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Virtual reality and mixed reality in the assessment of spatial memory

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Abstract

Spatial memory, a fundamental cognitive function, enables individuals to encode, store, and retrieve information about their surroundings. Traditional assessment methods, such as paper-based tests and laboratory paradigms, often lack ecological validity and fail to capture the complexities of real-world navigation. Recent advancements in digital technologies, particularly virtual reality (VR) and mixed reality (MR), have introduced innovative tools for more immersive and accurate spatial memory assessments. VR provides controlled, replicable environments that simulate real-world navigation, while MR enhances engagement by blending virtual elements with physical spaces. This narrative review explores the cognitive mechanisms underlying spatial memory, highlighting the roles of egocentric and allocentric reference frames, as well as the neural substrates involved. The review also examines key factors influencing spatial memory performance, such as age, sex, neurological and neurodegenerative diseases. Digital tools such as the virtual Morris water maze and the VR Supermarket Test have been shown to possess enhanced ecological validity and diagnostic potential, particularly in the context of detecting early cognitive decline in Alzheimer's disease. However, the field confronts several challenges, including the necessity for standardized protocols, the potential for adverse effects such as cybersickness, and the substantial cost associated with VR and MR systems. Future research directions in this field should include the integration of artificial intelligence for personalized assessments, and the combination of VR and MR tasks with neurophysiological techniques to advance understanding of spatial memory. Standardization, accessibility, and the creation of adaptive assessment for clinical populations will be crucial for optimizing the use of digital technologies in spatial memory research.

Keywords

Memory, spatial, digital technologies, virtual reality, mixed reality, neurodegenerative disorders

Introduction

Spatial memory is a type of episodic memory defined as a fundamental cognitive function that enables individuals to encode, store, and retrieve information regarding their surroundings and spatial relationships [1]. This cognitive ability supports learning of the spatial arrangement of objects and environments [2] and plays a crucial role in navigation, the ability to follow a path through the environment to find a target location [3]. For this reason, this capacity is indispensable for numerous daily activities, including navigating environments, recalling the location of objects, and familiarizing oneself with novel routes. Deficits in spatial memory are observed in a range of neurological conditions, including Alzheimer's disease, Parkinson's disease, and mild cognitive impairment [4–6]. This highlights the critical importance of assessing spatial memory for the early diagnosis and intervention of these conditions.

Conventional assessment methods for spatial memory, including paper-based tests [7–9], real-world experiments [5, 10, 11], and laboratory-based paradigms [12], have served as the standard for assessing this cognitive domain. However, these methods often suffer from limitations, including low ecological validity, resource-intensiveness, and an inability to scale efficiently for large populations. Recent advancements in digital technology have fundamentally transformed the assessment of spatial memory. Digital technology emerged as a significant tool for the assessment of spatial memory by offering innovative, scalable, and more ecologically valid methodologies in neuropsychological assessment and research. The utilization of virtual reality (VR) provides immersive, controlled environments that simulate real-world navigation, allowing researchers to study spatial memory with a high degree of precision [13, 14]. Mixed reality (MR) further enhances assessments by integrating digital overlays into real-world scenarios, thus providing a novel approach to the testing of spatial cognition in naturalistic settings [15, 16]. However, it should be noted that, despite their potential, digital assessment methods face challenges.

This narrative review explores the use of VR and MR in spatial memory assessment, discussing their advantages, limitations, and implications for research and clinical practice. The integration of insights from cognitive neuroscience, psychology, and technology is crucial in elucidating the transformative impact of digital tools on spatial memory assessment and identifying future research directions that can further enhance the field.

Spatial memory

Spatial memory is defined as the cognitive process of encoding, storing, recognizing and recalling spatial information about the environment and its elements (Table 1).

Table 1. Overview of spatial memory: key processes

Process	Description
Cognitive map	Mental representation of the environment that helps navigate using alternative routes
Egocentric	Body-centered spatial encoding based on sensory and motor information
Allocentric	External landmark-based spatial encoding independent of the observer
Route learning	Encoding and recalling paths in familiar or new environments
Landmark-based navigation	Uses external landmarks for navigation
Path integration	Involves egocentric navigation using self-motion cues
Object-location memory	The ability to recall the spatial relationship between objects and reference points

In their navigation of the environment, humans, like animals, are capable of acquiring knowledge of its configuration [3]. This process involves the establishment of a representation or knowledge of space that is analogous to the information provided by a map. Consequently, individuals can then direct their actions in a goal-directed manner consistent with their spatial aims. This entails the formulation of alternative routes that diverge from the original course, a process facilitated by the generation of a cognitive map, a spatial representation of the environment.

All of our spatial representations can be classified according to the type of reference frame they utilize [17]. Egocentric representations are defined by the encoding of spatial information in relation to the agent's own body or specific body parts. Conversely, allocentric representations define spatial information based on external landmarks or environmental boundaries, regardless of their positioning relative to the agent. In any task that demands spatial memory, an individual can utilize a single reference frame or strategy, depending on its efficacy, or alternatively, a combination of both [18].

Allocentric reference frames are independent of the observer and instead rely on environmental landmarks and external objects, playing a crucial role in large-scale, extrapersonal space and long-term spatial planning. Allocentric strategies have been shown to be more prominent in large-scale spaces and delayed response tasks, particularly for non-manipulable stimuli [19, 20]. In contrast, egocentric reference frames are closely tied to the body, utilizing sensory and motor properties to encode spatial information relative to the observer. These representations are particularly effective in small-scale, peripersonal space, allowing for immediate action and interaction with the environment. Egocentric strategies have been shown to be more efficient in immediate motor response tasks, particularly when processing three-dimensional, manipulable stimuli. Thus, allocentric processing facilitates long-term spatial recognition, while egocentric processing is characterized as immediate and action-oriented [21].

Among the spatial memory processes, route learning is a key function that allows individuals to navigate and recall paths through both familiar and novel environments [22]. Route learning is critical for daily activities, ranging from navigating a new city to recalling the layout of a familiar building. It involves the sequential encoding of spatial information and requires the integration of landmarks, directional cues and self-motion. For this reason, it requires the interplay of multiple cognitive processes. One of the most important is landmark-based navigation, which entails the utilization of salient landmarks to segment and encode a route. This allocentric navigation relies on an external, world-based reference frame, creating a map-like mental representation [23]. Egocentric navigation, which is based on body-centered representations provided by the vestibular system and proprioception, contributes to path integration by providing self-motion cues and turns. These cues allow individuals to update their position while moving during exploration [24].

Another critical component of spatial memory is object-location memory, which denotes the capacity to recollect the spatial relationship between objects and reference points or other objects [2]. This faculty is indispensable for routine activities, including the recovery of misplaced items, the navigation of familiar environments, and the recollection of object positions in dynamic settings. The successful retrieval of object-location memory is contingent upon the integration of these two reference frames, thereby facilitating the concurrent utilization of both egocentric and allocentric representations [2]. The egocentric representations emphasize the focus on object locations relative to the observer's position and movements. The allocentric representations represent object locations independently of the observer, using landmarks or environmental cues.

Neural substrates of spatial memory

Spatial memory is dependent on a network of interconnected brain structures that collaborate to encode, store, and retrieve spatial information. The hippocampus, entorhinal cortex, and associated subcortical and cortical regions are key components in this system [25]. These brain structures integrate both egocentric (body-centered) and allocentric (world-centered) frames of reference or spatial strategies, enabling efficient spatial memory [26, 27].

At the core of spatial memory, the hippocampus plays a crucial role in encoding spatial representations through the activity of place cells. These neurons fire when an individual is in a specific location, thereby effectively mapping out the environment [28]. This mechanism is further completed by the presence of grid cells in the medial entorhinal cortex, which provide a structured metric system for navigation by firing at multiple locations in a grid-like pattern [29]. In addition, head-direction cells in the anterior thalamus and postsubiculum encode an individual's orientation by signaling the direction of its head [30]. Additional specialized neurons, such as boundary vector cells and border cells found in the subiculum and medial entorhinal cortex, respectively, help define spatial relationships by responding to environmental boundaries and adapting to egocentric and allocentric spatial representations [31, 32].

The egocentric reference frame, which is body-centered, is primarily processed by the posterior parietal cortex. This region integrates sensory inputs to coordinate spatial perception with movement, playing a key role in goal-directed navigation [33]. Additionally, the precuneus plays a pivotal role in transforming multiple egocentric representations into action-relevant information [34]. In contrast, the allocentric reference frame, which is independent of the observer's position, is encoded by the retrosplenial and parahippocampal cortices. These regions process large-scale environmental features and encode stable, viewpoint-independent spatial layouts [35].

Efficient navigation depends on the integration of both egocentric and allocentric representations, facilitating dynamic updates in spatial orientation, and switching between egocentric and allocentric frames of reference [36]. The posterior parietal cortex, specifically area 7a, plays a crucial role in this transformation by integrating visual and proprioceptive information [37]. Similarly, the retrosplenial cortex facilitates reference frame transformations by receiving input from both the hippocampus and parietal cortex, enabling the conversion of sensory input into allocentric memory representations [38].

The influence of reward-based learning on spatial memory extends beyond the domain of spatial mapping. The medial prefrontal cortex has been shown to encode goal locations, thereby playing a role in decision-making and adaptive behavior [39]. Other regions, such as the orbitofrontal cortex, amygdala, and ventral striatum, have been identified as being crucial for reward-based spatial learning, allowing the brain to establish associations between locations and anticipated rewards [40].

With regard to the specific process of route learning, this is dependent upon the network of brain regions that process visuospatial, mnemonic, and motor information. The hippocampus, a primary brain structure, plays a pivotal role in this process. The right hippocampus plays a particularly salient role in allocentric (map-based) navigation, wherein individuals employ environmental cues to construct a cognitive map [41]. In contrast, the left hippocampus plays a more prominent role in egocentric route learning, where paths are learned in relation to one's own movement and perspective [42]. The cortex is another actor in this dynamic system. Specifically, the dorsolateral prefrontal cortex facilitates working memory and decision-making, which are critical for planning routes and recalling waypoints [43]. Concurrently, the orbitofrontal cortex contributes to reward-based navigation, wherein routes are learned and optimized based on prior experiences [44]. The posterior parietal cortex is involved in the processing of egocentric navigation cues, facilitating individuals' ability to track self-motion relative to landmarks [45]. Lesions to this region can result in topographical disorientation, characterized by difficulties in following or recalling routes [46]. The basal ganglia also play a role in habitual navigation [47], allowing routes to become automated over time. Dysfunction in the basal ganglia, as observed in Parkinson's disease and Huntington's disease, can result in impaired recollection of learned routes [48, 49]. The cerebellum, on the other hand, plays a pivotal role in motor coordination during navigation, particularly in adjusting walking speed and turns while learning a route [50].

With regard to the object-location memory, object-location memory relies on a complex interaction between the "what" (ventral stream) and "where" (dorsal stream) pathways in the brain [51]. The ventral pathway is responsible for recognizing objects, while the dorsal pathway facilitates their spatial localization. The hippocampus and entorhinal cortex collaborate to enable episodic memory processes, aiding individuals in recognizing familiar objects in novel environments and maintaining object positions within a given space. The medial temporal lobe, specifically the hippocampus, has been demonstrated to play a pivotal role. Research has indicated that damage to the right medial temporal lobe impairs object-location memory performance, suggesting that the right hippocampus is crucial in encoding and retrieving object-location associations [2, 52]. The parahippocampal gyrus and entorhinal cortex also play a significant role, with the posterior parahippocampal cortex integrating object-location associations into a coherent spatial framework [53], while the anterior parahippocampal cortex is more involved in encoding the spatial aspect of these associations [53, 54]. The entorhinal cortex and its grid cells facilitate the maintenance of a spatial map and the binding of objects to contextual information, thereby supporting the distinction between egocentric (self-referenced) and allocentric (environment-referenced) spatial representations [54].

By integrating spatial encoding, reference frame transformations, and reward-based learning, the brain constructs a comprehensive and adaptable spatial memory system. This intricate network facilitates effective interaction with the environment, employing both fixed and flexible spatial representations for orientation, memory of spaces and objects, route learning and goal-directed behavior.

Key factors influencing spatial memory performance

Spatial memory is influenced by a variety of biological, cognitive, and environmental factors. Research has identified that sex, age and neurological conditions are key factors influencing spatial memory performance, which are shaped by neurobiology and cognitive strategies (Table 2). It is imperative to understand these factors to develop effective assessment methods of spatial memory performance.

Table 2. Key factors influencing spatial memory

Factor	Impact on spatial memory
Sex differences	Sex-based strategy differences affect task performance depending on task demands and familiarity with the environment.
Aging	Age-related declines primarily impact allocentric navigation, reducing efficiency in dynamic spatial tasks.
Neurological conditions	Neurological conditions disrupt hippocampal and entorhinal cortex function, affecting route learning and object-location memory.

The existing literature suggests that sex differences in spatial memory are influenced by evolutionary, neurobiological, and cognitive strategy factors [55]. Specifically, men have been shown to prioritize allocentric navigation strategies, while women demonstrate a stronger reliance on egocentric cues [56]. Men tend to demonstrate superior performance in allocentric navigation, employing geometric and landmark cues to construct cognitive maps. Conversely, women demonstrate a propensity for egocentric navigation strategies, relying on sequential recall of turns and familiar landmarks [57]. In tasks that demand navigation based on landmarks, men tend to outperform women. However, when landmarks are removed, this advantage disappears [58]. Hormonal influences, particularly estrogen levels, have been linked to variations in spatial learning abilities across the menstrual cycle [59]. With regard to object-location memory, the majority of studies on sex differences in this domain have indicated a female advantage [60]. This superiority is not solely due to an enhanced ability to remember object locations but may instead stem from differences in cognitive processing strategies [61]. When controlling for object identity recognition, the female advantage disappears, indicating that women may rely more on contextual and categorical cues rather than absolute spatial encoding. Furthermore, object-location memory functions, at least in part, through automatic encoding, as no significant effects were observed between incidental and intentional learning conditions in object-location memory tasks [62]. Instead of possessing a fundamentally superior spatial memory, it is more plausible that women employ a different, more context-sensitive memory strategy that enhances their ability to recall object-locations, particularly in ecologically valid environments. This highlights the necessity of incorporating a comprehensive examination of memory components and retrieval conditions into the investigation of sex differences in spatial memory performance. In fact, the effectiveness of object-location memory is influenced by several factors, including landmark cues, environmental familiarity, and cognitive processes such as attention and working memory. Studies that have examined the performance of individuals engaged in tasks that require the encoding and retrieval of object locations have revealed differences in performance based on environmental complexity, self-motion, and prior experience [62]. Thus, the expertise and experience in spatial cognition modulates sex differences. The manifestation of sex differences in spatial memory is context-dependent and influenced by task demands, with differences being more pronounced in challenging learning conditions that require strong spatial skills [63]. Furthermore, the interplay between gender and expertise challenges the notion of fixed sex differences in spatial abilities, emphasizing the significance of training in the development of these skills.

With respect to age-related differences, a progressive decline in spatial memory performance is observed with age, with older adults generally exhibiting poorer spatial memory compared to younger adults. This decline is attributed to age-related cognitive changes, critical for spatial memory encoding and retrieval, particularly in tasks involving navigation, spatial working memory, and place learning [64]. Specifically, older adults demonstrate poorer performance in spatial memory tasks compared to younger adults, particularly in dynamic spatial tasks such as virtual navigation and cognitive mapping. However, monitoring of spatial cognition remains largely intact across age. Older adults exhibit comparable accuracy in self-assessments of their spatial performance, with the exception of navigational tasks [64]. Older adults demonstrate a stronger reliance on egocentric navigation strategies, favoring response-based approaches over allocentric strategies that require the use of a cognitive map [64]. This preference is mediated by lower confidence in spatial memory performance. Additionally, age-related declines in working memory and attentional processes may contribute to reduced efficiency in tracking and recalling spatial information over time, leading to greater errors in estimating navigation times and distances [64]. Older adults also demonstrate greater difficulty in tasks requiring spatial updating, particularly when recalling object locations after a delay, suggesting deficits in working memory and episodic memory integration [62]. Moreover, age-related differences were more pronounced in virtual environments than in real-world settings, potentially due to reduced familiarity and increased cognitive load associated with immersive technologies [62]. Furthermore, older adults have been shown to encounter greater challenges in tasks that demand spatial updating, particularly in the context of recalling object locations following a delay. This finding suggests potential deficits in the integration of working memory and episodic memory [62].

A number of neurodegenerative diseases have been shown to impact spatial memory due to temporal lobe degeneration, affecting learning and memory processes. In Alzheimer's disease, early impairments in the function of the hippocampus disrupt the ability to form and recall new routes [65]. Patients frequently exhibit "getting lost" behavior, characterized by their inability to integrate landmark and directional cues [66]. The entorhinal cortex and hippocampus, which play critical roles in allocentric and egocentric navigation, are among the first regions affected by tau pathology. Consequently, individuals in the preclinical stages of Alzheimer's disease often exhibit spatial disorientation and impaired wayfinding in familiar environments, even before significant memory deficits become apparent [65]. Similarly, in mild cognitive impairment, particularly among individuals at high risk of progressing to Alzheimer's disease, spatial navigation deficits are more pronounced than in age-matched controls. This finding further supports the notion that spatial impairments precede dementia [65]. Beyond Alzheimer's disease, other neurodegenerative conditions have also been shown to exhibit spatial memory impairments. For instance, frontotemporal dementia may present with spatial disorientation, though this is typically less pronounced than in Alzheimer's disease [67]. Similar findings have been reported in the context of Huntington's disease [49, 68] and Korsakoff syndrome [69], where impaired spatial memory has been documented, with deficits that vary based on disease severity. Individuals diagnosed with Parkinson's disease have been shown to exhibit impaired habit-based navigation, characterized by difficulties in recalling well-learned routes [48]. Additionally, their memory of indoor spaces using allocentric information is also impaired [5].

Some neurological disorders that are not classified as neurodegenerative, such as temporal lobe epilepsy and bilateral vestibulopathy, have also been shown to impair spatial memory. Patients diagnosed with temporal lobe epilepsy exhibit spatial navigation impairments, due to the atrophy of the hippocampus, which affects spatial memory encoding [70]. Furthermore, the vestibular system plays a crucial role in spatial cognition by providing essential information about balance, movement, and spatial orientation [71], as it has direct connections to key areas responsible for higher cognitive functions, including the hippocampus [72]. Bilateral vestibulopathy, a condition characterized by reduced or absent vestibular function on both sides [73], has been demonstrated to exhibit impaired spatial memory performance. Mild chronic vestibulopathy has been shown to impair functions that depend on vestibular input, such as balance, path integration, and rotational memory, while sparing cognitive functions reliant on visual input, including visuospatial memory and attention [71]. Using a 3D real-world pointing test, Gerb et al. [74] found that patients diagnosed with bilateral vestibulopathy and intact cognition exhibited impaired spatial accuracy, particularly after body rotations that depend on vestibular input. Notably, spatial impairments were most severe in patients with both vestibular and cognitive deficits [74].

Traditional methods of spatial memory assessment

A variety of methodologies have been developed for the evaluation of spatial memory. These methodologies encompass a wide range of approaches, from questionnaires and conventional paper-and-pencil tests to more advanced experimental paradigms that utilize mazes, object-location memory tasks and real-world navigation tasks.

Questionnaires assessing spatial memory compile self-reported spatial memory abilities, incorporating allocentric and egocentric strategies. The most widely utilized questionnaires are the Subjective Spatial Navigation Complaints Questionnaire [75], which assesses the frequency of spatial navigation complaints in everyday life, the Santa Barbara Sense of Direction Scale [8], which measures environmental spatial ability, and the Questionnaire on Everyday Navigational Ability [76], which detects spatial navigation impairment in real-world environments. These questionnaires have been predominantly employed to assess spatial memory abilities in dementia. As superior self-reported spatial memory has been demonstrated to correlate with greater life-space mobility, the control of this variable is obligatory in studies employing this approach [77].

Conventional neuropsychological evaluations of spatial memory frequently employ paper-and-pencil tasks. These tasks are widely utilized due to their ease of administration, cost-effectiveness, and ability to provide quantitative measures of spatial cognitive functions. For these reasons, these tests are employed in neuropsychological evaluations to measure key aspects of spatial cognition, including spatial perception, spatial working memory, and spatial organization. However, these methods may lack the ecological validity of real-world navigation tasks, as these assessments often fail to capture the complexities of real-world navigation, where dynamic spatial interactions in real-world settings play a crucial role. Additionally, while these tests provide valuable insights into spatial deficits, their reliance on manual scoring introduces subjectivity, potentially affecting consistency in clinical diagnoses. A widely utilized example is the Benton Judgment of Line Orientation Test [78], which evaluates an individual's capacity to estimate angular relationships between line segments, offering insights into spatial perception deficits associated with neurological disorders. While this test is beneficial in evaluating visuospatial abilities, its direct applicability to real-world spatial memory remains constrained. Similarly, the Wechsler Memory Scale Spatial Span Subtest [79] evaluates visuospatial working memory by requiring participants to recall the sequence of spatially arranged stimuli. This offers an index of the ability to retain and manipulate spatial information in the peripersonal space [79]. Other widely used test, such as the Rey-Osterrieth Complex Figure Test [80], extend beyond simple spatial recall by incorporating elements of organizational strategy and executive function. This test requires individuals to copy a complex geometric figure and later reproduce it from memory, providing valuable data on both immediate and delayed spatial memory recall. The Corsi Block-Tapping Test [81] further refines spatial working memory assessments by testing an individual's ability to recall and reproduce a sequence of tapped blocks, offering a reliable measure of visuospatial sequencing in the peripersonal space or on a two-dimensional screen.

In contrast to static paper-and-pencil tasks, maze-based paradigms engage individuals in dynamic spatial processing, requiring them to encode, retrieve, and apply spatial information to navigate a structured environment. Maze-based assessments have been a fundamental component of the evaluation of spatial memory, providing structured environments that emulate real-world navigation challenges [82]. These assessments, initially developed for animal studies, have been extensively adapted for human research, offering valuable insights into spatial learning, memory encoding, and navigation strategies. The Morris water maze has been a hallmark of neuroscience research, particularly in the domain of allocentric spatial memory and its relationship to hippocampal function [83]. This test, initially developed for animal models, involves the navigation of a hidden platform in a circular pool using distal visual cues. The adaptation of this test for implementation in a laboratory setting for the assessment of human subjects offers a measure of allocentric representation in navigational performance [77]. Poorer performance on this test is associated with greater brain atrophy and amyloid-β status in individuals diagnosed with Alzheimer's disease [77]. Another gold-standard test is the radial arm maze, which was originally developed for rodent studies but was later adapted for human assessment [84]. This maze consists of multiple arms radiating from a central hub, with some arms containing rewards. It is critical for participants to recall which arms they have visited, as this information is crucial for optimizing their navigation strategy. This test is an effective tool for assessing long-term spatial knowledge of reward locations and temporary spatial information about recently visited locations, which is referred to as spatial working memory [84].

Card-placing tests allow researchers to examine spatial memory based on egocentric, body-based, and allocentric, landmark-based, navigation strategies in non-navigational spaces [11]. Furthermore, studies assessing object-location memory that relies on both egocentric and allocentric spatial strategies in real environments frequently involve participants exploring structured settings, such as rooms, offices, or outdoor landscapes, and subsequently recalling or relocating specific objects [62]. Variables such as landmark availability, spatial layout complexity, and prior experience with the environment are manipulated to assess their effect on performance [62].

Real-world environments, such as buildings, city streets, or parks, have been utilized to assess wayfinding abilities. These paradigms offer high ecological validity but are more challenging to standardize. Studies have examined how individuals form cognitive maps by exploring these environments and subsequently recalling routes or recognizing landmarks [85]. Researchers have also employed structured navigation tasks within university buildings or hospitals to assess how well participants learn and recall specific routes. These tasks frequently entail free exploration, subsequently followed by recall tasks that evaluate memory for spatial locations and decision points [85].

Digital innovations in spatial memory assessment

Conventional, non-digital spatial memory assessments, while providing a foundational framework for neuropsychological research, exhibit several limitations that hinder their ecological validity, scalability, and adaptability. Classic paradigms are characterized by their reliance on controlled laboratory environments that do not fully replicate the complexities of real-world navigation. These assessments frequently require physical mobility, thereby limiting their applicability to populations with motor impairments or neurodegenerative conditions [86]. Moreover, paper-based and static computerized tasks, lack dynamic environmental interactions, preventing the evaluation of the use of spatial memory strategies during navigation and spatial flexibility [62]. The dependence on artificial, highly structured settings also reduces their relevance for real-life applications, as individuals navigate complex, unpredictable environments outside the laboratory. Furthermore, experimenter dependency in traditional assessments introduces variability in administration and scoring, reducing reliability and reproducibility [87].

The aforementioned limitations have prompted researchers to adopt digital technologies, with a particular emphasis on VR and MR-based paradigms. These technologies offer enhanced experimental control while maintaining the cognitive demands associated with real-world spatial memory [88]. The use of VR and MR in simulating real-world environments is a subject of considerable interest. VR systems utilize head-mounted displays to create an enclosed, immersive experience, with stereoscopic vision being a key feature influencing immersion. This feature enhances the perception of depth and realism, and immersive VR minimizes external interference by fully immersing users within a controlled virtual space [89]. This is achieved through the integration of advanced technologies, including motion tracking, spatialized audio, and haptic feedback, which collectively enhance the feeling of presence in the virtual world. For instance, the immersive VR system HTC Vive employs external base stations and Lighthouse technology for highly accurate motion tracking, enabling precise user movement detection through infrared signals. The HTC

Vive system also supports room-scale tracking, allowing users to navigate freely within a defined space, while its high-resolution display and refresh rates of up to 120 Hz contribute to a fluid and comfortable experience. The Meta Quest operates wirelessly without the need for a personal computer or external sensors, and it is equipped with the Qualcomm Snapdragon XR2 platform, integrating inside-out tracking via built-in cameras, ensuring portability and ease of use. The integration of MR within the Meta Quest further enhances the immersive experience by seamlessly blending virtual elements with the real world in real-time interactions. Devices such as the Microsoft HoloLens utilize holographic overlays to integrate digital content with physical environments, thereby offering a seamless and interactive user experience [16].

Traditional maze-based spatial memory assessments, such as the Morris water maze, have been successfully adapted into VR, allowing for controlled testing conditions while maintaining the fundamental cognitive demands of navigation [87] (Table 3). A notable example of this adaptation is the virtual Morris water maze, which replicates the fundamental principles of the original laboratory task while offering an immersive digital setting [90]. This innovation enables researchers to assess spatial memory and navigational abilities in humans without the constraints imposed by physical mobility, making it a valuable tool for clinical populations [87]. However, movement, as in real navigation, is also incorporated in these methodologies. Virtual cities and buildings provide immersive environments where participants navigate through simulated urban settings presented in VR [91]. These environments facilitate the assessment of landmark identification and route planning, thereby enabling more naturalistic evaluations of wayfinding and spatial memory [90]. The utilization of these large-scale scenarios has led to the emergence of detour navigation tests as a valuable research tool. These tests require individuals to adapt to unexpected obstacles, such as roadblocks, and to find alternative routes. They have been particularly useful in the study of navigational flexibility in aging populations and patients with neurodegenerative disorders [82, 86, 92]. The results of the research have demonstrated the presence of strong correlations between virtual navigation performance in these test settings and real-world spatial memory [92]. The VR Supermarket Test is another task that evaluates key aspects of spatial memory, including route learning, landmark recognition, and spatial orientation. This test allows for the acquisition of a brief measure of path integration, including measures of egocentric orientation, heading direction, allocentric memory, and central navigation preference [92]. The test has been widely adopted for the assessment of spatial navigation and object-location memory, thereby elucidating its utility in differentiating between healthy individuals and those with cognitive impairments, such as mild cognitive impairment and Alzheimer's disease [93]. In small-scale VR environments, the object-location memory test facilitates the evaluation of object-place associations through immersive technologies [62]. VR object-location memory tasks incorporate ecologically valid environments, such as habitual environments, house rooms, and design tasks, enabling precise manipulation of variables including object familiarity, positioning, movement, and retrieval demands. These VR tasks engage both egocentric and allocentric reference frames, wherein individuals encode object locations relative to their own position or in relation to environmental landmarks [62].

Table 3. Main VR applications in spatial memory assessment

Task	Main process
Virtual Morris water maze	Spatial navigation
Supermarket Test	Route learning, landmark recognition, and spatial orientation
Simulated cities and buildings	Recognition of landmarks and planned routes
Detour navigation tests	Navigational flexibility
Object-location tasks	Object-place associations

VR: virtual reality

MR-based evaluations adopt a hybrid approach by integrating spatial memory assessment into real-world environments. MR tools, such as MR Object-Location Memory Tasks, enhance memory assessment by placing virtual objects within real-world settings and requiring users to recall or interact with them later

[15]. Studies demonstrate that participants engaging with MR applications exhibit comparable performance to those using traditional neuropsychological tools, yet with enhanced motivation and immersion [16, 94]. Furthermore, MR-based assessments have been shown to result in fewer errors in recall tasks, particularly in environments where users can anchor virtual objects to real-world spatial cues [16].

The transition from conventional spatial memory assessments to VR and MR represents a substantial advancement in the field of spatial memory assessment, thereby enhancing ecological validity and experimental control. These technologies not only refine spatial memory assessment but also offer promising applications in the early diagnosis and rehabilitation of this cognitive process. Conventional methods are deficient in terms of real-world applicability and adaptability. Conversely, VR tasks, such as the virtual Morris water maze and the VR Supermarket Test, facilitate immersive, controlled evaluations of spatial strategies and their flexibility. Furthermore, MR technology serves to integrate virtual and physical environments, thereby enhancing recall accuracy and engagement through Object-Location Memory Tasks.

Applications of digital spatial memory assessment

As immersive technologies continue to evolve, their ability to provide realistic and engaging interactions will play a crucial role in various applications, including neuropsychological assessment. The integration of VR and MR into spatial memory research has expanded applications across cognitive neuroscience and neuropsychology, clinical diagnostics, and rehabilitation. In research settings, VR-based assessments, such as the virtual Morris water maze and virtual city navigation, facilitate controlled evaluations of spatial memory, allowing researchers to manipulate environmental variables and study egocentric and allocentric navigation strategies [87, 90]. Clinically, VR and MR are valuable tools for detecting cognitive impairments associated with neurodegenerative disorders, including Alzheimer's disease, by assessing spatial recall, route learning, and navigational flexibility in ecologically valid environments [87, 90]. Furthermore, MR-based tools, such as Object-Location Memory Tasks, enhance real-world applicability by integrating virtual objects into physical spaces, improving recall accuracy and engagement [16, 94]. These technologies also support cognitive training and rehabilitation, offering immersive interventions tailored to individuals with spatial memory deficits. As VR and MR continue to evolve, their application in cognitive assessment is expected to enhance early diagnosis, personalized interventions, and the development of more effective therapeutic strategies.

In the domain of neuroscience, VR and MR facilitate the study of spatial navigation by providing controlled yet ecologically valid environments where researchers can analyze memory encoding, retrieval strategies, and cognitive flexibility. In clinical neuropsychology, these technologies play a crucial role in early diagnosis and monitoring of neurodegenerative conditions, allowing for precise detection of spatial disorientation and memory deficits, enhancing ecological validity while maintaining experimental rigor. In the domain of rehabilitation, the integration of interactive VR simulations holds significant promise for the development of personalized cognitive training programs, based on individual spatial memory deficits. These programs have the potential to assist patients in their recovery from brain injuries or neurological disorders by enhancing their spatial cognition in a safe and adaptive environment. As VR and MR technologies continue to evolve, their integration into these fields is expected to lead to significant advancements in spatial memory assessment, intervention strategies, and our understanding of spatial memory processes.

Challenges of digital spatial memory assessment

The utilization of VR and MR in the assessment of spatial memory presents considerable challenges, despite their advantages in ecological validity and immersion. A primary challenge pertains to standardization and reliability. Research has demonstrated that variations in virtual environments and task designs can yield divergent outcomes, thereby complicating the establishment of uniform assessment protocols that facilitate comparisons across studies [82]. The absence of standardized virtual environments can result in inconsistencies in the measurement and interpretation of spatial memory performance [90].

A review of the existing literature indicates that, in experimental settings, VR is particularly effective for controlled, repeatable assessments, while MR offers advantages in ecologically valid, real-world applications. However, MR assessments are more susceptible to variability in environmental factors, such as lighting, object occlusion, and user movement constraints, which can influence task performance [87]. Furthermore, while MR has shown promise in enhancing object-location memory tasks through interactive overlays and multisensory engagement, its validation against standardized cognitive tests remains less established compared to VR [87].

A further salient challenge concerns the question of ecological validity in comparison to conventional methods. While VR and MR have been demonstrated to simulate real-world navigation scenarios with greater efficacy than traditional assessments, they nevertheless remain deficient in terms of the complexity found in real-world navigation, owing to their limited sensory feedback. Furthermore, immersion-related distortions, such as motion sickness and cybersickness, have the potential to adversely affect performance, particularly among elderly and clinical populations [95].

Technical limitations also present a significant issue, particularly in the context of MR-based assessments, where the accuracy of spatial tracking is contingent on the quality of the hardware, which exhibits considerable variation across devices [88]. The operation of VR systems is contingent upon the use of high-resolution displays and precise motion tracking, which ensure that the spatial relationships depicted are accurate and representative of real-world spatial cognition [16]. Furthermore, difficulties in operating these devices can affect cognitive load and engagement. It has been demonstrated that not all populations are equally at ease with the utilization of these technologies. This phenomenon is particularly salient in the context of elderly individuals and those suffering from cognitive impairments. The aforementioned circumstances have the potential to introduce biases in assessment outcomes. While digital spatial memory assessments can be engaging, the novelty of VR and MR environments can influence cognitive performance, making it difficult to distinguish between true memory deficits and technology-induced effects. Some studies have indicated that users unfamiliar with VR and MR navigation perform worse due to increased cognitive demand, rather than actual impairments in spatial memory [96]. To address this issue, personalized habituation protocols are mandatory.

Finally, accessibility and cost remain significant barriers to widespread implementation. VR and MR systems are expensive, which limits their use in clinical and research settings. In these settings, professionals are accustomed to administering paper and pencil tests in rooms with simple furniture and minimal space. Additionally, conventional assessments are characterized by their ease of administration, largely due to the standardization of their implementation, which is an integral component of the professional training curriculum. Conventional assessments predominantly consist of scaled tests or tests that present a substantial corpus of normative data, a consequence of their extensive utilization in the past. This extensive usage has afforded researchers and clinicians a substantial body of data from which they can draw comparisons regarding the performance of their subjects. In order to ensure the reliability and comparability of VR and MR spatial memory results across diverse populations, it is imperative that standardized protocols and validation studies are established.

Future directions

The field of spatial memory assessment has been significantly impacted by advancements in VR and MR evaluations. These technologies offer promising potential for enhancing standardization, usability, and diagnostic precision in research and clinical applications.

Without requiring complex set-ups, the development of mobile-based applications and web-based platforms has facilitated bedside spatial assessment as well as large-scale data collection and remote assessment, thereby expanding research possibilities to diverse populations across different age groups and clinical conditions [97]. Application-based pointing tasks using mobile devices have been developed to provide rapid, bedside assessments of spatial orientation and memory. The use of built-in smartphone sensors to measure 3D pointing accuracy, based on the 3D real-world pointing test [98, 99], under different conditions allows differentiation of egocentric and allocentric spatial processing demands and shows high reliability, correlating well with established self-report scales of spatial ability [100]. These mobile pointing tests provide an ecologically valid, scalable, and practical alternative to VR or pen-and-paper assessments, bridging the gap between traditional clinical tools and real-world spatial demands.

Integration of artificial intelligence and machine learning in future advancements has the potential to further refine these tools, making them more adaptable to individual cognitive profiles and real-world navigation challenges [101]. The integration of artificial intelligence into spatial memory assessment represents a promising direction for research. Machine learning algorithms have the potential to analyze large datasets derived from digital navigation tasks, identifying patterns that may elude conventional analysis techniques. These capabilities could enhance the predictive accuracy of cognitive decline in conditions such as Alzheimer's disease and mild cognitive impairment. Furthermore, the adaptation of tasks to the individual characteristics of patients has the potential to create personalized assessments that are tailored to their cognitive profiles, thereby enhancing the sensitivity and specificity of spatial memory assessment.

In the future, studies should aim to standardize VR and MR spatial navigation memory tasks for clinical applications and investigate their effectiveness in differentiating spatial strategies, including the analysis of brain function during task performance. The integration of wearable technologies, such as eye-tracking devices and EEG headsets, facilitates the analysis of spatial memory processes by capturing real-time cognitive and neurophysiological responses [88]. These technologies hold significant potential in clinical settings, particularly for the early detection of spatial memory deficits observed in neurological conditions [102, 103].

MR provides spatial cues from real-world contexts while retaining the experimental control afforded by digital environments. Future research should explore the optimal balance of virtual and physical elements in MR tasks to maximize ecological validity without compromising standardization.

Furthermore, ethical considerations and inclusivity must serve as guiding principles in future research initiatives. It is imperative that studies ensure the accessibility of digital spatial memory tasks to individuals across the spectrum of technological proficiency and physical ability, thereby promoting inclusivity and accessibility in research methodologies.

In summary, the future of spatial memory assessment is in the integration of VR and MR with artificial intelligence and brain function assessment technologies, all with robust, standardized protocols. Collaborative efforts among the domains of cognitive neuroscience, computer science, and clinical practice will be essential to harness these innovations effectively, enhancing the early diagnosis and intervention of spatial memory impairments in neurological disorders.

Conclusions

The evaluation of spatial memory has undergone substantial advancement in recent years, largely due to the integration of digital technologies, particularly VR and MR. These methodologies have emerged as a significant improvement over conventional approaches, offering immersive, ecologically valid, and scalable alternatives. VR and MR have been particularly effective in enhancing the precision and realism of evaluations related to navigational abilities, object-location memory, and route learning. Conventional assessment methods, which include questionnaires and mazes, have proven to be valuable sources of information. However, they often lack the degree of real-world applicability that is essential for many applications. VR-based tasks, such as the virtual Morris water maze and the VR Supermarket Test, offer controlled environments while preserving ecological relevance. MR-based assessments further enhance engagement by integrating digital and physical elements. These technologies hold great promise for the early diagnosis of neurodegenerative diseases.

Despite their advantages, VR and augmented reality face challenges such as standardization, accessibility, and user adaptation. Variability in virtual environments and hardware limits the comparability of studies, while cybersickness and cognitive load affect performance. High costs also hinder widespread clinical adoption. For this reason, future research should prioritize standardization and artificial intelligence-driven assessments. Combining VR and MR with neuroimaging and physiological tracking can help researchers gain deeper insights into spatial cognition.

The integration of VR and MR into research focused on spatial memory constitutes a transformative shift in the field of cognitive assessment. While these technologies enhance diagnostic precision, further refinement is necessary to improve usability and accessibility. Interdisciplinary collaboration will be crucial in driving future innovations in spatial memory evaluation.

Abbreviations

MR: mixed reality

VR: virtual reality

Declarations

Author contributions

SGN: Conceptualization, Writing—original draft. LS: Conceptualization, Writing—original draft. MM: Validation, Writing—review & editing, Supervision. All authors read and approved the submitted version.

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The authors declare that they have no conflicts of interest.

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