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# Mixed Reality as Context-Aware Infrastructure for Aging-in-Place

## Realidad Mixta como Infraestructura Sensible al Contexto para Envejecer en el Entorno Habitual

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**Abstract.** Population aging is increasing the need for support models that preserve autonomy, functional independence, emotional well-being, and participation in everyday environments. Although extended reality technologies are increasingly discussed in health, rehabilitation, and gerontechnology, mixed reality is often framed mainly as an immersive tool or as a technical variation within the extended reality continuum. This perspective may overlook its broader conceptual value for aging-in-place, where digital support must remain connected to physical spaces, daily routines, social relationships, and changing functional needs. This article develops a conceptual perspective rather than an empirical evidence synthesis. Drawing on interdisciplinary contributions from digital health, gerontechnology, human-computer interaction, implementation science, and ethical innovation, it examines mixed reality as a context-aware infrastructure for aging-in-place. The analysis highlights five conceptual attributes that distinguish mixed reality from other immersive modalities: embodied interaction, environmental continuity, situated cognition, perceptual anchoring, and bidirectional interaction between digital and physical environments. These attributes suggest that mixed reality should not be viewed only as a medium for delivering isolated interventions, but as a potential infrastructure for integrating cognitive, motor, emotional, and relational support within everyday life. The article further argues that its relevance may increase when combined with artificial intelligence, ambient assisted living technologies, and adaptive digital health systems. However, its implementation raises important ethical, clinical, and social challenges, including accessibility gaps, digital exclusion, privacy risks, technological dependence, usability barriers, and unequal adoption across care contexts. Mixed reality should therefore be approached not merely as an emerging immersive technology, but as a conceptual pathway for designing more adaptive, situated, and person-centered support systems for aging-in-place. Its future contribution will depend on responsible design, inclusive implementation, and frameworks that prioritize clinical meaning, human dignity, and equitable access.

**Keywords.** mixed reality; aging-in-place; context-aware infrastructure; gerontechnology; person-centered support.

**Resumen.** El envejecimiento poblacional está incrementando la necesidad de modelos de apoyo que preserven la autonomía, la independencia funcional, el bienestar emocional y la participación de las personas mayores en sus entornos cotidianos. Aunque las tecnologías de realidad extendida se discuten cada vez más en salud, rehabilitación y gerontecnología, la realidad mixta suele presentarse principalmente como una herramienta inmersiva o como una variación técnica dentro del continuo de la realidad extendida. Esta perspectiva puede limitar la comprensión de su valor conceptual para el envejecimiento en el entorno habitual, donde el apoyo digital debe mantenerse conectado con los espacios físicos, las rutinas diarias, las relaciones sociales y las necesidades funcionales cambiantes. Este artículo desarrolla una perspectiva conceptual, no una síntesis empírica de evidencia. A partir de contribuciones interdisciplinarias de la salud digital, la gerontecnología, la interacción humano-computadora, la ciencia de la implementación y la innovación ética, se examina la realidad mixta como una infraestructura sensible al contexto para envejecer en el entorno habitual. El análisis destaca cinco atributos conceptuales que diferencian a la realidad mixta de otras modalidades inmersivas: la interacción corporizada, la continuidad ambiental, la cognición situada, el anclaje perceptivo y la interacción bidireccional entre los entornos digitales y físicos. Estos atributos sugieren que la realidad mixta no debe entenderse únicamente como un medio para aplicar intervenciones aisladas, sino como una posible infraestructura para integrar apoyos cognitivos, motores, emocionales y relacionales en la vida cotidiana. Asimismo, se argumenta que su relevancia puede aumentar cuando se articula con inteligencia artificial, tecnologías de asistencia ambiental y sistemas adaptativos de salud digital. Sin embargo, su implementación plantea desafíos éticos, clínicos y sociales importantes, como las brechas de acceso, la exclusión digital, los riesgos de privacidad, la dependencia tecnológica, las barreras de usabilidad y la adopción desigual en distintos contextos de atención. En consecuencia, la realidad mixta debe abordarse no solo como una tecnología inmersiva emergente, sino como una vía conceptual para diseñar sistemas de apoyo más adaptativos, situados y centrados en la persona durante el envejecimiento en el entorno habitual. Su aporte futuro dependerá de un diseño responsable, una implementación inclusiva y marcos que prioricen el significado clínico, la dignidad humana y el acceso equitativo.

**Palabras clave.** realidad mixta; envejecimiento en el hogar; infraestructura sensible al contexto; gerontecnología; apoyo centrado en la persona.

## 1. Introduction

Population aging is reshaping healthcare systems worldwide, not simply through increasing longevity, but through the growing complexity of care needs associated with multimorbidity, functional decline, cognitive vulnerability, and social isolation. In this context, older adult care increasingly demands models that move beyond episodic, disease-centered interventions toward more adaptive, person-centered, and context-aware approaches capable of supporting autonomy, participation, and quality of life (World Health Organization, 2015; Beard et al., 2016).

Concurrently, healthcare is undergoing a broader digital transformation driven by intelligent systems, connected environments, wearable monitoring, and immersive interfaces. These technologies are progressively shifting care from institution-centered delivery toward distributed, personalized, and interactive ecosystems (Topol, 2019; Wang et al., 2024). Within this transformation, extended reality (XR) technologies—including virtual reality (VR), augmented reality (AR), and mixed reality (MR)—have attracted increasing interest for rehabilitation, education, mental health, and assistive care applications. However, much of the discourse surrounding XR in health continues to treat these modalities primarily as technological variants distinguished by immersion level or interface architecture, rather than as systems with fundamentally different implications for care design (Milgram & Kishino, 1994; Skarbez et al., 2021).

This distinction is particularly relevant in older adult care, where the suitability of digital interventions depends not only on technical capability, but also on how technologies interact with embodiment, sensory processing, cognition, environmental familiarity, and everyday functioning. Fully immersive VR may offer controlled therapeutic environments yet can also reduce environmental awareness and create perceptual disconnection from real-world contexts. AR enhances physical environments with digital overlays but often provides limited depth of interaction with virtual elements. MR occupies a conceptually distinct position by enabling persistent bidirectional interaction between digital objects and the physical world, preserving spatial awareness while supporting embodied engagement with context-sensitive virtual content (Speicher et al., 2019; Cabric et al., 2021).

This distinction may be more than technological. Older adult care increasingly requires interventions that integrate physical rehabilitation, cognitive stimulation, emotional engagement, environmental adaptation, and social support within ecologically meaningful contexts. Technologies that merely simulate experience may not address this multidimensional complexity. MR, by combining real-world continuity with interactive digital augmentation, may offer a fundamentally different substrate for care—one capable of supporting not only isolated interventions, but broader models of adaptive assistance, relational engagement, and intelligent care integration. Despite growing interest in MR applications, the field has largely emphasized empirical feasibility, usability, and intervention outcomes, with comparatively less attention to the conceptual implications of MR as a care model. Treating MR simply as another immersive tool risks underestimating its theoretical significance in the reconfiguration of geriatric care.

Accordingly, this paper advances a conceptual perspective: mixed reality should be understood not merely as an emerging immersive technology, but as a potentially transformative paradigm for older adult care. By examining its theoretical distinctiveness, care-relevant mechanisms, translational opportunities, and ethical tensions, this article argues that MR may reshape how autonomy, rehabilitation, social connection, and intelligent support are conceptualized in aging populations.

The remainder of this article is organized as follows. Section 2 examines the conceptual distinctiveness of mixed reality relative to other extended reality modalities. Section 3 discusses mixed reality as a cognitive-motor-emotional care infrastructure. Section 4 explores its implications for transforming older adult care through autonomy support, relational care, person-centered adaptation, and integration with intelligent care ecosystems. Section 5 addresses the main ethical, clinical, and translational tensions associated with implementation. Section 6 outlines a future research agenda, and Section 7 summarizes the main conclusions.

## 2. Why Mixed Reality Is Conceptually Different

### *2.1. Embodied Interaction Rather Than Detached Immersion*

A defining conceptual distinction of MR lies in its relationship with embodiment. Care technologies are not neutral delivery mechanisms; they shape how individuals perceive their bodies, navigate environments, and engage with therapeutic tasks. Traditional immersive systems, particularly VR, often rely on temporary perceptual displacement, requiring users to suspend engagement with their physical surroundings in favor of digitally constructed environments. While this can be advantageous for controlled simulation, it may be less aligned with the needs of older adults, whose care frequently depends on preserving bodily orientation, spatial awareness, and confidence in real-world movement.

MR instead supports embodied interaction by integrating digital elements into the user's existing physical environment, allowing action to remain anchored in bodily experience rather than displaced from it. This distinction aligns with embodied cognition perspectives, which emphasize that cognitive processes are inseparable from sensorimotor engagement with the world rather than isolated internal computations (Wilson, 2002; Barsalou, 2008). From this perspective, therapeutic engagement is not simply a matter of information delivery, but of meaningful bodily participation.

For older adults, this has important implications. Rehabilitation, mobility training, and assistive support are not abstract cognitive exercises; they involve real movement, balance, orientation, and physical interaction with surrounding space. A system that preserves bodily continuity while augmenting interaction may therefore be conceptually better aligned with geriatric care than technologies that require temporary disengagement from the physical world.

### *2.2. Environmental Continuity and Ecological Validity*

Older adult care frequently depends on contextual realism. Functional independence is expressed not in abstract laboratory performance, but in everyday environments—homes, clinics, community spaces, and social settings where cognition, mobility, and decision-making unfold in context. Technologies that remove users from these environments may offer therapeutic control, but they may also reduce ecological transfer. MR offers a different logic. Because digital content remains integrated with physical surroundings, interventions can preserve environmental continuity rather than replacing it. This creates conditions for ecologically valid interaction, in which therapeutic or assistive processes unfold within recognizable contexts rather than isolated simulations.

This distinction matters because successful aging interventions often depend on context-sensitive adaptation. Balance training, medication reminders, navigation support, object localization, or task sequencing are inherently environmental activities. Their effectiveness depends not only on the cognitive or motor task itself, but on its relationship with the user's lived environment. MR enables intervention within context rather than outside it, potentially strengthening translational relevance between therapeutic interaction and daily functioning. From a care perspective, ecological validity is not merely a methodological concern—it is a clinical one. Technologies that better reflect real-world interaction may be more likely to support meaningful functional transfer, autonomy, and sustainable engagement.

### *2.3. Situated Cognition and Context-Aware Interaction*

The conceptual distinctiveness of MR also emerges through situated cognition. Cognitive functioning does not occur in abstraction; it is shaped by environmental cues, spatial relationships, embodied action, and contextual interpretation. For older adults, particularly those experiencing cognitive vulnerability, contextual scaffolding can be central to orientation, memory support, and functional independence. MR is uniquely positioned to leverage this relationship because it allows digital assistance to be spatially and contextually embedded within the environment where cognition occurs. Rather than presenting decontextualized prompts or isolated exercises, MR can align support with real objects, locations, and ongoing activities.

This has significant implications for care design. A reminder anchored to the location of medication storage, a navigation cue aligned with a hallway, or task guidance integrated into domestic routines reflects a fundamentally different model of cognitive support than traditional screen-based prompting. The intervention becomes situated rather than external. This conceptual shift aligns with contemporary views of cognition as distributed across individuals, environments, and artifacts rather than confined within the individual mind. In this sense, MR may function not simply as a therapeutic medium, but as an adaptive cognitive ecology capable of augmenting real-world functioning.

### *2.4. Bidirectional Interaction and Hybrid Agency*

A further distinction lies in interaction architecture. Many digital health technologies remain essentially unidirectional: systems deliver content, prompts, or simulations to passive users. Even interactive systems often constrain agency within predefined digital scenarios. MR introduces a more reciprocal interaction model. Physical actions can modify digital states, while digital elements can respond dynamically to environmental and behavioral changes. This creates hybrid agency, in which therapeutic engagement emerges through continuous negotiation between user, environment, and computational system.

This matters in older adult care because agency is deeply linked to autonomy, dignity, and sustained participation. Technologies perceived as externally imposed or overly prescriptive may reduce engagement, particularly among users sensitive to dependence or technological intimidation. By contrast, systems that preserve meaningful interaction and responsiveness may better support person-centered care principles.

Hybrid agency also opens the possibility for adaptive interventions. Rather than static exercises or scripted experiences, MR systems may evolve in response to performance, behavior, fatigue, affective state, or environmental conditions. This makes MR conceptually closer to responsive care infrastructure than to conventional digital therapeutic delivery.

### *2.5. Preservation of Spatial Awareness and Perceptual Anchoring*

Spatial orientation is especially relevant in aging populations, where mobility confidence, fall risk, sensory decline, and environmental awareness directly affect safety and independence. Technologies that compromise perceptual grounding may inadvertently introduce cognitive burden or disorientation. MR offers a conceptual advantage through perceptual anchoring: digital content remains spatially registered within the real environment, preserving awareness of surrounding physical reality. This contrasts with immersive displacement, where real-world reference points may be reduced or absent.

The importance of this distinction extends beyond comfort. Spatial continuity supports safer movement, reduces perceptual conflict, and maintains orientation during interaction. For older adults, these factors may significantly influence acceptability, trust, and sustained use. Perceptual anchoring also contributes to a deeper conceptual point: MR preserves continuity between intervention space and lived space. Care does not occur in an isolated artificial domain; it unfolds within the same environment where daily life, risk, autonomy, and social interaction take place.

## 3. Mixed Reality as a Cognitive-Motor-Emotional Care Infrastructure

Mixed reality (MR) should not be understood solely as a delivery platform for discrete interventions, but as a potential care infrastructure capable of integrating multiple therapeutic dimensions simultaneously. Older adult care rarely involves isolated functional domains; mobility limitations frequently intersect with cognitive decline, emotional vulnerability, reduced motivation, and social disengagement. Conventional intervention models often address these dimensions separately, creating fragmented therapeutic pathways that may inadequately reflect the lived complexity of aging. MR introduces a different possibility: a unified interaction environment where physical action, cognitive engagement, and affective experience can be activated concurrently.

This integrative potential is conceptually significant because aging-related functional decline is rarely domain-specific. Cognitive impairment may affect gait confidence; emotional distress may reduce rehabilitation adherence; social isolation may diminish motivation for self-care. Care technologies that compartmentalize intervention targets may therefore fail to address the multidimensional nature of functional aging. MR, by contrast, creates an interactive substrate in which therapeutic engagement emerges through simultaneous embodied, cognitive, and emotional participation rather than sequential intervention silos.

### *3.1. Embodied Cognition and Therapeutic Engagement*

The therapeutic relevance of MR is strongly aligned with embodied cognition frameworks, which argue that cognition is fundamentally shaped by bodily interaction with the environment rather than operating independently from sensorimotor experience (Barsalou, 2008; Wilson, 2002). This perspective is particularly relevant in older adult care, where physical capability, perceptual interpretation, and cognitive performance are deeply interdependent. Traditional digital cognitive interventions often rely on screen-based abstraction, separating cognitive tasks from bodily engagement. While these approaches may support targeted stimulation, they do not necessarily reflect how cognition functions in everyday life, where decision-making, orientation, attention, and memory are embedded in movement and environmental interaction. MR enables therapeutic engagement through embodied action, allowing cognitive processes to emerge through physically situated tasks rather than decontextualized exercises.

This distinction is especially relevant for rehabilitation contexts involving executive function, motor planning, navigation, or dual-task performance, where cognitive and physical demands naturally overlap. Rather than training cognition apart from action, MR allows intervention design to reflect the integrated nature of real-world functioning.

### *3.2. Cognitive-Motor Integration and Functional Transfer*

One of the most compelling conceptual advantages of MR lies in its capacity to support simultaneous cognitive-motor activation. Older adult functioning depends heavily on the coordination of these systems. Everyday activities such as walking while navigating, preparing meals, managing medications, or responding to environmental cues require continuous integration between motor control, attention, working memory, and executive processing. This has important clinical implications because many traditional interventions artificially isolate therapeutic domains. Motor rehabilitation may emphasize repetitive physical movement, while cognitive interventions target memory or attention separately. Yet functional independence depends on integration, not separation.

MR provides a framework for task-oriented intervention that more closely approximates real-world demands. By embedding cognitive challenges within physically interactive environments, it may better support ecological transfer between therapeutic activity and everyday performance. Position frameworks in movement-related XR research have increasingly emphasized the importance of distinguishing immersive technologies according to their capacity to support real-world embodied cognitive-motor interaction rather than generic immersion (Šlosar et al., 2022). For older adults, this suggests a shift from isolated capacity training toward functionally integrated therapeutic design.

### *3.3. Motivational Reinforcement and Sustained Engagement*

A persistent challenge in geriatric intervention is adherence. Even clinically effective programs often fail when engagement declines due to monotony, perceived irrelevance, emotional fatigue, or reduced confidence. Motivation is therefore not secondary to intervention effectiveness; it is structurally central. MR may offer an important conceptual advantage by transforming therapeutic participation from repetitive obligation into meaningful interaction. Immersive engagement, responsive feedback, embodied task completion, and contextual relevance may increase perceived agency and reduce the passivity often associated with conventional rehabilitation experiences.

This aligns with self-determination perspectives in health behavior, which emphasize autonomy, competence, and meaningful engagement as critical determinants of sustained participation (Ryan & Deci, 2000). Technologies that merely prescribe tasks may reinforce disengagement; systems that foster active participation may strengthen intrinsic motivation. For older adults, motivational reinforcement is particularly important because physical decline, fear of failure, or social isolation may undermine long-term engagement with care programs. MR's capacity to combine challenge, responsiveness, and experiential participation may therefore represent not simply a usability advantage, but a clinically relevant therapeutic mechanism.

### *3.4. Multisensory Engagement and Affective Modulation*

Older adult care is not purely functional; emotional state significantly shapes therapeutic outcomes, participation, and perceived quality of life. Anxiety may impair rehabilitation performance, loneliness may reduce motivation, and emotional disengagement may limit cognitive participation. Care technologies that ignore affective dimensions risk reducing intervention effectiveness. MR offers a distinct multimodal interaction environment capable of engaging visual, auditory, spatial, and behavioral systems simultaneously. This multisensory richness may enhance attentional engagement, emotional salience, and experiential immersion in ways that conventional interfaces cannot.

From a conceptual perspective, this matters because emotional engagement is not simply a secondary outcome—it can function as a therapeutic mediator. Positive affect may increase persistence, reduce avoidance behaviors, and strengthen perceived competence. Social presence, contextual familiarity, and meaningful interaction may similarly influence emotional receptivity to care. Emerging digital health scholarship increasingly recognizes affective computing, adaptive interfaces, and emotionally responsive interaction as relevant dimensions of future care ecosystems (Picard, 1997; Riva et al., 2022). MR provides a plausible infrastructure through which these affective mechanisms may become therapeutically operational.

### *3.5. From Intervention Tool to Therapeutic Substrate*

Taken together, these characteristics suggest that MR should not be framed merely as another intervention technology. Its significance lies less in isolated applications than in its ability to function as a therapeutic substrate—a flexible infrastructure capable of integrating movement, cognition, affect, environmental interaction, and adaptive support within coherent care experiences.

This distinction is critical. A technology framed as a tool remains peripheral to care delivery; a technology framed as infrastructure has the potential to reshape care architecture itself.

In older adult care, where autonomy, participation, safety, emotional well-being, and functional independence are deeply interconnected, this shift in perspective may be especially important. MR's conceptual promise lies not in reproducing existing interventions with greater technological sophistication, but in enabling more integrated, ecologically grounded, and person-responsive models of therapeutic engagement.

## 4. Reframing Older Adult Care Through Mixed Reality

The significance of mixed reality (MR) in older adult care extends beyond its capacity to enhance isolated therapeutic interventions. Its broader relevance lies in its potential to reconfigure how care itself is conceptualized, delivered, and experienced. Traditional models of geriatric care have often been structured around episodic clinical encounters, reactive intervention, and compartmentalized management of physical, cognitive, and psychosocial needs. While these approaches remain clinically necessary, they are increasingly insufficient for addressing the complex, dynamic, and context-dependent realities of aging. Contemporary care demands models that are continuous, adaptive, person-centered, and responsive to changing functional needs (World Health Organization, 2015).

Within this context, MR should be considered not merely as an intervention technology, but as a possible enabler of care model transformation. Its capacity to integrate environmental awareness, embodied interaction, contextual adaptation, and intelligent augmentation positions it closer to care infrastructure than therapeutic device. This distinction opens a broader conceptual discussion about how older adult care may evolve toward models that prioritize autonomy, relational engagement, personalization, and responsive ecosystem support.

### *4.1. Supporting Autonomy Beyond Compensatory Assistance*

Autonomy is a central principle in healthy aging and person-centered care, yet conventional digital assistance often approaches autonomy through compensation alone—providing reminders, alerts, or passive monitoring that address deficits without meaningfully supporting agency. While such tools may improve safety, they can also reinforce dependency if users are positioned primarily as care recipients rather than active participants. MR enables a different logic of support. Because assistance can be spatially embedded, context-aware, and interactively aligned with real-world activities, support may become more participatory than directive. Guidance can be integrated into everyday action rather than delivered as external instruction, preserving user engagement in task execution rather than replacing it.

This distinction is conceptually important because autonomy in aging is not simply the absence of dependence, but the preservation of meaningful agency, decision-making capacity, and confidence in managing daily life (Sixsmith & Sixsmith, 2008). MR therefore offers the possibility of augmenting functional autonomy rather than merely compensating for its decline.

### *4.2. From Clinical Intervention to Relational Care*

Older adult care is not exclusively biomedical. Emotional well-being, belonging, companionship, and social connectedness are integral determinants of health, particularly in populations vulnerable to loneliness, reduced mobility, or social isolation. Yet digital health innovation has historically prioritized monitoring, efficiency, and functional performance over relational dimensions of care. MR introduces possibilities for rethinking this imbalance. Through embodied interaction, social presence, and responsive virtual agents, care experiences may become relational rather than purely transactional. The significance of this shift lies not in technological novelty, but in alignment with contemporary care paradigms that recognize emotional and interpersonal dimensions as clinically meaningful components of well-being.

Social presence theory suggests that perceived meaningful interaction, even in mediated environments, can influence emotional engagement, trust, and behavioral participation (Biocca et al., 2003). In older adult contexts, where isolation itself is associated with adverse physical and psychological outcomes, technologies capable of fostering relational engagement may extend beyond assistive function toward psychosocial care support. This does not imply replacing human relationships with digital mediation. Rather, it suggests that MR may become part of broader relational care architectures that complement caregiver interaction, social participation, and emotional support.

### *4.3. Advancing Person-Centered and Adaptive Care*

One of the defining limitations of conventional intervention models is standardization. Older adults are frequently treated through generalized protocols that insufficiently account for heterogeneity in cognition, sensory capacity, emotional state, functional ability, technological familiarity, or environmental context. Person-centered care frameworks emphasize that effective care must align with individual preferences, lived realities, capabilities, and goals rather than solely with clinical classifications (McCormack & McCance, 2017). MR may be especially compatible with this principle because it enables dynamic adaptation of interaction environments in response to user characteristics and contextual needs.

Adaptive interface complexity, personalized therapeutic pacing, context-sensitive prompts, multimodal interaction adjustment, and individualized environmental augmentation become conceptually feasible within MR ecosystems. This capacity positions MR not simply as a delivery mechanism, but as an architecture for responsive care personalization. For aging populations, where functional trajectories may fluctuate and needs evolve over time, such adaptability is particularly relevant.

### *4.4. Mixed Reality Within Intelligent Care Ecosystems*

The transformative potential of MR becomes more pronounced when considered alongside broader digital health infrastructures. Emerging care models increasingly incorporate artificial intelligence (AI), Internet of Things (IoT) systems, wearable sensing, ambient monitoring, and predictive analytics to support aging in place and proactive care delivery (Peek et al., 2014; Wang & Lin, 2024). However, many of these systems remain operationally invisible or interactionally passive, collecting data and generating decisions without meaningful experiential engagement from the older adult. MR may function as the experiential interface layer of intelligent care ecosystems, translating ambient intelligence into understandable, contextually actionable, and embodied interaction.

In this framing, MR becomes not merely an application, but a mediating layer between user and smart environment. A monitoring system may detect fall risk, but MR can render guidance spatially in context. AI may identify behavioral anomalies, but MR can communicate adaptive support through interactive assistance rather than abstract notification. This conceptual integration reframes MR as a bridge between computational intelligence and human-centered care experience.

### *4.5. Toward Responsive and Distributed Care Models*

Taken together, these dimensions suggest that MR aligns with broader transitions in healthcare from episodic treatment toward distributed, adaptive, and preventive care models. Rather than concentrating therapeutic interaction within clinics or isolated intervention programs, MR may support continuity of care across domestic, community, and hybrid care environments. This is particularly relevant for aging populations, where functional decline often unfolds gradually, unpredictably, and within everyday settings rather than clinical spaces. Technologies capable of extending meaningful care interaction into real-world environments may help reduce the gap between intervention and lived experience.

The most important conceptual implication is therefore not that MR improves specific therapeutic tasks, but that it may contribute to redefining care architecture itself—from reactive intervention toward continuous, context-aware, person-responsive support.

## 5. Ethical, Clinical, and Translational Tensions

The conceptual promise of mixed reality (MR) in older adult care should not obscure the substantial tensions that accompany its implementation. Technologies positioned as transformative in healthcare frequently encounter barriers that extend far beyond technical performance, including inequitable access, usability limitations, ethical uncertainty, and challenges of real-world integration. These concerns are particularly salient in aging populations, where sensory variability, cognitive heterogeneity, socioeconomic disparities, and differing levels of technological familiarity shape both feasibility and acceptability. Accordingly, if MR is to be considered a legitimate emerging care paradigm rather than a speculative innovation, its limitations must be treated as structural concerns rather than secondary implementation details.

### *5.1. Accessibility, Inclusion, and the Risk of Digital Exclusion*

One of the most immediate tensions surrounding MR adoption concerns accessibility. Advanced immersive systems often assume levels of sensory capacity, motor dexterity, digital literacy, and financial access that cannot be uniformly expected among older adult populations. Technologies designed without explicit accommodation for age-related variability risk reproducing exclusion under the guise of innovation.

This challenge extends beyond device usability. Digital exclusion is shaped by intersecting structural factors, including socioeconomic inequality, educational disparities, geographic barriers, and limited access to digital infrastructure (Czaja et al., 2006; Peek et al., 2014). Older adults in resource-constrained settings may face compounded barriers, particularly where access to specialized hardware, technical support, or stable connectivity remains limited.

If MR becomes framed as a future standard of care without addressing these inequities, it may unintentionally widen disparities between technologically privileged and underserved populations. A care paradigm that cannot scale inclusively risks reinforcing rather than reducing vulnerability.

### *5.2. Cognitive Burden, Sensory Overload, and Clinical Suitability*

MR's immersive and multisensory characteristics, often framed as strengths, may also introduce clinical concerns. Older adults are not a homogeneous user group; sensory decline, vestibular sensitivity, attentional limitations, mild cognitive impairment, or neurodegenerative conditions may substantially alter how immersive systems are perceived and tolerated. Complex interaction environments may increase cognitive load, generate confusion, or reduce task confidence rather than enhancing engagement. Similarly, dense visual augmentation, ambiguous interface cues, or excessive multimodal stimulation may contribute to perceptual fatigue or sensory overload.

These concerns are not merely usability inconveniences; they raise questions of clinical suitability. Technologies that demand adaptation to computational logic rather than adapting to user capability risk undermining therapeutic value. Human-centered design in aging contexts therefore becomes an ethical necessity rather than a design preference (Czaja & Lee, 2007). The central question is not whether older adults can adapt to MR, but whether MR systems can be responsibly designed around the realities of aging.

### *5.3. Privacy, Surveillance, and Data Governance*

MR systems capable of environmental mapping, behavioral monitoring, gesture recognition, spatial tracking, biometric capture, and adaptive interaction raise significant privacy concerns. In older adult care, where monitoring technologies are increasingly justified in the name of safety, the distinction between supportive observation and intrusive surveillance becomes ethically blurred.

This tension is particularly acute in domestic environments. Aging in place technologies often extend monitoring into highly intimate spaces, capturing behavioral routines, movement patterns, and potentially emotionally meaningful interactions. When integrated with AI or ambient sensing ecosystems, MR may amplify both the granularity and interpretability of personal data.

While surveillance-oriented systems may improve risk detection, they may also compromise dignity, autonomy, and perceived control. Ethical digital health scholarship has consistently emphasized that healthcare innovation should not normalize opaque monitoring or data extraction without meaningful governance, transparency, and user agency (Mittelstadt, 2019; Floridi et al., 2018). The challenge is therefore not only technical data protection, but governance design that preserves trust and respect for older adults as autonomous participants rather than passive data subjects.

### *5.4. Autonomy Enhancement or Technological Dependence?*

A recurring ethical paradox in assistive innovation is that technologies intended to support autonomy may inadvertently produce new forms of dependency. Systems that guide behavior, structure decision-making, or automate functional support may reduce immediate burden, but overreliance on technological mediation raises concerns about diminished agency, learned dependence, or erosion of confidence in self-directed functioning.

This concern is particularly relevant in aging care, where autonomy is both a clinical and ethical objective. If assistance becomes overly directive, invisible, or algorithmically prescriptive, users may lose opportunities for active participation in decision-making or skill maintenance. The ethical question is therefore not whether assistance is beneficial, but how assistance is structured. Technologies that augment agency differ fundamentally from technologies that replace it.

MR's interactive nature offers the possibility of participatory support, but this outcome is not guaranteed. Design choices will determine whether MR becomes empowering infrastructure or paternalistic automation.

### *5.5. Translational Reality: From Innovation to Real-World Care Systems*

A final tension concerns translational feasibility. Healthcare technologies often demonstrate conceptual promise under controlled conditions while encountering substantial barriers in routine implementation. Integration into older adult care requires compatibility not only with users, but with clinicians, caregivers, institutions, workflows, reimbursement structures, training systems, and regulatory expectations. Implementation science has repeatedly shown that technological effectiveness alone does not determine adoption; organizational readiness, stakeholder engagement, contextual fit, and delivery infrastructure are equally decisive (Damschroder et al., 2009; Proctor et al., 2011).

This is especially relevant for MR, whose deployment may require hardware management, onboarding support, maintenance, interdisciplinary coordination, and adaptation across care settings. Technologies designed as experimental innovations may struggle when confronted with the realities of fragmented health systems, caregiver burden, or limited implementation capacity. If MR is to evolve from conceptual promise to genuine care paradigm, translational strategy must be treated as a central research and policy concern rather than an afterthought.

### *5.6. Beyond Technological Optimism*

The emergence of MR in aging care invites justified enthusiasm, but conceptual innovation must remain grounded in critical realism. The relevant question is not whether MR is technologically impressive, but whether it can be ethically governed, clinically appropriate, socially inclusive, and operationally sustainable.

Transformative care paradigms are defined not by novelty, but by their capacity to improve human care without reproducing inequity, dependency, or exclusion. MR's future relevance in older adult care will depend less on technical sophistication than on whether its development remains aligned with these foundational principles.

## 6. Future Research Agenda

If mixed reality (MR) is to be understood as an emerging paradigm in older adult care rather than merely a novel intervention platform, future research must move beyond short-term feasibility demonstrations and fragmented application testing. The next phase of inquiry should focus not simply on whether MR can be used in aging populations, but on how it can be responsibly designed, clinically integrated, and sustainably implemented within real-world care ecosystems. This requires a research agenda that reflects the conceptual complexity of MR as adaptive infrastructure rather than isolated technological intervention.

### *6.1. From Static Applications to Adaptive Mixed Reality Environments*

A critical research priority lies in the development of adaptive MR systems capable of responding dynamically to user variability. Older adults represent a highly heterogeneous population, with substantial differences in sensory capacity, cognitive function, mobility, emotional state, and technological familiarity. Static intervention models are unlikely to adequately address this diversity.

Future MR research should therefore prioritize systems capable of real-time adaptation based on performance, fatigue, behavioral patterns, contextual conditions, or affective state. Adaptive difficulty calibration, context-sensitive prompting, personalized sensory modulation, and intelligent interaction pacing may substantially improve usability and therapeutic relevance. Such developments align with broader trajectories in intelligent human-computer interaction and personalized digital therapeutics (Nahum-Shani et al., 2018). The key challenge is ensuring that adaptation enhances user agency rather than increasing algorithmic opacity.

### *6.2. Longitudinal and Ecologically Valid Research*

Current immersive health research remains heavily dominated by pilot studies, short intervention windows, and controlled experimental conditions. While these studies are valuable for early validation, they provide limited insight into sustained adoption, long-term adherence, or real-world care integration.

If MR is positioned as a care paradigm, research must increasingly move toward longitudinal ecological evaluation. This includes home-based deployments, hybrid clinical-community implementations, and real-world studies examining how older adults interact with MR systems over time. Questions of usability persistence, intervention fatigue, functional transfer, caregiver integration, and contextual adaptation remain insufficiently understood. This shift reflects a broader methodological need in digital health research: moving from proof-of-concept toward implementation realism (Mohr et al., 2017).

### *6.3. Participatory Co-Design With Older Adults*

A recurring limitation in digital health innovation is the tendency to design technologies for older adults rather than with them. Such approaches risk embedding assumptions about capability, usability, motivation, and care priorities that may not align with lived experience.

Future MR research should place participatory co-design at the center of development processes. Older adults should be considered active design stakeholders rather than end-stage usability testers. This is especially important for immersive technologies, where embodiment, trust, comfort, and emotional response are central to experience quality. Participatory design approaches may improve not only usability, but also acceptability, trust, ethical legitimacy, and long-term engagement (Sanders & Stappers, 2008). For aging care technologies, co-design is not merely methodological refinement—it is foundational to responsible innovation.

### *6.4. Responsible Integration of Artificial Intelligence*

The convergence of MR with artificial intelligence (AI) presents major opportunities for adaptive assistance, contextual interpretation, predictive support, and emotionally responsive interaction. However, it also introduces substantial ethical and governance challenges. Future research should examine how intelligent MR systems can remain transparent, interpretable, and autonomy-supportive. Questions surrounding explainability, algorithmic bias, privacy governance, informed consent, and decision delegation become increasingly important when care systems move from passive assistance toward intelligent adaptation.

This is particularly relevant in older adult care, where vulnerabilities related to cognitive decline, technological asymmetry, or reduced digital literacy may amplify ethical risk. Responsible AI frameworks should therefore become integral—not peripheral—to MR research agendas (WHO, 2021).

### *6.5. Implementation Science and Health System Integration*

Technological innovation alone does not produce care transformation. Even conceptually strong systems may fail if implementation realities are neglected. Future research must therefore address integration into actual care environments, including clinician workflows, caregiver roles, organizational readiness, infrastructure demands, and reimbursement feasibility.

Implementation science offers useful frameworks for understanding these translational challenges, yet immersive aging technologies have only minimally engaged this perspective. Questions of training burden, interoperability, clinical acceptance, maintenance logistics, and institutional scalability require systematic investigation. If MR is to evolve beyond experimental novelty, implementation research must become a central—not secondary—pillar of the field.

### *6.6. Equity, Cultural Context, and Global Applicability*

Finally, future research must avoid reproducing a technologically narrow or geographically limited vision of aging care. Much digital health innovation reflects assumptions rooted in high-resource contexts, potentially limiting relevance across diverse healthcare systems and cultural environments. MR research should explicitly examine affordability, accessibility, infrastructure dependency, language adaptation, cultural interaction norms, and implementation feasibility in low- and middle-income settings. Equity-oriented innovation requires designing for diversity rather than retrofitting inclusion after development.

If MR is genuinely to become a care paradigm, it must be conceptually scalable not only across technologies, but across populations, health systems, and social realities. Taken together, these priorities suggest that the future of MR research in older adult care should move beyond technological demonstration toward responsible ecosystem development. The central question is no longer whether MR can support aging care, but under what conditions it can do so ethically, inclusively, and sustainably.

## 7. Conclusions

Mixed reality should be understood not merely as another immersive technology within the extended reality continuum, but as an emerging paradigm with the potential to reshape older adult care. Its conceptual relevance lies in its capacity to integrate embodied interaction, environmental continuity, contextual adaptation, and intelligent augmentation within care experiences that more closely reflect the multidimensional realities of aging. Unlike technologies designed for isolated intervention delivery, MR offers a framework through which cognitive, motor, emotional, and relational dimensions of care may be addressed in a more unified and ecologically grounded manner. This repositioning shifts the discussion from technological novelty toward care transformation, particularly in the context of autonomy support, person-centered intervention, and responsive care ecosystems.

At the same time, MR's transformative promise should be approached with critical realism. Its future role in older adult care will depend not only on technical advancement, but on whether systems can be designed to remain clinically appropriate, ethically governed, socially inclusive, and operationally sustainable. If developed responsibly, MR may contribute to the transition from episodic and reactive care models toward adaptive, context-aware, and participatory approaches that better align with the evolving needs of aging populations.

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