reality (VR) more inclusive for older adults: Investigating aging effect on target selection and manipulation tasks in VR. Proc. CHI Conf. Hum. Factors Comput. Syst. 1–17.
Xu, T.B., Mostafavi, A., Boot, W.R., Czaja, S., Kalantari, S., 2025. Assessing the feasibility and efficacy of virtual reality navigational training for older adults. Innov. Aging 9 (1) igae099.
Yeo, A., Kwok, B.W.J., Joshna, A., Chen, K., Lee, J.S.A., 2024. Entering the next dimension: a review of 3D user interfaces for virtual reality. Electronics 13 (3), 600.
Young, S.D., Adelstein, B.D., & Ellis, S.R. ,2006. Demand characteristics of a questionnaire used to assess motion sickness in a virtual environment. IEEE Virtual Reality Conference (VR 2006). IEEE Virtual Reality Conference (VR 2006), Alexandria, VA, USA. https://doi.org/10.1109/vr.2006.44.
Yu, D., Li, X., Lai, F.H.-Y., 2023. The effect of virtual reality on executive function in older adults with mild cognitive impairment: a systematic review and meta-analysis. Aging Ment. Health 27 (4), 663–673.
Zalewski, C.K., 2015. Aging of the human vestibular system. Semin. Hear. 36 (3), 175–196.
Zeuwts, L.H.R.H., Iliano, E., Smith, M., Deconinck, F., Lenoir, M., 2021. Mental fatigue delays visual search behaviour in young cyclists when negotiating complex traffic situations: a study in virtual reality. Accid. Anal. Prev. 161 (106387), 106387.
Zheleva, A., Durnez, W., Bombeke, K., Van Wallendael, G., & De Marez, L. ,2020. Seeing is believing: The effect of video quality on quality of experience in virtual reality. 2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX). 2020 Twelfth International Conference on Quality of Multimedia

Experience (QoMEX), Athlone, Ireland. https://doi.org/10.1109/qomex48832.2020.9123075.
Zhu, S., Sui, Y., Shen, Y., Zhu, Y., Ali, N., Guo, C., Wang, T., 2021. Effects of virtual reality intervention on cognition and motor function in older adults with mild cognitive impairment or dementia: a systematic review and meta-analysis. Front. Aging Neurosci. 13, 586999.
Zubala, A., MacGillivray, S., Frost, H., Kroll, T., Skelton, D.A., Gavine, A., Gray, N.M., Toma, M., Morris, J., 2017. Promotion of physical activity interventions for community dwelling older adults: a systematic review of reviews. PloS One 12 (7), e0180902.