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Navigational object-location memory assessment in real and virtual environments: A systematic review

Tania Llana[a,b,c,1], Marta Mendez[a,b,c,*,2], M.-Carmen Juan[d,3], Magdalena Mendez-Lopez[e,f,4]

[a] Department of Psychology, University of Oviedo, Faculty of Psychology, Plaza Feijoo s/n, Oviedo, Asturias 33003, Spain
[b] Neuroscience Institute of Principado de Asturias (INEUROPA), Faculty of Psychology, Plaza Feijoo s/n, Oviedo, Asturias 33003, Spain
[c] Instituto de Investigación Sanitaria del Principado de Asturias (ISPA), Av. del Hospital Universitario, s/n, Oviedo, Asturias 33011, Spain
[d] Instituto Universitario de Automática e Informática Industrial, Universitat Politècnica de València, C/Camino de Vera, s/n, Valencia 46022, Spain
[e] Department of Psychology and Sociology, University of Zaragoza, Pedro Cerbuna 12, Zaragoza, Aragón 50009, Spain
[f] IIS Aragón, San Juan Bosco, 13, Zaragoza, Aragón 50009, Spain

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A B S T R A C T

Navigational object-location memory (OLM) is a form of spatial memory involving actual or virtual body displacement for repositioning previously encoded objects within an environment. Despite its potential for higher ecological validity measures, navigational OLM has been less frequently assessed than static OLM. The present systematic review aims to characterize the methodology and devices used for OLM assessment in navigational real and virtual environments and synthesize recent literature to offer a comprehensive overview of OLM performance in both pathological and non-pathological adult samples. A search through four different databases was conducted, identifying 39 studies. Most studies assessed navigational OLM in healthy adults by 2-dimensional or 3-dimensional computerized tasks, although immersive Virtual Reality (VR) devices were also frequently employed. Small environments and objects with high-semantic value were predominantly used, with assessment mainly conducted immediately after learning through free-recall tasks. The findings revealed that healthy samples outperformed clinical ones in navigational OLM. Men showed superior performance compared to women when cues or landmarks were used, but this advantage disappeared in their absence. Better results were also noted with shorter intervals between learning and recall. Fewer OLM errors occurred in real environments compared to both immersive and non-immersive VR. Influences of environmental features, object semantics, and participant characteristics on OLM performance were also observed. These results highlight the need for standardized methodologies, the inclusion of a broader age range in populations, and careful control over the devices, environments, and objects used in navigational OLM assessments.

Abbreviations: 2D, 2-dimensional; 3D, 3-dimensional; AD, Alzheimer's disease; AMCI, Amnestic mild cognitive impairment; AR, Augmented Reality; FMRI, Functional Magnetic Resonance Imaging; FOV, Field of view; HD, Huntington's disease; IEEG, Intracranial Electroencephalography; IVR, Immersive Virtual Reality; KS, Korsakoff's syndrome; MCI, Mild cognitive impairment; MRI, Magnetic Resonance Imaging; MTL, Medial temporal lobe; NiVR, Non-immersive Virtual Reality; OLM, Object-location memory; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RBMT, Rivermead Behavioral Memory Test; TLE, Temporal Lobe Epilepsy; VR, Virtual Reality; WOS, Web Of Science; WWW, What-Where-When.

* Correspondence to: Department of Psychology, University of Oviedo, INEUROPA, ISPA, Plaza Feijoo s/n, Oviedo, Asturias 33003, Spain.
E-mail addresses: llanatania@uniovi.es (T. Llana), mendezlmarta@uniovi.es (M. Mendez), mcarmen@dsic.upv.es (M.-C. Juan), mmendez@unizar.es (M. Mendez-Lopez).
[1] Orcid: https://orcid.org/0000-0002-0422-6168
[2] Orcid: https://orcid.org/0000-0003-1718-7492
[3] Orcid: https://orcid.org/0000-0002-8764-1470
[4] Orcid: https://orcid.org/0000-0002-4249-602X

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1. Introduction

Spatial memory is a type of episodic memory that enables the acquisition, storage, and retrieval of the location of elements in space and the recognition of whether they have changed their position [1]. An important feature of spatial memory, known as object-location memory (OLM), is defined as the ability to remember the position of objects in the environment [2]. This process, constantly used in our daily life, is not a unitary skill, so it can be divided into different components, such as the processing of object information, the processing of position information, and the integration of both components [2]. Because of that, OLM is typically organized into two broad functional pathways: the ventral or "what" pathway, more implicated in visual object recognition, and the dorsal or "where" pathway, with an important role in the localization of objects in space [3]. Effective spatial OLM requires the use and combination of both dorsal and ventral visual processing pathways as the ability to locate objects in space involves both egocentric and allocentric representations, i.e. transient action-oriented egocentric self-object associations and more persistent representational allocentric object-object or environment-object associations [4]. The use of both types of representations appears to be influenced by factors such as the degree of self-motion between the presentation and retrieval phases, the size and structure of the spatial environment, and the level of prior experience in that environment [4].

The storage and retrieval of object locations is influenced by both external and internal factors [5]. Among the external factors, the characteristics and complexity of the environment have a significant impact on how locations are encoded and retrieved. The effectiveness of spatial memory can vary depending on specific task demands [6] and the formulation of action plans and attitudes towards the environment [7], environmental type and contextual familiarity [8–10], and landmark attributes [11]. In terms of internal factors, age [12], gender [13,14], whose effects can be modulated by prior experience [15], individual cognitive processes [16], and motivational factors such as self-efficacy beliefs [17] can influence how individuals store and retrieve spatial information.

The crucial role of the medial temporal lobe (MTL) in episodic memory is well known [18]. Several studies have found that damage in the right MTL leads to an OLM impairment [2,19]. Particularly the hippocampus, an MTL region, plays a vital role in cognitive mapping and episodic memory by consolidating object details, recognizing familiar objects in novel environments, and processing object-location information [20]. However, the hippocampus is not the only structure that plays an important role in OLM. Other structures, such as the parahippocampal gyrus and the entorhinal cortex, are involved in the accuracy of memory for both object-identity and object-location in humans [18,20]. The posterior parahippocampal cortex is involved in the encoding of both the object associated with a location and the location associated with an object, integrating object information within a spatial framework [18]. In contrast, the anterior parahippocampal cortex has a role in the encoding of the spatial aspect and is specifically involved in the encoding of the location associated with an object [18]. The entorhinal cortex plays a specific role in the retention of contextual information and the binding of objects to their contextual surroundings. This enables the joint representation of the relationship between an object's identity and its spatial and contextual information [20].

The OLM may be affected by certain pathological processes. For example, the spreading of TAU proteins, targeting the entorhinal cortex and subsequently extending to the hippocampus, which characterizes healthy aging, but also pathological conditions such as mild cognitive impairment (MCI) or Alzheimer's disease (AD), is associated with impairment in OLM [20–22]. Huntington's Disease (HD), a type of autosomal degenerative disorder, also reported OLM deficits [23]. The anterior temporal lobectomy for the treatment of epilepsy is another clinical condition that frequently induces alterations in OLM [24]. The OLM is also studied in preclinical animal models that replicated conditions affecting episodic memory, like sleep deprivation and high-fat diets [25,26].

Given the impact of various pathological processes on OLM, accurate assessment methods are crucial for understanding and diagnosing these impairments. Neuropsychological assessment of memory in humans includes a wide variety of standardized instruments [27]. Paper-and-pencil and computerized tasks, which offer a set of predefined stimuli delivered in a controlled environment, are effective in the assessment of cognitive constructs but less reliable in predicting functional behavior as expressed in everyday tasks [28], showing a moderate level of ecological validity in estimating real-world performance [27]. Visuo-spatial memory has been studied less than other components of episodic memory, such as auditory-verbal memory processes [29]. To enhance ecological validity in the neuropsychological assessment of memory, new tools and technologies have been created. These include tasks involving everyday activities, like recalling where objects are placed in various daily life situations [27].

Initially, OLM assessment involved tasks where participants were presented with visual scenes and arrays and were required to identify changes within these visual elements or to reconstruct the spatial arrangement of previously observed objects [29]. However, these tasks did not allow researchers and clinicians to conduct a comprehensive assessment of OLM [29]. The aforementioned tasks have the potential for verbal mediation, whereby participants may use verbal strategies to assist memory, confounding the assessment of purely visuospatial memory [29]. These tasks use visual static stimuli, neglecting the integration of multisensory, more naturalistic information [29]. The stimuli are often overly abstract, which may make the tasks less representative of memory challenges encountered in everyday life [29]. Furthermore, these tasks often require a drawing response or graphomotor processes that depend on visuoperceptual and/or visuoconstructional skills [29]. To overcome these limitations, current efforts are focused on developing more comprehensive, ecologically valid, and purely visuospatial assessment tools that use dynamic and multisensory stimuli to better represent real-world scenarios. These tools should be designed to minimize the potential for verbal mediation by discouraging the use of verbal strategies [29]. The use of realistic and contextually relevant stimuli is employed to improve the generalizability of assessment results [29]. Furthermore, the assessment should be designed to avoid the need for graphomotor responses, to focus exclusively on visuospatial memory without the confounding influence of other cognitive skills, with developments that allow for the distinction of memory for figurative detail from memory for spatial location, to provide a high degree of experimental control, and to include the automatization of measurements to quantify behavior, thus avoiding the inconvenience of manual recording and scoring of responses [29,30].

The assessment of OLM can be classified as a function of the main features presented in the OLM tasks, which are: environment, device and/or method, and items (see Fig. 1).

Considering the environment in which the task is developed, OLM tasks can be carried out in static environments or reaching spaces, which involve the grasping distance portion of space and do not require participant's displacement; or in navigational environments, which refer to the space within walking distance, implying either real or non-real displacements [31]. Note that, in static environments, people can solve the task without changing their position or perspective view and do not require any kind of movement or displacement. Examples of OLM tasks in static environments are paper or computerized matrices that contain images of objects, and participants must memorize and recall or recognize their positions later [32]. Conversely, navigational OLM tasks encompass two different types of body displacement: real or non-real. Real body displacement involves walking freely (i.e., real active displacement) or guided by an experimenter (i.e., passive-guided displacement) within a controlled space during an encoding phase and the recall of object locations afterward [33]. Non-real body displacement consists of active exploration tasks (i.e., non-real active

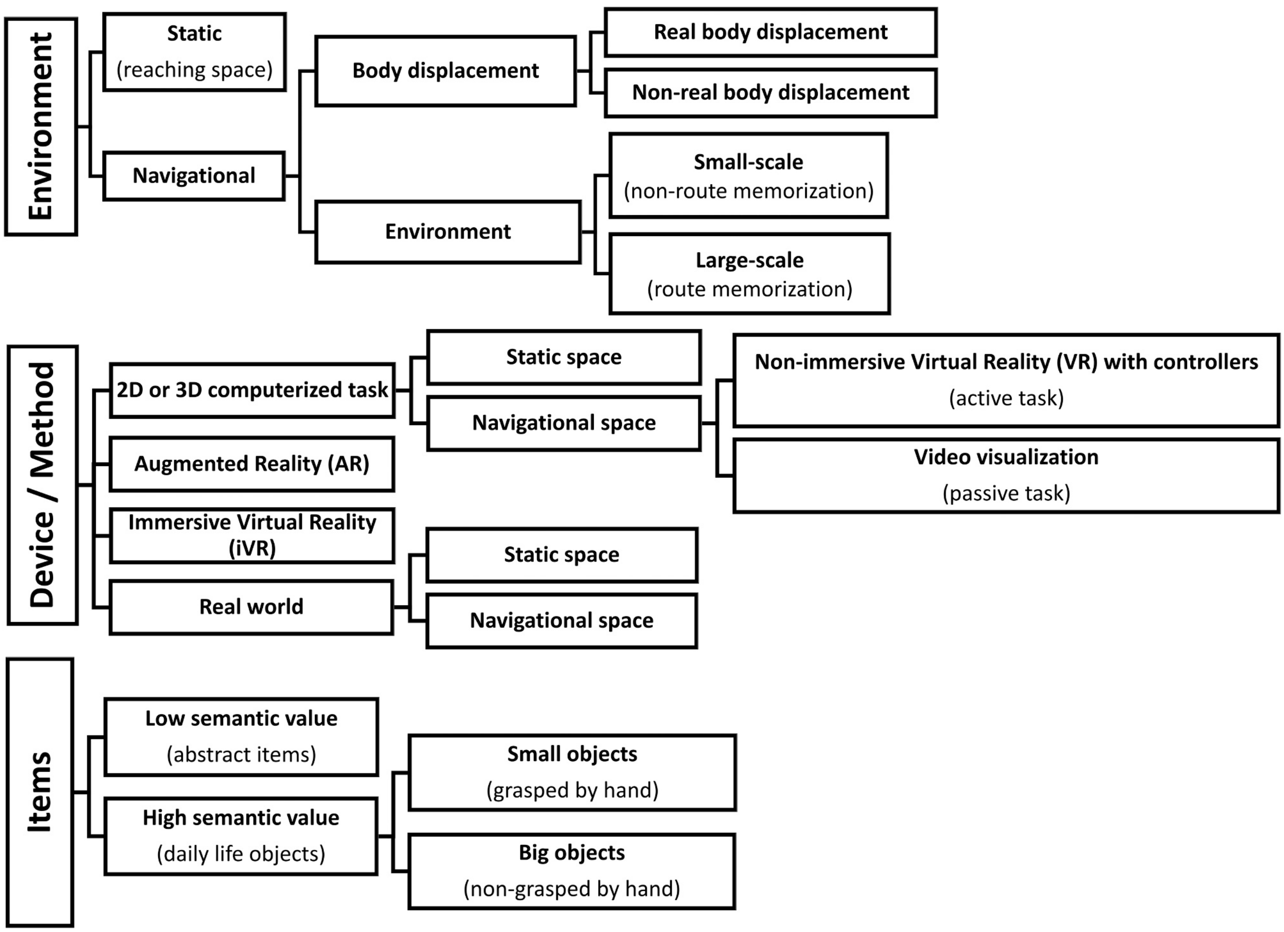

Fig. 1. Features characterizing a task for OLM assessment.

displacement) carried out using a joystick or keyboard to control participant's movements within a computer-simulated environment [34], or passive-guided tours (i.e., non-real passive displacement) using a pre-recorded video of the environment from the subject's perspective, where objects' locations are situated [35]. The sceneries simulating environments in OLM tasks replicate small-scale environments, such as enclosed spaces (e.g., a room in a house), where participants do not need to recall routes [36], or large-scale environments, such as buildings, where routes should be memorized to recall the position of the objects [37].

Methods and devices employed in OLM tasks vary widely across studies. Computerized 2D or 3D tasks are used frequently because they facilitate task programming and performance scoring. Both navigational and static tasks can be implemented easily in a controlled space using computers. An example of a static computerized task is the recall of object locations previously presented in a static environment, such as a picture [38]. Navigational computerized tasks can also be differentiated as tasks with active exploration, for example, the navigation in a non-immersive Virtual Reality (niVR) environment where locations of objects must be explored and recalled afterwards [39], and tasks with passive navigation, for example, a first-person view video visualization of an environment where exploration of different objects is required for later localization [40]. OLM tasks can also be assessed in real-world scenarios. As in computerized tasks, real-world OLM tasks can be differentiated as those using static environments, for example, the memorization of objects located in a plexiglass cube and their subsequent recall [41], and those employing navigational environments, for example, the exploration, memorization, and later recall of object locations in a laboratory [42]. Augmented Reality (AR) or immersive Virtual Reality (iVR)-based tasks have been developed to increase ecological validity. Compared to real-world tasks, these tasks facilitate the control of delivered stimuli, the manipulation of variables, and measurement recording [36]. AR-based tasks include non-real 3D objects in the real world to supplement reality [36], for example, testing the OLM in a room within the campus facilities [43]. Tasks based on iVR allow users' interaction in the virtual environment and can be carried out via a room-sized cube (known as the CAVE system) or a head-mounted display [30,44].

In the OLM tasks, items can be categorized as either abstract, with low-semantic value (e.g., geometric figures or symbols [45]), or as familiar daily objects with high-semantic value [43]. Furthermore, objects with high-semantic value can be small daily objects, such as those that can be held or grasped by hand [46], or big items, such as buildings [47].

1.1. Aim of the present systematic review

In neuropsychological assessment, the examination of OLM in navigational environments has received comparatively less attention than its evaluation in static environments or, indeed, other forms of spatial memory. Nevertheless, the assessment of OLM in navigational contexts may offer assessments of greater ecological validity, as it closely aligns with the cognitive processes employed in numerous everyday life activities [48]. Performance in navigational OLM tasks is often affected by conditions such as MCI and AD [20], which are nowadays significantly prevalent. The combined use of these tasks and neuroimaging techniques contributes to elucidating the role of brain regions in episodic memory processes [49,50]. Navigational tasks for assessing OLM in human memory research have exponentially increased in recent years. For these reasons, the aims of the present systematic review are to: (i) describe and compare the methodology and devices employed for OLM assessment in navigational real and virtual environments, and (ii) synthesize and coherently present the results of recent literature on the functioning of OLM in navigational environments, providing a comprehensive overview of OLM performance in both pathological and non-pathological samples of adults.

This review provides an update and detailed characterization of the different methods and devices used to assess OLM in navigational real and virtual environments. This includes computerized tasks, VR devices, and real-world environments, highlighting the differences and similarities in their use and effectiveness, examining their frequency of use and specific advantages, and comparing performance outcomes, which has not been extensively addressed in the literature. The review focuses on navigational OLM assessments, analyzing studies that involve actual or virtual body displacement and providing insights into how these dynamic assessment methods may reflect real-world memory processes. The synthesis of findings from both pathological and non-pathological adult samples will provide an understanding of how navigational OLM performance varies across different populations, highlighting the significant differences in performance and emphasizing the importance of considering clinical populations in OLM research, detailing how men and women perform differently under different conditions, and discussing the implications of these differences for future research. The review also examines the impact of different environmental configurations, characterized by varying size and complexity, on memory performance. It investigates how the inclusion of high-semantic-value objects can facilitate enhanced memory retrieval processes and considers the factors that should be controlled in experimental designs.

2. Method

2.1. Search and study selection

Scopus, Web Of Science (WOS), PubMed and PsycInfo databases were used for the present bibliographic search. A restriction on date of publication was applied, resulting in the inclusion only of articles published in the last 15 years (between 2008 and 2023). The final search was carried out on July 22nd, 2023. We applied a comprehensive search strategy combining algorithms and keywords related to the assessment with different tools of memory for object-location associations in human samples: ("Object-location memory") AND ("human*") AND ("assessment"), ("Object-location memory") AND (("virtual reality") OR ("augmented reality")), ("Allocentric memory") AND ("human*") AND ("assessment"), as well as ("Allocentric memory") AND (("virtual reality") OR ("augmented reality")).

This systematic review was conducted following the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [51].

2.2. Inclusion and exclusion criteria

The inclusion criteria used in this systematic review were: (1) human studies including adult samples; (2) articles published between 2008 and 2023; (3) studies reporting memory for object-location associations as performance outcome; (4) studies performed in either passive or active-navigational environments during the acquisition and/or testing phase.

The exclusion criteria were: (1) case studies, review papers, letters to the editor, editorials, brief communications, notes, meeting abstracts and theoretical articles; (2) articles not written in English; (3) unpublished works that had not undergone peer-review; (4) articles lacking results focused on memory performance; (5) studies reporting average data of performance from a set of trials; (6) studies that assessed the spatial localization of a set of identical objects; (7) articles that assessed object-location memory in reaching spaces or non-navigational environments.

2.3. Screening for inclusion

Two authors performed a blind review of all search results to determine whether the retrieved studies met the criteria. Firstly, after removing duplicates, only titles and abstracts were screened, and the articles that did not meet the criteria were excluded. Secondly, the full texts of the remaining articles were assessed to consider inclusion.

3. Results

3.1. Study selection

A total of 1246 articles were found in the first identification process. Of them, 978 studies remained after duplicates were removed. After reviewing the titles and abstracts, 722 articles were removed. A full-text review was conducted on 256 articles, resulting in the exclusion of 212. Finally, a total of 44 articles were selected for this systematic review (see Fig. 2). The studies are detailed in Table 1.

We conducted a data synthesis to summarize key information from the reviewed articles. In Table 1, we include sample characteristics, experimental setting, method used to present the information, number and characteristics of items employed, retention intervals established, experimental conditions, tests carried out to assess OLM in navigational environments, as well as main results obtained for each study.

3.2. Sample characteristics

A significant portion of the reviewed non-clinical studies primarily focused on healthy young adult populations [30,33,34,36,37,40,43,45,46,52–72]. Within this group, two specific studies evaluated OLM

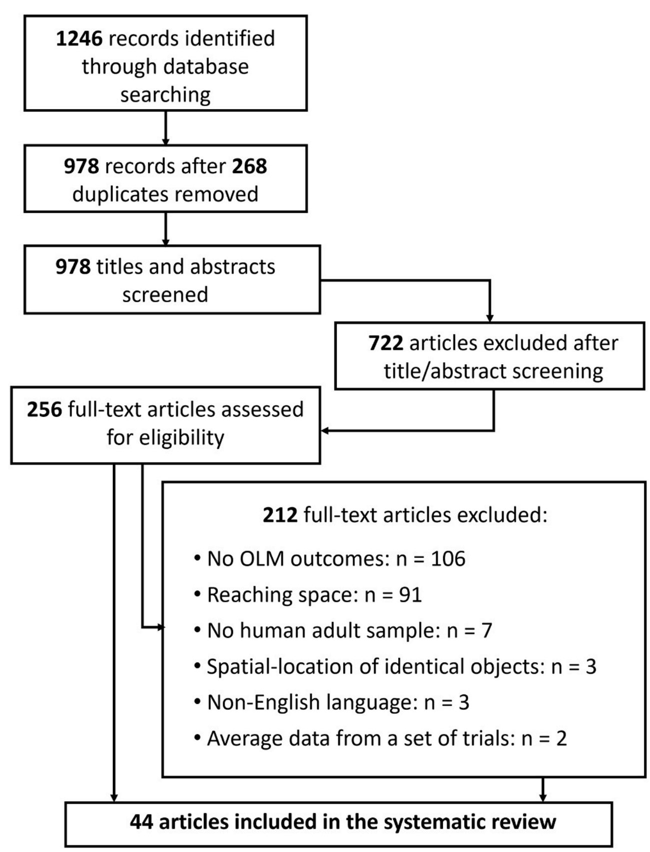

Fig. 2. Flowchart of literature search and study selection process.

Table 1
Main relevant navigational OLM assessment information extracted from the reviewed studies.

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
Barhorst-Cates et al. [52]	N = 123 HYA* with simulated FOV* loss 4 experiments: Exp1: n = 28 (19 F*; MA* = 20.3 ± 3.7) Exp2: n = 30 (15 F; MA = 22.3 ± 5.6) Exp3: n = 37 (20 F; MA = 20.27 ± 2.0) Exp4: n = 28 (19 F; MA = 23.43 ± 6.17)	Large-scale environment. Indoor environment (building hallway).	Real	High-semantic value items. 3 (Exp1) or 4 (Exp2) large everyday objects (i.e., freight elevator).	Immediately after learning (no delay).	Exp1 and Exp2: Compare active and passive locomotion in a passive search on OLM* performance. Exp3: Compare severe and mild FOV restriction in an active search on OLM performance. Exp4: Compare active and passive search paradigms on OLM performance.	Decision task: Physically point to and verbally state the quadrant and degree of objects' locations.	Exp1 and Exp2: No differences between locomotion conditions in absolute pointing error with 3 or 4 target objects. Exp3 and Exp4: No differences between FOV restriction conditions and search conditions in absolute pointing error.
Buttussi and Chittaro [53]	N = 199 HYA 2 experiments: Exp1: n = 127 (20 F; MA = 21.83 ± 1.70; RA* = 20–31) Exp2: n = 72 (34 F; MA = 22.90 ± 1.99; RA = 19–29)	Small-scale Indoor (cabin of an aircraft) and outdoor (airport area) environments. iVR* (HTC Vive Pro) and niVR* (computerized task controlled by a gyroscope (TGY) or by a virtual joystick (TVJ) on the touchscreen devices.	VR* 3D*	High-semantic value items. Indoor VE* : 8 small everyday objects (i.e., soccer ball). Outdoor VE: 8 large objects (aircrafts with different colors, types and sizes).	Exp1: immediately after learning (no delay). Exp2: Immediately after learning (no delay), and 2 weeks after learning.	Exp1: Investigated three VR setups (iVR headset (VRH), niVR with TGY, and niVR with TVJ) and two locomotion methods (teleport (TLP), and steering (STR)) in indoor/outdoor VEs for OLM tasks. Exp2: Examined OLM retention with VRH+TLP and TVJ+STR in both indoor and outdoor VEs.	Free-recall task: Replace objects in original positions in indoor/ outdoor VE 2D* maps. Verbal decision task: Determine object's proximity to a landmark in both indoor/ outdoor VEs.	Exp1: In indoor VE, TLP had poorer free-recall than STR ($p < .05$); in outdoor VE with TVJ setup, STR underperformed TLP in free-recall ($p < .05$). TVJ showed lower verbal decision accuracy than TGY and VRH with STR locomotion in outdoor VE ($ps < .05$); higher verbal decision accuracy in TLP compared to STR with TVJ setup ($p < .05$). Exp2: Increased free-recall errors and decreased verbal decision performance observed two weeks post-learning compared to immediately after, in both indoor and outdoor VEs ($ps < .001$).
Caffò et al. [77]	N = 104 aMCI* : n = 51 Subgroups: 1. aMCI single domain: n = 28 (17 F; MA = 69.89 ± 5.17; ME = 9.46 ± 5.21) 2. aMCI multiple domain: n = 23 (15 F; MA = 73.91 ± 4.72; ME = 5.74 ± 3.0) Controls: n = 53 (29 F; MA = 68.06 ± 5.96; ME = 9.7 ± 4.31)	Small-scale VE. Outdoor environment (circular invisible arena). niVR (computerized task controlled by joystick) device.	3D	Low-semantic value item. One geometric figure (yellow sphere).	Immediately after learning (no delay).	Compared groups in OLM performance, factoring in environment shape (rectangular/square) and landmark-target relationship (positional/ directional), across five conditions: layout only (LO), layout with positional/directional landmark, positional landmark only, and directional landmark only.	Decision task: Identification of the location where an object was placed among four options after a perspective change.	Worse OLM performance in aMCI subgroups compared to controls ($ps < .01$). No differences between aMCI subgroups. Controls similarly learned positional and directional relationships, while aMCI subgroups struggled with directional landmark-target relationships.
Castegnaro et al. [20]	N = 100 aMCI patients: n = 23 (10 F;	Small-scale VEs. 3 outdoor environments.	VR	High-semantic value items. 12 small	Immediately after learning (no delay)	Comparison between groups in OLM	Free-recall task: Object replacement.	Free-recall task: aMCI showed larger distance error and

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	MA = 71.7 ± 7.5; ME* = 15.3 ± 3.4). Subgroups: 1. aMCIu* : n = 7 (4 F; MA = 73.1 ± 8.3; ME: 16.0 ± 3.2) 2. aMCI-* : n = 7 (1 F; MA = 67.2 ± 6.4; ME = 14.6 ± 4.2) 3. aMCI+ *: n = 9 (5 F; MA = 74.1 ± 7.0; ME = 15.4 ± 3.0) Controls: n = 77 Subgroups: 1. HYA: n = 53 (31 F; MA = 24.1 ± 3.0; ME = 18.5 ± 2.7) 2. HOA* : n = 24 (16 F; MA = 68.8 ± 5.7; ME = 15.5 ± 3.9)	iVR (HTC Vive) device.		everyday objects (4 / environment).		performance. MRI* scan.	Object-in-context task: Identify which of the four alternatives (objects) was previously presented in a specific environment.	larger frequency rate of location-binding error compared to HOA ($p \leq .03$). Object-in-context task: Higher percentage of correct responses in aMCI- than in aMCI+ ($p = .03$). Association between larger alEC* volumes and a higher percentage of correct responses ($p < .05$).
Chai and Jacobs [54]	N = 82 HYA (RA = 18–25). Subgroups: 1. Women: n = 41 (MA = 19.8 ± 1.9) 2. Men: n = 41 (MA = 19.2 ± 1.1)	Small-scale VE. Outdoor environment (octangular grassy terrain). niVR (computerized task controlled by joystick) device.	3D	Low-semantic value item. One small geometric object (blue spike-like crystal).	Immediately after learning (no delay).	Comparison in OLM between groups with different cue types (positional or directional).	Free-recall task: Replace objects in their original positions after positional changes.	Better OLM performance in men than women under both cue conditions ($ps < .001$), with higher sex differences in the directional-cue trials.
Chai and Jacob) [55]	N = 51 HYA. Subgroups: 1. Women: n = 25 (MA = 20.7 ± 2.95; RA = 18–33) 2. Men: n = 26 (MA = 20.4 ± 1.96; RA = 18–27)	Small-scale VE environment. Outdoor environment (octangular grassy terrain). niVR (computerized task controlled by joystick) device.	3D	High-semantic value items (decision task A): 8 / 16 / 32 large everyday objects. Low-semantic value item (decision task B and free-recall task): Geometric object (blue spike-like crystal).	Immediately after learning (no delay).	Comparison between groups in 3 different OLM tasks with different cue types (decision task A: only positional cues; decision task B: only directional cues; free-recall task: both directional and positional cues, one of them removed).	Decision task A: Choose which 2 out of 4 objects changed location in a 2D task with varying object path lengths. Decision task B: Select the correct object location from 2 options. Free-recall task: Replace objects after positional changes without positional or directional cues.	Decision task A: No sex differences in any path length condition. Decision task B: Better men's performance at the smallest target-decoy distance when adding a geographical slant cue ($p = .02$). Free-recall task: The directional cue removal significantly affected men ($p = .02$) but not women. Worse performance when positional cues were removed ($p = .028$).
Chan et al. [56]	N = 20 HYA (10 F; MA = 24; RA = 18–35)	Large-scale VE. Indoor environment (virtual house with 5 rooms). niVR (computerized task controlled by joystick) device.	3D	High-semantic value items. 20 small everyday objects (4 / room).	One day after learning.	Explored the impact of emotional experiences (positive (P), negative (Neg), or neutral (Neu) and occurrence rate intermittent (Int) or constant (Cons)) on OLM task. Investigated functional brain correlates during these emotional OLM tasks using fMRI* scan.	Computerized decision task: Determine if the object was previously located in the room, presented as static images.	Faster responses in the Cons condition compared to both the Neu and the Int conditions ($ps < .01$). Faster responses in Neg than in P condition ($p < .05$). Increased PHG* activity in the ConsNeg condition compared to others ($ps < .05$).
Doeller and Burgess [34]	N = 48 HYA (0 F; MA =	Small-scale VE. Outdoor environment.	3D	High-semantic value items. 4 small everyday	Immediately after learning (no delay).	Studied overshadowing in location learning with local boundary	Free-recall task: Replace objects	Overshadowing: LB group made more replacement errors

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	21.9; RA = 18–37)	niVR (computerized task controlled by keyboard) device.		objects (overshadowing experiment). 8 small everyday objects (blocking experiment, 4 objects / cue).		(B), landmark (L), or both (LB), and blocking effects among two different local landmarks, a landmark and a boundary, and two opposite boundary sections.	in their original locations.	than L group ($p < .05$). Blocking: Learning L was hindered by another prior L or B learning (*ps* $< .001$), but learning B was not impacted by prior L learning or learning the opposite B section.
Draschkow and Võ [33]	N = 16 HYA (11 F; MA = 20.7; RA = 18–26)	Large-scale environment. Indoor environment (4 house rooms).	Real	High-semantic value items. 120 small everyday objects (15 task-relevant and 15 task-irrelevant objects / room in the learning phase). 80 small everyday objects (40 distractors / 40 absent objects).	After learning and verbal free-recall task (non-time specified).	Compared OLM performance between object handling (Hand) and finding (Find) conditions. Examined the impact of object relevance (relevant: Rel / irrelevant: Irre) and object identity memory on OLM performance.	Search task: Locate the object in the previously presented room and location. Verbal free-recall task: Write down names of remembered objects, whether searched or non-searched.	Faster fixation on Rel than Irre objects in Hand condition ($t = -2.58$). Previously free-recalled objects were searched faster ($t = -3.88$). Longer search times for recalled Irre objects ($t = -3.26$), but shorter for non-recalled Rel objects in Hand than Find ($t = 2.03$).
Draschkow and Võ [57]	N = 10 HYA (9 F; MA = 19.7; RA = 19–21)	Small-scale VEs with 16 indoor environments (living room, kitchen, bedroom, bathroom). iVR with HTC Vive HMD* and wireless controller.	VR	High-semantic value items. 240 everyday objects: Small (10 / room) and large (5 / room).	Immediately after learning (no delay).	Exploration of consistent (consistent (Cons) / inconsistent (Incons)) and object type (global (G) / local (L)) variables in a self-built OLM task.	Free-recall task: Replace objects in their original locations.	Lower mean distance error for G objects compared to L objects. G object memory improved with longer viewing time versus L objects (*ts* ≤ -2.748). Smaller mean distance for Cons objects than Incons objects.
Evensmoen et al. [58]	N = 31 HYA (0 F; MA = 21, RA = 18–27)	Small-scale VEs. 35 indoor environments with 16 square cells. niVR (computerized task controlled by joystick) device.	3D	High-semantic value items. 175 large objects (5 / environment).	After a 15 s distractor task.	Explored the link between brain activity and granularity gradient (Fine (F), Medium (M), Coarse representations) in an OLM task using fMRI scans, focusing on regions of interest ROIs* : HC* and EC*).	Free-recall task: Replace objects in their correct positions on a 2D map.	Greater activation in the posterior HC (average % BOLD* signal) for F representations (*ps* $< .0001$) and the intermediate HC for M representations (*ps* $< .0002$). Higher activation in the posterior EC for both M and F representations (*ps* $\leq .028$) and the intermediate EC for M representations ($p = .018$).
Fernandez-Baizan et al. [59]	N = 94 HYA (47 F; men's MA = 20.98 ± 3.79; women's MA = 19.74 ± 2.1).	Small-scale environment. Indoor environment (rectangular room with the usual objects and furniture).	Real	Low-semantic value items. 3 cards (circle, triangle, cross).	After learning and the change of the participants' position (while blindfolded).	Exploration of sex differences in an OLM task.	Free-recall task: Replace cards in their correct positions on a round template with 8 possible locations.	Better OLM performance in men than women during the first and last trials (*ps* $\leq .045$).
Fernandez-Baizan et al. [73]	N = 28 HOA (16 F; MA = 71.25 ± 9.50). Subgroups: 1. Younger group (62–66 years): n = 8 (5 F) 2. Middle group (67–74 years): n = 10 (5 F)	Small-scale environment. Indoor environment (rectangular room with the usual objects and furniture).	Real	Low-semantic value items. 3 cards (circle, triangle, cross).	After learning and the change of the participants' position (while blindfolded).	Exploration of sex differences in an OLM task.	Free-recall task: Replace cards in their correct positions on a round template with 8 possible locations.	No significant differences between men and women ($p = .672$).

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	3. Older group (> 75 years): n = 10 (6 F)							
Fernandez-Baizan et al. [60]	N = 55 (32 F) Subgroups: 1. HYA (16 F; MA = 20.21 ± 2.85; RA = 18–28). 2. HOA (16 F; MA = 71.19 ± 6.94; RA = 60–82).	Small-scale environment. Indoor environment (rectangular room with the usual objects and furniture).	Real	Low-semantic value items. 3 cards (circle, triangle, cross).	After learning and the change of the participants' position (while blindfolded).	Exploration of age and sex differences in an OLM task.	Free-recall task: Replace cards in their correct positions on a round template with 8 possible locations.	The HYA group outperformed the HOA group in all blocks (*ps* ≤ .003). Young men outperformed older men and young women outperformad older women (*ps* < .001).
Frings et al. [74]	N = 22 TLE* patients (RA = 17–60; range DurEp* = 1–39). Subgroups: 1. Women left TLE: n = 4 (MA = 37 ± 7; mean DurEp = 28 ± 6) 2. Men left TLE: n = 8 (MA = 34 ± 5; mean DurEp = 18 ± 5) 3. Women right TLE: n = 4 (MA = 32 ± 4; mean DurEp = 17 ± 5) 4. Men right TLE: n = 6 (MA = 38 ± 7; mean DurEp = 21 ± 5)	Small-scale VE. Indoor environment (rectangular room with walls). Video-visualization computerized task (28'' video).	3D	Low-semantic value items. 5 different coloured and geometrical objects.	After a 24'' control task.	Exploration of TLE lateralisation and sex differences in an OLM task. fMRI scan.	Decision task: Determine the accuracy of the object's location.	No significant effects of group (right/left TLE), sex, or their interaction on OLM performance. Longer DurEp linked to poorer OLM performance (*p* < .05). Increased BOLD signal in the occipitoparietal cortex, dorsolateral prefrontal cortex, and PHG during OLM task execution (*p* < .001).
Glikmann-Johnston et al. [49]	N = 70 TLE patients: n = 30. Subgroups: 1. uHIPP* : n = 15 (10 F; MA = 38.1 ± 10.2; 7 right TLE) 2. uATL* : n = 15 (9 F; MA = 39.3 ± 13.5; 6 right TLE) Comparison groups: n = 40. Subgroups: 1. IGE* : n = 15 (9 F; MA = 27.9 ± 12.5) 2. Controls: n = 25 (13 F; MA = 37.8 ± 13.3)	Small-scale VE. 8 indoor environments (house rooms). niVR (computerized task controlled by joystick) device.	3D	11 test items: 3 low-semantic value items (geometric shapes presented 15 times in various locations). 8 high-semantic value items (small common objects).	After learning and a navigational task (non-time specified).	Comparison between groups in OLM performance. Relationship between OLM performance and other spatial memory variables (navigation and floor plan drawing). MRI scan for uHIPP and IGE groups.	Free-recall task: Object replacement using positional cues.	TLE groups recalled fewer objects than comparison groups (*ps* ≤ .008). More accurately located objects led to reduced navigation time (*p* = .004) and improved floor plan drawing (*p* = .0005). No link between HC asymmetry and OLM performance.
Glikmann-Johnston et al. [48]	N = 101 HD* patients: n = 38. Subgroups: 1. pHD* : n = 24 (15 F; MA = 44.71 ± 8.54) 2. eHD* : n = 14 (4 F; MA = 54.71 ± 7.61) TLE patients: n = 30. Subgroups: 1. uHIPP: n = 15 (10 F; MA = 38.13 ± 10.24) 2. uATL: n = 15	Small-scale VE. 8 indoor environments (house rooms). niVR (computerized task controlled by joystick) device.	3D	11 test items: 3 low-semantic value items (geometric shapes presented 15 times in various locations). 8 high-semantic value items (common objects).	After learning and a navigational task (non-time specified).	Comparison between groups in OLM performance. Relationship between OLM performance and other neuropsychological tasks (navigation, floor plan drawing, PAL*, RCFT*, and SDMT*).	Free-recall task: Object replacement using positional cues.	eHD and pHD groups remembered fewer objects than controls (*p* < .009). More accurately located objects correlated with less time in navigation, better floor plan drawing ability, fewer PAL errors, improved delayed RCFT recall, and higher SDMT scores (*ps* ≤ .029).

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	(9 F; MA = 39.3 ± 13.5) Controls: n = 33 (16 F; MA = 48.06 ± 8.27)							
Glikmann-Johnston et al. [23]	N = 68 HD patients: n = 36. Subgroups: 1. pHD: n = 24 (14 F; MA = 45.33 ± 8.19) 2. eHD: n = 12 (4 F; MA = 55.17 ± 7.99) Controls: n = 32 (16 F; MA = 48.47 ± 8.06)	Small-scale environment. 8 indoor environments (house rooms). niVR (computerized task controlled by joystick) device.	3D	11 test items: 3 low-semantic value items (geometric shapes presented 15 times in various locations). 8 high-semantic value items (common objects).	After learning and a navigational task (non-time specified).	Comparison between groups in OLM performance. MRI scan (ROIs: HC, caudate nucleus, and putamen).	Free-recall task: Object replacement using positional cues.	HD patients recalled fewer objects than controls (p = .001). No link found between assessed ROIs and OLM performance.
Hampstead et al. [40]	N = 12 HYA (5 F; MA = 25.8 ± 4.0; ME = 16.8 ± 2.7)	Large-scale VEs with 3 environments (apartment, movie theater complex, cityscape). Video-visualization in 60" videos.	3D	High-semantic value items. Key features (number not specified).	30 minutes after learning.	Comparison between a navigational memory task and an OLM task. fMRI scan.	Free-recall task: Draw a map of each environment and place key features within the correct spatial location.	More anterior left HC activation in the OLM task than in the navigational memory task. Association between OLM performance and activation in dorsal and ventral visual brain streams.
Helbing et al. [36]	N = 21 HYA (14 F; MA = 24.3; RA = 18–38)	Small-scale VE. 5 indoor environments (house rooms). iVR (HTC Vive) device.	VR	High-semantic value items. 100 everyday category-appropriate objects (20 / environment; 15 small and 5 large objects / environment).	After two learning experimental conditions and an object recognition task (non-time specified).	Comparison of OLM between two learning experimental conditions (search / memorization) and between two object types (targets / distractors).	Free-recall task: Replace small objects using large objects as cues.	Longer gaze durations led to better item replacement (ps < .001), with greater benefits for distractors over targets (p < .001). Targets were placed more accurately in the search condition compared to the memorization condition (p < .001).
Janzen et al. [79]	N = 44 KS* patients: n = 20 (4 F; MA = 60.20 ± 7.70; EL* = 3) Controls: n = 24 (5 F; MA = 57.79 ± 6.90; EL = 5)	Small-scale VEs. 4 outdoor environments. Video-visualization computerized task (30–40" videos).	3D	High-semantic value items. Target item (a bird). 2 possible landmarks (a bench and a slide).	After learning (direct condition) and after learning and a 10"-delay (delay condition).	Comparison of OLM performance across groups considering reference frames (congruent/ incongruent), delay (immediate/10-second), and landmark presence. Correlation of OLM with neuropsychological tasks (MRT* and RBMT−3 *). Examining the link between GCA* / MTLA* presence and OLM performance via MRI.	Free-recall task: Position the bird in the correct tree, with or without a landmark.	KS patients underperformed compared to controls (p < .005). Higher scores in trials with landmarks than without (p < .005), and in immediate over delayed trials (p = .02). Controls fared worse in no-landmark trials during 10-second delays (p = .008). Better OLM linked with improved MRT performance (p = .005).
Keil et al. [61]	N = 60 HYA (28 F; MA = 24.7 ± 3.2; RA = 19–33)	Small-scale real environment. Indoor environment (empty room). AR* (Microsoft HoloLens) device.	AR	Low-semantic value items. 6 green cylinders, each of them marked with a unique letter.	3 minutes after learning.	Comparison between 2 grid conditions (presence/ absence) on OLM.	Free-recall task: Replacement of objects in their original locations.	Object-location recall was more accurate with the availability of a holographic grid (p = .001).
Kroft et al. [42]	N = 40 aMCI patients: n = 15 (MA = 65.8 ± 11.14; ME = 16.2 ± 3.17).	Small-scale environment. Indoor environment (room with 10 different tables).	Real	High-semantic value items. 50 small objects (5 / table).	1 minute after learning.	Comparison between navigational OLM performance and computerized-reaching OLM performance.	Decision task: determine, between two given tables, on which one a	Better navigational than reaching OLM performance in both control (p < .001) and aMCI groups (p = .006), with no

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	Controls: n = 25 (MA = 62.68 ± 4.47; ME = 16.52 ± 1.69) Non-significant sex differences.						specific object was placed.	group differences in navigational OLM.
Kunz et al. [50]	N = 22 Epilepsy patients: (10 F; MA = 29.0 ± 10.0)	Small-scale VE. Outdoor environment (grassy plane with distal cues rendered at infinity). niVR (computerized task controlled by keyboard) device.	3D	High-semantic value items. 8 everyday objects (not specified).	Immediately after learning (no delay).	Characterization of HC activity during OLM task by iEEG* in 16 patients.	Free-recall task: replace objects in their original positions with later feedback provided.	Better OLM performances with more distinct preferred theta phases in cue representations (*ps* ≤ .044).
Ladyka-Wojcik et al. [39]	N = 30 HOA (22 F; MA = 75.82 ± 6.0; ME = 15.55 ± 2.49) One participant excluded for analyses. A subset of 20 participants completed additional blocks of the OLM task in a second session.	Small-scale VEs. 6 outdoor environments with 4 different landmarks at each cardinal direction. niVR (computerized task controlled by keyboard) device.	3D	High-semantic value items. 5 small everyday objects / environment.	Immediately after learning (no delay).	Comparison of matched vs. switched reference frames in OLM tasks (Allocentric Learning (AL)-Allocentric Testing (AT), AL-Egocentric Testing (ET), Egocentric Learning (EL)-ET, EL-AT) and their relation to MoCA* and NSQ* scores.	Free-recall task: object replacement in original positions using egocentric and allocentric references.	Lower accuracy in egocentric than allocentric frame (*p* < .001), in switch trials compared to non-switch (*p* = .04), and in EL-AT over AL-ET switching (*p* < .001). MoCA influenced errors in all conditions (*ps* < .01); NSQ affected errors in EL-ET and EL-AT (*ps* < .01).
Li et al. [45]	N = 19 HYA No other information.	Large-scale VE. Indoor environment (bedroom and living room connected by a hallway). iVR (nVisor SX111 HMD) device.	VR	Low-semantic value items. 8 coloured, geometric-shaped objects on different pieces of furniture (e.g., a cabinet).	Immediately after the previous trial (no delay).	Comparison between searching blocks of trials in accuracy of different OLM variables.	Visual searching task: locate objects within the virtual environment.	Improvements across blocks in the percentage of trials where subjects initially fixated the correct room side, (all *ps* ≤ .004).
Mazurek et al. [62]	N = 58 HYA: n = 26 (17 F; MA = 20; RA = 18–24) HOA: n = 32 (19 F; MA = 70; RA = 61–85)	Small-scale environment. Indoor environment (office room).	Real	High-semantic value items. 16 small everyday objects (8 / session).	2 hours after learning.	Comparisons between groups on OLM among object, location, and temporal recall in the task. Comparisons between OLM and other memory tasks (RAVLT*, object relocation) and subjective memory complaints (MAC-Q*, EMQ*).	WWW* task: recall objects, their locations, and the session in which they were hidden.	The HYA group demonstrated superior recall of the WWW combination than the HOA group (*p* = .043). Best performers in immediate word recall and retention in RAVLT remembered more WWW combinations (*ps* ≤ .018). Higher accuracy in object relocation tasks also improved WWW performance (*p* = .033). Elevated MAC-Q scores were associated with fewer WWW combinations completed (*p* = .037).
Méndez-López et al. [43]	N = 15 HYA: n = 15 (7 F; MA = 26.6; RA = 25–30) Children: n = 97 (MA = 6.9; RA: 5–9). 5, 6, 7, 8, and 9-year-old subgroups.	Small-scale environment. Indoor environment (room with boxes on the floor). AR device.	AR	High-semantic value items: Small everyday objects ranging from 1 to 5 per trial, based on difficulty level.	Immediately after learning (no delay).	Comparison of OLM performance between HYA and five child subgroups across varying difficulty levels.	Free-recall task: returning objects to their original positions.	Higher HYA group scores than 5- and 6-year-olds in overall performance (*p* = .02). Children underperformed compared to HYAs in two of the three hardest levels (*ps* <

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
								0.005). No gender differences.
Merhav and Wolbers [72]	N = 96 (48 F) 3 experimental conditions: EE* : n = 32. 2 subgroups: HYA: n = 16 (8 F; MA = 24.19 ± 0.72) HOA: n = 16 (8 F; MA = 71.5 ± 1.0) AE* : n = 32. 2 subgroups: HYA: n = 16 (8 F; MA = 24.0 ± 0.8) HOA: n = 16 (8 F; MA = 71.3 ± 1.1) CE* : n = 32. 2 subgroups: HYA: n = 16 (8 F; MA = 23.94 ± 0.8) HOA: n = 16 (8 F; MA = 71.8 ± 1.5)	Small-scale environment. Outdoor environment. iVR (Oculus DK 2 HMD) device.	VR	High-semantic value items. 20 small everyday objects.	2 hours after learning.	Explored group differences and the influence of environmental cues in the ability to update OLM information.	Free-recall task: displacement to the location where the object appeared for the last time.	More distance errors in HOA than in HYA ($p = .006$). HYA performed better than HOA when it was not required to update information ($p < .005$). More distance errors in both groups when updating was required ($ps \leq .024$). More distance errors in EE than in AE, and in AE than in CE ($ps < .005$). In both EE and AE, the greater the information updating deficit, the greater the relative proximity to the original locations ($ps \leq .023$).
Min-Park et al. [75]	N = 4 TLE patients (2 F; MA = 27.8 ± 8.7)	Small-scale VE. Outdoor environment (circular grassy plane). niVR (computerized task controlled by keyboard) device.	3D	High-semantic value items. 4 small everyday objects.	Immediately after learning (no delay).	Examined the link between intrahippocampal functional connectivity and OLM performance, as well as its correlation with movement during OLM task encoding (walking/stationary conditions) using iEEG.	Free-recall task: repositioning objects to their original locations.	Increased theta coherence between contralateral electrode pairs correlated with more distance errors in the OLM task ($p = .006$). There was a linear relationship between theta coherence and OLM performance in stationary conditions ($p = .002$).
Muñoz-Montoya et al. [37]	N = 46 HYA (26 F; men's MA = 24.65 ± 8.54; women's MA = 23.73 ± 7.71)	Large-scale environment. 2 building floors with proximal and distal cues. AR (Tango smartphone, Lenovo Phab 2 Pro) device.	AR	High-semantic value items. 8 small everyday objects (3 / first floor, 5 / second floor).	3 minutes after learning.	Explored gender differences in OLM and its relationship with various variables, including other OLM measures and neuropsychological assessments (verbal object-recall, map-pointing, self-reported strategies, anxiety values).	Free-recall task: replacement of objects in their original positions.	Men took longer to learn than women ($p = .049$). Fewer correctly recalled objects in verbal tasks linked to worse OLM accuracy ($p = .001$). Better map-pointing correlated with improved OLM accuracy ($p < .001$). More self-reported strategies led to faster OLM completion ($p = .028$). Higher anxiety increased learning time ($p = .007$).
Murcia-López and Steed [63]	N = 20 HYA (9 F; MA = 26 ± 5.3)	Small-scale. Indoor environment (empty room). iVR (HMD system, Oculus Rift DK2) and niVR (computerized task controlled by keyboard) devices.	Real VR 3D	High-semantic value items 3 identical small objects.	Immediately after learning (no delay).	Exploration of fidelity in iVR and niVR environments (low/ high detail); avatar in iVR and niVR environments (presence/absence), and the effect of level of immersion in the learning condition	Free-recall task: replace objects in their original positions in the real environment.	Lower mean placement error with avatar in low detail ($p = .026$). Lower error in iVR than niVR in high detail ($p = .002$). Least errors in real environment learning condition

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
						(iVR/niVR/ eal environment) on OLM performance.		followed by iVR, then niVR ($p < .001$).
Newman and McNamara [64]	HYA 6 experiments: Exp1: n = 25 (13 F; MA = 19.36 ± 1.04) Exp2: n = 20 (10 F; MA = 22.95 ± 5.41) Exp3: n = 23 (16 F; MA = 22.32 ± 2.56) Exp4: n = 22 (15 F; MA = 22.85 ± 2.83) Exp5: n = 24 (8 F; MA = 21.00 ± 1.87) Exp6: n = 22 (5 F; MA = 22.82 ± 4.49)	Small-scale VE. Outdoor environment [infinite ground plane with 4 (iVR) or 2 (niVR) landmarks]. Exp1 and Exp2: iVR (HTC Vive HMD and wireless controller) device. Exp3, Exp4, Exp5, and Exp6: niVR (computerized task controlled by keyboard) device.	VR 3D	Low-semantic value item (one yellow post/ trial).	Immediately after learning (no delay).	Comparison of OLM performance across three conditions in high-semantic (Exp1) and low-semantic (Exp2) landmarks: all-landmarks, 2 A landmarks, and 2B landmarks. Evaluation of high-semantic landmarks in three scenarios (Exp3): both-landmarks, close-landmark, and distant-landmark, with further assessments in aerial perspective (Exp4), learning and testing in aerial perspective (Exp5), and learning and testing in ground perspective (Exp6).	Free-recall task: Replace the object in its original position.	Greater accuracy with all landmarks than with 2B landmarks ($p = .001$) using high-semantic landmarks. Higher accuracy in both-landmarks than in close or distant landmarks ($ps \leq .004$) with high-semantic landmarks. Superior performance in both-landmarks condition with ground perspective learning/testing compared to aerial perspective, regardless of landmark type.
Picucci et al. [65]	N = 91 HYA. Subgroups: 1. Women: n = 46 (MA = 25.2 ± 1.4; RA = 23–27) 2. Men: n = 45 (MA = 26.4 ± 1.2; RA = 23–28)	Small-scale VE in an indoor setting, featuring a rectangular or square room with either all white walls or one blue wall, and four black floor patches. niVR (computerized task controlled by joystick) device.	3D	Low-semantic value item. One geometric-shaped object (yellow sphere).	2 seconds after learning (no distractor task).	Comparison of groups in OLM performance in five environments: rectangular room without landmarks (RWL), with near (RNL) or distant landmarks (RFL), and square room with near (SNL) or distant landmarks (SFL).	Four-alternative decision task: decide the location where the object was presented.	No gender differences in RWL; men outperformed women in rectangular and distant-landmark conditions ($ps < .05$), completing tasks faster with less walking in landmark conditions ($ps < .05$). Women took longer and traveled more in RWL ($ps < .01$); better performance with less time and distance in near versus far conditions ($ps < .01$).
Plancher et al. [78]	N = 51 HOA: n = 21 (17 F; MA = 76.95 ± 5.8; RA = 67–88) aMCI: n = 15 (8 F; MA = 78.06 ± 5.76; RA = 70–88) AD* : n = 15 (13 F; MA = 76.53 ± 5.51; RA = 69–88)	Large-scale outdoor VE. 2 urban VEs with 9 scenes each one. niVR (computerized task controlled by “real” car components, i.e., steering wheel, gas pedal, and brake pedal) device.	3D	High-semantic value items Large objects (e. g., a bench, a post office).	Immediately and 20 minutes after learning.	Comparison of OLM performance between groups. Exploration of active and passive encoding effects on OLM performance.	Verbal free-recall task: verbally situate the elements of each scene in relation to each object. Decision WWW task: whether a written sentence is correct or not.	AD and aMCI recalled less OLM information than HOA ($ps < .001$). Lower OLM recall scores in AD than in aMCI ($p < .01$). Higher OLM recall scores in the active encoding compared to passive ($p < .05$). AD showed lower scores in the decision task than HOA ($p < .001$). aMCI showed lower scores in the decision task than HOA, but higher scores than AD ($ps < .05$). What recognition in the decision task was higher than both Where and When recognition ($p < .001$).

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
Plancher et al. [66]	N = 72 HYA (32 F; MA = 22.23 ± 3.94)	Large-scale outdoor VE featuring a town with 12 varied scenes. niVR (computerized task controlled by "real" car components, i.e., steering wheel, gas pedal, and brake pedal) device.	3D	High-semantic value items. 36 large objects (e.g., buildings, cars; 3 objects/ scene).	Immediately after learning (no delay).	Comparison of OLM performance across three learning conditions: Passive (Pass), Planning (Plan), and Interaction (Int).	Free-recall task: replace objects by drawing an environment map. Cued-recall task: replace objects using a prepared 2D map. Decision task: determine if an object, its location, or the direction turn matches a previously seen scene.	Free-recall task: Higher performance in Plan and Int than Pass ($ps \leq .05$). Cued-recall task: Plan outperforms Pass ($p < .05$); men outperform women ($p < .001$). Decision task: no significant effects.
Postma et al. [67]	N = 115 Men HYA: n = 17 (MA = 29.2 ± 5.7; RA = 19–39) Women HYA: n = 19 (MA = 25.6 ± 5.5; RA = 19–39) Middle-aged men: n = 29 (MA = 51.2 ± 6.3; RA = 40–59) Middle-aged women: n = 25 (MA = 49.2 ± 4.7; RA = 40–59) Men HOA: n = 13 (MA = 70.1 ± 8.7) Women HOA: n = 12 (MA = 64.4 ± 3.4)	Large-scale environment. Outdoor environment (parking).	Real	High-semantic value object. A real car (participants' car).	Variable between participants.	Comparison of OLM performance across the different groups.	Free-recall task: replace the object on a 2D map. Verbal free-recall task: verbally describe the location of the object.	Free-recall task: older people made more map errors ($ps < .01$); younger men outperformed middle-aged men, opposite for women ($p < .01$). Verbal free-recall: women mentioned landmarks more ($p = .007$); men focused more on metrics ($p = .001$).
Quent et al. [30]	HYA 4 experiments: PilotExp: n = 16 (8 F; MA = 26.38 ± 3.52) Exp1: n = 25 (18 F; MA = 24.52 ± 2.83) Exp2A: n = 24 (11 F; MA = 25.0 ± 3.71) Exp2B: n = 72 (50 F; MA = 26.12 ± 6.53)	Small-scale VE. Indoor environment (kitchen). iVR (device not specified).	VR	High-semantic value items. 20 small everyday objects (12 kitchen objects and 8 nonkitchen objects).	Approximately 2.5 minutes after learning (with a distractor task).	Relationship between OLM and expectedness to find objects in specific locations, involving uniform expectancy values for kitchen and nonkitchen objects (Exp1) or a diverse range of object-location pairings (Exp2A and Exp2B).	Free-recall task: replace objects in their original location. Computerized decision task: decide, among three possible locations, where the given object was placed.	Memory shows a U-shaped pattern with event expectancy, with better recall for highly expected or highly unexpected object locations in both free-recall and computerized decision tasks.
Rosas et al. [76]	N = 16 TLE: n = 8 (5 F; MA = 50 ± 6.5) Controls: n = 8 (5 F; MA = 50.3 ± 7.6)	Small-scale VE. Indoor environment (square room). niVR (computerized task controlled by joystick) device.	3D	High-semantic value item. One big wood box (target) between 15 identical non-rewarded wood boxes (distractors)	Immediately after learning (no delay).	Comparison of OLM performance across groups.	Decision task: decide if the object was correctly located in a screenshot presentation.	Control group had faster reaction times than TLE group ($p < .008$); TLE made more errors identifying targets than control ($p < .001$). Both groups made more errors with targets than distractors ($p < .05$).
Sakamoto and Spiers [68]	N = 60 HYA (RA = 18–35). Subgroups: 1. NatJap* : n = 20 (10 F; women's MA =	Large-scale VE. Indoor environment (grocery store). niVR (computerized	3D	High-semantic value items. 16 small everyday objects (grocery items; 12 listed and 4	Immediately after learning (no delay).	Comparison of OLM performance across three cultural groups. Investigation of sex differences in OLM.	Free-recall task: replace objects in their original positions on a 2D map.	NatJap group had higher accuracy than JapAm and NorAm groups ($ps \leq .04$). Women recalled more locations and spent

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Table 1 (*continued*)

Study	Sample	Experimental setting	Visualization	Items	Retention interval	Experimental conditions	Test	Main results
	20.6 ± 1.3; women's ME = 14.5 ± 2.4; men's MA = 21.2 ± 1.9; men's ME = 14.9 ± 2.2) 2. JapAm* : n = 20 (10 F; women's MA = 21.5 ± 2.3; women's ME = 14.0 ± 1.9; men's MA = 22.1 ± 3.5; men's ME = 14.3 ± 2.3) 3. NorAm* : n = 40 (20 F; women's MA = 20.5 ± 3.3; women's ME = 14.0 ± 1.9; men's MA = 20.3 ± 2.0; men's ME = 14.0 ± 1.4)	task controlled by joystick) device.		incidental items).				more time collecting objects than men (*ps* < .001).
Shih et al. [69]	N = 90 HYA: n = 45 HOA: n = 45 No other information	Small-scale environment. Indoor environment (desktop with 3 surfaces).	Real	High-semantic value items. 24 small everyday objects (12 targets and 12 distractors)	Immediately after learning (no delay).	Comparison of OLM performance between groups and under different encoding conditions: Incidental (Inc) or intentional (Int).	Free-recall task: replace objects in their original positions in the environment after viewing a picture with the objects placed in it.	HYA group exhibited better OLM performance than HOA group (*ps* ≤ .017). Int outperformed Inc in most measures (*ps* ≤.035).
Spiers et al. [46]	N = 40 HYA (20 F, MA = 20.36 ± 2.72) No significant sex differences in age or educational level.	Large-scale VE. Indoor environment (grocery store). niVR (computerized task controlled by joystick) device.	3D	High-semantic value items. 16 small everyday objects (grocery items; 12 listed and 4 incidental items).	Not specified.	Exploration of sex differences in an OLM task.	Free-recall task: replace objects in their original positions on a 2D map.	Women showed higher accuracy and efficiency in item location than men (*ps* ≤.038) but took more time than men (*p* = .029).
Tenbrink et al. [70]	N = 37. HYA (32 F; MA = 22.8 ± 3.4). Subgroups: with / without time-limit (participants' distribution not specified)	Small-scale VE. Indoor environment (Collapsed room mock-up with simulated rubble). niVR (video-visualization) device.	3D	High-semantic value items. 8 big and small everyday objects.	Immediately after learning (no delay).	Comparison of OLM performance under time pressure conditions: with time limit versus without time limit.	Free-recall task: draw the environment and objects' locations on a blank sheet of paper.	Participants produced better drawings in the without time-limit condition compared to the time-limit condition (*p* < .01).
Zhou and Mou [71]	HYA 2 experiments: Exp1: n = 72 (36 F) Exp2: n = 49 (25 F) No other information	Small-scale VE. Outdoor environment (grassland with 4 cues). iVR (HMD with joystick) device.	3D	High-semantic value items. 4 small everyday objects.	Immediately after learning (no delay).	Investigation of environmental cue effects on wall removement in OLM across four conditions: circular wall and cone array (ConeCirc-ConeCir); 2 cone array arcs (ConeArc-ConeArc); 2 arcs of the circular wall (ConeArc-WallArc); 2 cone array and wall arcs (ConeArc-ConeWallCirc). Assessment of the impact of two cue types: boundaries (LB-B) and landmarks (LB-L), on OLM.	Free-recall task: replace objects in their original positions.	Memory declined from learning to testing phase in ConeArc-ConeArc and ConeArc-WallArc conditions (*ps* ≤.04). For LB-B, memory decreased for 3 and 4 object-locations from learning to testing (*ps* ≤.002), but no such interaction in LB-L condition.

Note: Sample = Sample characteristics; Experimental setting = Environmental features and devices utilized for evaluating object-location memory; Visualization= Method used to present information; Items = Number and type of items employed; Retention interval = Duration between participants' initial exposure to information and the subsequent testing phase; Experimental conditions = Primary goals and experimental conditions employed; Test = Type of object-location memory tasks employed; Main results = main object-location memory results. Abbreviations used: 2D = 2-dimensional; 3D= 3-dimensional; AD: Alzheimer's disease; AE: Allocentric encoding; alEC = Anterolateral entorhinal cortex; aMCI = Amnestic mild cognitive impairment; aMCI+ = aMCI with biomarker-positive studies; aMCI- = aMCI with biomarker-negative studies; aMCIu = aMCI without biomarker studies; AR = Augmented reality; BOLD = Blood oxygen level dependent; CE: Combined encoding; DurEp = Duration of epilepsy (in years); EC = Entorhinal cortex; EE: Egocentric encoding; eHD = early Huntington's disease stage; EMQ = Everyday memory questionnaire; Exp = Experiment; F = Female; fMRI = Functional magnetic resonance imaging; FOV = Field of view; GCA = Global cortical atrophy; HC = Hippocampus; HD = Huntington's disease; HMD = Head-mounted display; HOA = Healthy older adults; HYA = Healthy young adults; iEEG = Intracranial electroencephalography; IGE = Idiopathic generalized epilepsy; iVR = Immersive virtual reality; JapAm = Japanese Americans; KS = Korsakoff's syndrome; MA = Mean age ± standard deviation (in years); MAC-Q = Memory complaint questionnaire; ME = Mean education ± standard deviation (in years); MoCA = Montreal cognitive assessment; MRI = Magnetic resonance imaging; MRT = Mental rotation task; MTLA = Medial temporal lobe atrophy; NatJap = Native Japanese; niVR = Non-immersive virtual reality; NorAm = North Americans; NSQ = Navigation strategies questionnaire; OLM = Object-location memory; PAL = Paired associates learning; pHD = premanifest Huntington's disease; PHG = Parahippocampal gyrus; RA = Range age (in years); RAVLT = Rey auditory verbal learning test; RBMT-3 = Rivermead behavioral memory test - third edition; RCFT = Rey-Osterrieth complex figure test; ROIs = Regions of interest; SDMT = Symbol digit modalities test; TLE = Temporal lobe epilepsy; uATL = Unilateral anterior temporal lobectomy; uHIPP = Unilateral hippocampal atrophy; VE= Virtual Environment; VR= Virtual Reality; WWW = What-Where-When.

exclusively in male participants [34,58]. Additionally, some studies included healthy young adults together with children [43], middle-aged individuals [67], and healthy older adults [60,62,67,69,72]. Only two studies focused exclusively on OLM performance in healthy older adults [39,73].

Out of the 44 studies reviewed, 12 utilized clinical samples, encompassing a range of conditions: patients with epilepsy [48–50, 74–76], patients with amnestic MCI (aMCI) [20,42,77,78], patients with AD [78], patients with HD [23,48] and patients with Korsakoff's syndrome (KS) [79]. Among these, eight studies focused on clinical populations of young and middle-aged individuals [23,48–50,74–76,79]. The remaining four studies focused on OLM performance in older clinical populations [20,42,77,78]. Notably, across all these studies, there was a consistent representation of both male and female participants.

3.3. Main objectives of the reviewed studies

Nearly half of the reviewed studies focused on group differences in OLM performance [20,23,37,42,43,46,48,49,52,54,55,59,60,62,65, 67–70,72–74,76–79]. Within this subset, nine studies investigated how OLM execution varied between clinical groups and healthy controls [20, 23,42,48,49,76–79], and seven compared OLM performance across different clinical groups [20,23,48,49,74,77,78]. The research by Barhorst-Cates et al. [52] uniquely assessed OLM performance in the context of varying degrees of simulated field of view (FOV) loss. Additionally, 11 studies delved into gender differences in OLM [37,43,46,54, 55,59,60,65,67,73,74], while six studies aimed at understanding the impact of age on OLM [43,60,62,67,69,72]. Moreover, one study [68] specifically focused on the influence of cultural factors on OLM performance among healthy participants.

A notable 11.36 % of the reviewed studies focused on examining the impact of environmental features of OLM performance [53,63,65,71, 77]. Within this group, four articles specifically investigated how the shape and detail of the environment affect OLM [63,65,71,77]. Two studies were dedicated to understanding the differences in OLM performance between real and virtual environments, including comparisons between niVR and iVR devices [53,63]. Additionally, one study explored the variations in OLM performance between indoor and outdoor settings [53]. Similarly, a quarter of the studies delved into the effects of environmental cues or landmarks on OLM [34,54,55,61, 63–65,71,72,77,79]. These studies varied in focus, with some examining the impact of different cues such as positional or directional, high-semantic or low-semantic, and landmarks or boundaries [34,54,55, 64,71,77]. Others assessed the influence of the presence of cues [61,63, 72,79] or their location within the environment, such as the proximity of distant or close landmarks [64,65]. Furthermore, three of the reviewed articles specifically aimed at understanding the effects of perspective or frames of reference on OLM performance [39,64,79].

Several studies were dedicated to exploring the impact of various object characteristics, as well as the effect of different learning, searching and locomotion conditions on OLM performance [30,33,36, 45,52,53,57,66,69,75,78]. Specifically, three of these studies focused on the relationship between gaze duration gaze on objects and OLM performance [33,36,57]. Additionally, seven studies delved into the strategies employed by subjects in searching and learning, and how these strategies affect OLM execution [33,36,45,52,66,69,78]. Furthermore, three works studied the effect of different locomotion techniques on OLM performance [51,52,75]. In particular, the research by Quent et al. [30] aimed to understand the association between the subjects' expectations and their performance in OLM tasks. The study conducted by Shih et al. [69] focused on exploring how different encoding strategies influence OLM. Another primary objective among the reviewed studies was to examine the effect of varying time intervals on OLM recall [53, 79].

A significant portion of the studies focused on investigating the relationship between OLM performance and brain structural or functional correlates. Among these, four studies utilized Magnetic Resonance Imaging (MRI) [20,23,49,79] as their primary investigative tool. Four studies also employed functional MRI (fMRI) to explore this relationship [40,56,58,74]. Additionally, two studies conducted their research using intracranial Electroencephalography (iEEG) [50,75].

Complementing these neuroimaging and electrophysiological approaches, some articles delved into the association between OLM performance and other neuropsychological tasks [33,37,39,42,49,62,79]. These studies also extended their research to include subjective cognitive abilities [37,39,62] and the influence of emotional states on OLM performance [37,56,70].

3.4. Experimental setting, items and conditions

Most studies assessed OLM through 2D or 3D computerized tasks, with 21 employing niVR devices along with controllers [23,34,39,46, 48–50,53–56,58,63–66,68,75–78] and four assessing OLM using a passive video-visualization task [40,70,74,79]. The assessment of OLM in real-world settings was conducted in 13 studies [33,37,42,43,52,59–63, 67,69,73], with three of them incorporating AR devices [37,43,61]. In 10 of the 44 reviewed studies, iVR devices were utilized [20,30,36,45, 53,57,63,64,71,72].

In the reviewed studies, a significant majority (77.27 %) utilized items of high-semantic value, such as everyday objects [20,23,30,33,34, 36,37,39,40,42,43,46,48–50,52,53,55–58,62,63,66–72,75,76,78,79]. Of these, 25 studies focused on small, hand-graspable objects [20,23,30, 33,34,36,37,39,42,43,46,48,49,53,56,57,62,63,68–72,75,79], while 11 studies investigated OLM tasks involving larger objects [36,52,53,55,57, 58,66,67,70,76,78]. However, two studies did not specify the size of the objects used [40,50]. Conversely, 31.82 % of the studies employed items with low semantic value (e.g., geometric figures) [23,45,48,49,54,55, 59–61,64,65,73,74,77]. The number of object-locations to be recalled varied considerably across studies. Eight studies specifically focused on the recall of just one object's position [54,55,64,65,67,76,77,79]. Nearly half of the studies required participants to remember the position of four to eight items per trial [20,34,36,39,42,43,45,50,52,53,55,56, 58,61,62,70,71,74,75]. The highest number of object-locations presented in a single trial for recall was 32 [55].

In the analyzed studies, most utilized small-scale environments that did not require memorization of routes [20,23,30,34,36,39,42,43,48–50,53–55,57–65,69–77,79]. In contrast, a subset of the studies focused on large-scale environments that involved learning routes [33,37,40,45,46,52,56,66–68,78]. Regarding the type of environment, indoor spaces were employed in 21 studies with small-scale environments [23,30,36,42,43,48,49,53,57–63,65,69,70,73,74,76] and in eight studies with large-scale environments [33,37,40,45,46,52,56,68]. On the other hand, outdoor spaces were used in 13 studies featuring small-scale environments [20,34,39,50,53–55,64,71,72,75,77,79] and in four studies with large-scale environments [40,66,67,78].

The variety of OLM tasks employed in different studies was quite broad. Many studies utilized free-recall tasks, which included: object replacement in the original environment (i.e., returning objects to their initial positions within the same setting) [20,30,33,34,37,43,45,57,59–61,64,71,73,75,79]; object placement on a 2D map or blank paper (i.e., participants were required to place objects on a two-dimensional representation, such as a map or blank sheet) [40,46,53,58,66–68,70]; recall with altered perspectives (i.e., tasks where object locations had to be recalled despite changes in the observer's viewpoint) [39,54,55]; and object replacement with supportive elements (i.e., using aids like cues, landmarks, or feedback to assist in object placement) [23,36,48–50,79]. Other free-recall tasks included: object replacement in a real environment (i.e., independent of whether the learning condition was in a real or virtual setting) [63]; object replacement in a real environment after viewing a static image [69]; displacement of the participant to the location where the object previously appeared [72]; verbal description of object locations (participants described the locations of objects verbally instead of placing them) [67,78]. Decision tasks were also commonly used for OLM assessment. These included: object decision tasks (i.e., decisions about objects, like identifying which object was in a particular location or closest to a specific landmark) [20,53,55,74]; location decision tasks (i.e., deciding the placement of a given object) [30,42,52,65,77]; combined object and location decision tasks (i.e., participants decide, often using static pictures, whether an object was correctly placed) [56,66,76]. Additionally, two studies used a What-Where-When (WWW) task, requiring the recall of objects, their locations, and their temporal characteristics [62,78].

Regarding the retention intervals or delayed periods in the OLM studies, a significant portion assessed OLM immediately after the learning phase. Specifically, more than half of the studies conducted the OLM assessment with no delay or distractor task [20,34,39,43,45,50,52–55,57,59,60,63–66,68–71,73,75–79]. On the other hand, 12 studies incorporated a brief or unspecified-duration distractor task or used a time interval of three minutes or less [23,30,33,36,37,42,48,49,58,61,74,79]. Only six studies assessed OLM after longer periods, employing retention intervals of 20 minutes [78], 30 minutes [40], two hours [62,72], one day [56], and two weeks [53].

3.5. Main OLM results

3.5.1. OLM performance in clinical samples

Studies investigating OLM among patients with either aMCI or AD generally showed that these patients exhibited poorer performance in various free-recall and decision-based OLM tasks than healthy participants [20,77,78]. Nevertheless, one study reported comparable performance levels in aMCI patients and healthy controls on interactive OLM tasks [42]. Additionally, patients with Temporal Lobe Epilepsy (TLE) [49,76], HD [23,48], and KS [79] also demonstrated poorer OLM performance when compared to control groups.

Some studies focused on OLM performance within specific clinical subgroups. For instance, patients with AD performed worse than those with aMCI [78]. Among the latter, the study by Castegnaro et al. found better OLM scores in aMCI participants who tested negative for biomarkers compared to biomarker-positive participants [20]. However, no significant differences in OLM scores were found between aMCI participants with either a single domain or multiple domains [77], between patients with right versus left TLE [74], between TLE patients with unilateral hippocampal atrophy and those who underwent unilateral anterior temporal lobectomy [49], or between premanifest and manifest HD patients [23]. Similarly, comparable OLM performance was noted when contrasting different clinical groups, such as TLE and HD patients [48]. The study by Barhorst-Cates et al. [52] reported no significant differences in OLM performance between individuals with mild and severe FOV restrictions. Furthermore, other research highlighted a correlation between a longer duration of epilepsy and poorer OLM performance [74].

3.5.2. Sex, age, and cultural differences in OLM

Investigations of sex differences in OLM tasks revealed that men generally performed better in free-recall tasks and took less time to complete tasks when provided with cues, landmarks, or a 2D map for object replacement [46,54,55,59,65,66,68]. Additionally, men were found to resolve OLM tasks faster than women in the absence of landmarks [65]. The study of Postma et al. [67] observed that women more frequently referred to environmental landmarks, while men relied more on metric cues. However, three studies reported superior OLM performance in women than in men [37,46,68], and other three studies found no significant sex differences [43,73,74].

Regarding age differences, studies noted poorer OLM performance in older adults compared to younger or middle-aged adults [60,67,69,72]. Moreover, these differences were found when other cognitive abilities, such as the updating of OLM information, were not required, even though both age groups performed worse when the updating was required [72]. Additionally, the study of Fernandez-Baizan et al. [60] also showed an interaction between sex and age, with better OLM performance in young men than in older men, and in young women than in older women. Mazurek et al. [62] did not find age differences in overall OLM performance but found that older adults recalled fewer complete WWW combinations than younger adults. When comparing young with middle-aged adults, better OLM performance was noted among men but not among women [67]. Mendez-Lopez et al. [43] observed that young adults generally outperformed 5–6-year-old children, and children aged 5–9 showed lower accuracy in more difficult levels of an OLM task than young adults. The study by Sakamoto and Spiers [68] is unique in exploring cultural effects on OLM, finding that native Japanese participants performed better than both North American and Japanese American participants.

3.5.3. Neuroimage and electrophysiology of OLM performance

The use of neuroimaging techniques revealed a positive correlation between the volumes and activations in MTL regions, such as the hippocampus, entorhinal cortex, and parahippocampal gyrus, and the accuracy of responses in both clinical and non-clinical samples [20,56,58,74]. Specifically, the research by Evensmoen et al. [58] identified a link between higher activations in the posterior hippocampus and entorhinal cortex with improved accuracy in OLM tasks. This study also found that increased activations in the intermediate hippocampus and both the intermediate and posterior entorhinal cortex were associated with less precise object replacement. Additionally, Hampstead et al. [40] discovered a relationship between activations in the anterior left hippocampus and OLM task performance.

Contrastingly, some studies found no significant relationship between the volumes of the MTL or the presence of cortical atrophy and OLM performance [23,49,79]. Moreover, other brain regions, including the occipitoparietal cortex, dorsolateral prefrontal cortex, and both the dorsal and ventral visual streams, have been implicated in the process of OLM [40,74].

Electrophysiological studies observed an association between hippocampal theta cycles and OLM performance in patients with epilepsy [50,75]. Specifically, iEEG recordings during OLM recall demonstrated stimulus-specific hippocampal theta phases that indicate reactivation of spatial location [50].

3.5.4. Associations between OLM performance and other cognitive functions and emotional states

Research exploring the relationship between OLM performance and other neuropsychological tasks has revealed several interesting associations. Studies have found that better performance in navigational OLM tasks correlates with improved results in various cognitive and spatial tasks, such as navigational tasks [48,49], mental rotation tasks [79], floor-plan drawing tasks and map-pointing tasks [37,48,49], reaching OLM tasks [42,62], visuospatial learning and memory tasks [48], verbal learning and memory tasks [33,37,62], psychomotor speed tasks [48], as well as general cognition [39]. However, Janzen et al. [79] found no correlation between OLM performance and the Rivermead Behavioral Memory Test (RBMT), which evaluates everyday memory skills. Interestingly, the research by Kroft et al. [42] highlighted a generally superior performance in both aMCI and control groups in navigational OLM tasks compared to reaching OLM tasks.

The relationship between OLM performance and subjective cognitive abilities, as well as emotional states, has been explored in various studies. The use of self-reported strategies during OLM tasks was associated with reduced time spent on these tasks, indicating more efficient performance [37]. Subjective memory complaints were linked with poorer OLM performance [39,62]. Interestingly, one study found no correlation between OLM performance and scores on the Everyday Memory Questionnaire, which assesses memory failures in daily life [62]. Additionally, higher levels of anxiety and stress were found to impact OLM performance negatively [37,70]. The study by Chan et al. [56] observed that negative emotional valences of items, as well as a constant schedule of emotional events, led to increased response speed in OLM tasks compared to positive emotional valences and intermittent scheduling of emotional events, suggesting that the emotional context and the regularity of emotional stimuli can influence the speed of responses in memory tasks.

3.5.5. Environmental characteristics and OLM performance

Results of the studies that explored OLM through different real or virtual environments showed that participants generally showed better OLM performance in real environments compared to both iVR and niVR [63]. When comparing iVR and niVR devices, better OLM performance was noted in high-detail environments using iVR, but this advantage was not found in low-detail environments [63]. Using a virtual joystick in niVR resulted in poorer performance than using niVR with a gyroscope or an iVR headset [53].

The influence of environmental shape on OLM performance is noteworthy. Men generally outperform women in rectangular environments, particularly when landmarks, whether near or far, are present [65]. This gender difference in performance, however, is not evident in square environments [65]. Furthermore, altering the overall shape of the environment during testing is likely to affect recall abilities adversely [71].

Regarding the use of cues or landmarks, research indicates enhanced OLM performance when landmarks are present compared to their absence. Furthermore, utilizing all available landmarks leads to better results in both real and virtual environments than when some are omitted [61,64,79]. The type of cue also impacts OLM execution, with better performance observed using nearby or close landmarks as opposed to distant ones [64,65]. Worse scores in OLM were shown when removing boundaries than when removing landmarks [71]. In studies examining the use of positional versus directional landmarks, gender-specific effects were noted in the latter: men showed decreased OLM performance when directional landmarks were removed [54,55], and they worsened overall with the removal of positional cues [55]. Differences between these two types of landmarks were also evident in healthy versus clinical populations. While healthy participants showed similar execution with both positional and directional landmarks, patients with aMCI exhibited poorer OLM performance using directional landmarks [77].

Another variable in VR environments is the presence of an avatar. Including an avatar led to improved OLM outcomes in low-detail environments, although this was not the case in high-detail environments [63]. Interestingly, Doeller and Burgess [34] explored OLM performance using two distinct cues: intramaze landmarks and environmental boundaries. Their findings suggest that intramaze landmarks involve associative learning, whereas environmental boundaries are linked to incidental learning.

Frames of reference employed could also affect OLM performance, finding better scores in allocentric than egocentric frames of reference [39,72]. Furthermore, one study showed better performance when both egocentric and allocentric frames of reference could be used to solve the task [72]. The study of Janzen et al. [79] observed no differences in OLM performance between congruent frames of reference, where both egocentric and allocentric strategies successfully solve the task, and incongruent frames of reference, where only the allocentric strategy is successful. Complementary to this, the study of Merhav et al. [72] found that deficits in updating OLM information were positively correlated with greater relative proximity to the locations of the original objects, irrespective of the use of egocentric or allocentric strategies. Regarding perspective shifting, supra-optimal performance was observed when a target location was learned and tested from a ground-level perspective, and all landmarks were available during object replacement, compared to an aerially-level perspective [64]. OLM scores were negatively affected by shifting frames of reference, particularly when transitioning from an egocentric frame of reference during the learning phase to an allocentric one during testing [39].

3.5.6. The influence of object-specific characteristics on OLM performance

Regarding object characteristics and OLM performance, studies found that longer gaze durations improved OLM performance, with higher benefits for big objects than for small objects and for distractors than for target objects [36,57]. The study of Li et al. [45] explored learning across trials and observed OLM improvement when participants first fixated on the environment side and surfaces on which the objects were located. Chai et al. [55] found no association between OLM execution and the number of objects employed in the task. On the other hand, Rosas et al. [76] found poorer OLM performance with targets than with distractors in both patients with TLE and healthy adults.

Studies also found longer object fixations on objects considered semantically relevant compared to those considered irrelevant [33]. Similarly, objects that align with a subject's expectations are more effectively recalled than those that are unexpected or incongruent with their anticipations [57]. Interestingly, the study by Quent et al. [30] found a U-shaped curve in the relationship between expectancy and recall. This curve indicates that both the most and the least expected objects were remembered better than those with a moderate level of expectancy. The interplay between an object's relevance and the participant's interaction with it during the search process is also noteworthy. Relevant objects that were not previously recalled are remembered more quickly, while irrelevant objects that were previously recalled are remembered more slowly in tasks requiring recollection compared to tasks without a recollection component [33].

3.5.7. The influence of learning strategies and locomotion on OLM

The influence of searching or learning strategies on OLM performance has been a key focus in several studies. Higher OLM scores were associated with strategies that require participants' greater involvement or active engagement [36,66,78]. Similarly, intentional encoding, where participants consciously focus on memorizing object locations, showed better OLM performance than incidental encoding [69]. However, the study of Barhorst-Cates et al. [52] observed no differences in OLM performance between active and passive searching.

Regarding the effects of locomotion on OLM, it has been observed that object replacement is generally more accurate when participants are stationary compared to when they are moving, and these results are reflected in brain activity [75]. Buttusi and Chittaro [53] found that different types of locomotion in VR environments can influence OLM performance. For instance, using a steering displacement seemed beneficial for OLM with an iVR headset and non-immersive niVR controlled by a gyroscope. In contrast, a teleport displacement was more advantageous for OLM with niVR controlled by a virtual joystick. Interestingly, the study of Barhorst-Cates et al. [52] found no differences in OLM performance between active and passive locomotion.

3.5.8. The influence of retention interval on OLM performance

Retention interval effects were also explored, finding that, compared to immediate recall of objects, the addition of delay intervals produced lower OLM scores in both indoor and outdoor virtual environments [53, 79]. Healthy adults performing an OLM task with a 10-second retention interval benefit from the use of cues under these delay conditions, whereas patients with KS do not [79].

4. Discussion

Spatial memory, particularly navigational OLM, has received comparatively less attention than other memory systems. This memory process, primarily mediated by the MTL, enables us to recall and recognize the locations of previously encountered objects, facilitating efficient daily functioning. This systematic review thoroughly investigated diverse methodologies employed to explore navigational OLM with the primary objective of presenting a comprehensive overview of the current state of research, encompassing key findings and insights.

From the reviewed studies, it is evident that a significant portion of non-clinical research has predominantly centered around healthy young adult populations, with some studies specifically examining OLM exclusively in males [30,33,34,36,37,40,43,45,46,52–59,61–71]. Contrastingly, a uniform representation of both male and female participants was observed across all clinical studies. The non-clinical studies reviewed that focused solely on male participants for OLM assessment failed to justify this exclusive focus, despite existing reviews and meta-analyses [80] showing sex differences in various episodic memory tasks, including OLM. Furthermore, findings indicate that women generally perform better than men in these tasks, with men exhibiting greater performance variability [80,81]. These previous findings highlight the importance of including both sexes in OLM research to achieve more robust conclusions about OLM functions. Additionally, the reviewed studies highlight the need to explore OLM in both males and females, considering the observed correlations between sex, landmark use, and OLM performance. Men tend to outperform women in the presence of cues or landmarks [54,55,59,65,66], while women excel when landmarks are absent [37,46,68]. This discrepancy may be attributed to men relying more on the spatial representation of landmarks and women relying more on verbal representation [82]. Interestingly, studies involving children [43] and patients with TLE [74] found no significant sex differences in OLM, suggesting that age and clinical conditions may modulate the relationship between sex and OLM. Moreover, two studies reported better OLM performance in women but with longer execution times than men [46,68], indicating a potential dissociation between accuracy and the time spent resolving an OLM task.

Interestingly, certain non-clinical studies extended their focus to include a diverse range of age groups, incorporating children [43], middle-aged individuals [51], and healthy older adults [39,60,62,67,69, 72,73]. This helps researchers to gain insights into how OLM functions and evolves at different life stages. Studying children provides an understanding of the developmental aspects of OLM. Incorporating middle-aged individuals adds another layer of complexity, considering that cognitive abilities may undergo changes during this life stage. However, the inclusion of healthy older adults is crucial as it will allow researchers to explore how OLM performance and participants' strategies in navigational environments may change with age, as may other similar memories [83]. This is particularly relevant given the importance of OLM for daily activities [84]. Studying OLM in older adults may also provide valuable information for understanding age-related cognitive decline or identifying factors contributing to maintaining robust OLM in later life. However, no studies have comprehensively assessed the entire lifespan; instead, they focus on specific age groups. Incorporating a diverse range of age groups within the same study allows us to discern the dynamic nature of cognitive processes across various life stages. This approach could contribute to a more comprehensive understanding of the factors influencing OLM and its implications for individuals across different ages. Nevertheless, while including a range of age groups is beneficial for understanding age-related decline in OLM, it presents a challenge in designing tasks that are appropriate across lifespan and clinical conditions. The simplicity of tasks designed for older adults or individuals with MCI may prove inadequate for younger or healthier individuals, resulting in ceiling effects. Conversely, tasks designed for younger and healthier individuals may be too challenging for older adults or participants with MCI, resulting in floor effects. Thus, it is recommended that future research consider the development of adaptive or scalable tasks that can be appropriately adjusted for different age groups and cognitive abilities. This approach would help to provide a more accurate assessment of OLM across the lifespan, while reducing the likelihood of ceiling and floor effects.

The studies that involved clinical samples cover various conditions such as aMCI, AD, TLE, HD, and KS [20,23,42,48–50,74–79], demonstrating altered OLM performance in these disorders. Similarly, OLM executions in older adults were worse than in young or middle-aged adults [60,67,69,72]. In these clinical conditions, as well as in healthy aging, alterations in the MTL have been previously documented [85,86]. These changes align with findings from neuroimaging and electrophysiological studies [20,40,50,56,58,74,75]. Intriguingly, when comparing clinical subgroups' OLM performance, no significant differences were found [23,48,49,52,74,77], suggesting a potential impairment in OLM regardless of the specific location of MTL lesions. This observation is consistent with earlier research [87], suggesting a broader impact on OLM abilities that transcends the exact lesion site within the MTL.

OLM in navigational environments was primarily assessed by 2D or 3D computerized tasks, utilizing high-semantic value items, such as everyday objects, and focused on small-scale environments that did not require memorization of routes, using free-recall tasks with no delay or distractor task. Notably, studies incorporated niVR devices along with controllers [23,34,39,46,48–50,53–56,58,63–66,68,75–78] or iVR devices [20,30,36,45,53,57,63,64,71,72]. Only a smaller proportion of studies assessed OLM in real-world settings [33,37,42,43,52,59–63,67, 69,73], with some incorporating AR devices [37,43,61]. The predominant use of high-semantic value items [20,23,30,33,34,36,37,39,40,42, 43,46,48–50,52,53,55–58,62,63,66–72,75,76,78,79] and the reliance on computerized tasks, especially niVR devices, suggests a focus on controlled and reproducible experimental conditions. The diversity of methodologies highlights the need for standardization to ensure a comprehensive understanding of OLM in navigational environments across contexts and technologies. This can be achieved by making the testing environment as comparable as possible; reporting scoring systems, task specifics, and outcome measures; and establishing clear protocols for task administration, including instructions for participants, task duration, and allowable interactions, to minimize variability and facilitate replication studies. Also, the predominant focus on small-scale environments [20,23,30,34,36,39,42,43,48–50,53–55,57–65,69–77, 79] suggests a common trend toward investigating OLM in simpler spatial contexts. This might be attributed to the controlled nature of small-scale settings, facilitating reproducibility and experimental precision. In contrast, the subset of studies addressing large-scale environments [33,37,40,45,46,52,56,66–68,78] aimed to capture navigation and memorization of routes as integral aspects of OLM in the real world.

A significant portion of the reviewed studies investigate the influence of environmental features on OLM performance. Their findings highlight the considerable attention given to understanding how environmental factors and cues contribute to OLM outcomes in various contexts. Articles specifically explored how the shape and detail of the environment impact OLM [63,65,71,77]. Additionally, studies delved into the effects of environmental cues or landmarks on OLM, examining various cues such as positional or directional cues [54,55,77], high-semantic or low-semantic cues [64], and boundaries or landmarks [34,71]. Some studies focused on the presence or location of cues, including the proximity of landmarks [61,63–65]. The presence, removal, and proximity of landmarks impact OLM, suggesting that the ease of processing and recalling object locations is influenced by the presence of nearby landmarks compared to their absence or the presence of distant landmarks, independently of sex [61,64,65,79]. Articles specifically aimed at understanding the effects of perspective or frames of reference [39,64,72,79] reveal that the influence of frames of reference on OLM performance is notable, with research generally showing better outcomes when using an allocentric frame of reference than an egocentric one [39,72]. This suggests that individuals tend to perform better in OLM tasks when they rely on external references in the environment rather than their own perspective or position. On the contrary, Janzen et al. [79] found no significant effects regarding the congruence of frames of reference in OLM execution, suggesting that allocentric strategies alone are sufficient for resolving an OLM task. Other findings emphasize the significance of maintaining consistent perspectives during both learning and testing phases for optimal memory recall. The research indicates that OLM scores are negatively affected when there is a shift in frames of reference [39,64], leading to a disconnection between the learned and recalled environments and posing challenges for accurate memory retrieval.

In studies investigating OLM across various real and virtual environments, notable differences in performance were observed based on the type of environment and the devices used [53,63]. Findings underscore the impact on OLM of the environment's realism and the interaction methods within virtual settings. They highlight the importance of considering the design and interface of VR technologies when they are used for tasks involving spatial memory and learning [53,63]. The realism and physical engagement offered by real environments might facilitate better spatial learning and memory retention, with the studies showing fewer OLM errors in real environment conditions than in both iVR and niVR conditions [63]. The quality and richness of the virtual environment play a crucial role in OLM performance, particularly for immersive technologies [64,79]. There was also a difference in OLM performance when comparing niVR with different control mechanisms, showing that the more intuitive and natural interaction with the environment provided by gyroscopes and iVR headsets [53] might better support spatial memory processes.

The type and size of objects employed in the OLM tasks, as well as the duration of objects' visual fixation, also modulate OLM performance: the longer the gaze durations, the higher the benefits in OLM performance, especially in large and distractor objects [36,57]. This might be attributed to the more challenging processing of these objects, requiring a longer gaze duration.

Furthermore, numerous studies have underscored the influence of objects' semantic relevance and subjects' expectancy on OLM. Draschkow and Võ [33] propose that individuals tend to focus on objects they find meaningful, potentially improving memory retention for these items, highlighting the complex dynamics between relevance, prior recall, and memory performance, and emphasizing the importance of both the intrinsic properties of the objects and the context of their retrieval. They also emphasize the role of cognitive schemas and expectations in memory processing [57], where congruence with pre-existing knowledge facilitates better recall. Highly predictable and highly surprising items stand out in memory, possibly due to their enhanced salience or distinctiveness [30].

The way that subjects search and learn objects' locations, as well as the way they move through the environment in navigational OLM tasks, also affects OLM performance. Relative to searching and learning processes, the studies suggest that the more actively involved a person is in these processes, the better their OLM performance tends to be [36,66,78]. Similarly, studies also highlight the importance of active, deliberate memorization strategies in enhancing OLM [69]. Locomotion techniques employed within different studies point to a reduced cognitive load when stationary, allowing for better focus on memorizing object locations [75]. These findings are supported by brain activity patterns, indicating a neurological basis for this phenomenon [75]. Moreover, not only subjects' movement affects OLM performance, but also the type of movement depending on the device employed, highlighting the ways in which different VR navigation methods can affect OLM performance [53]. However, Barhorst-Cates et al. [52] observed no significant differences in OLM performance between active and passive locomotion, adding another layer of complexity to the understanding of how movement and engagement in the learning environment influence OLM performance. This suggests that the connection between locomotion and OLM is complex and may be influenced by factors such as the task's nature (e.g., in decision tasks with lower cognitive load, locomotion techniques may have a lesser impact on OLM performance) or the environment (e.g., subjects' movement in real environments may exert less influence on OLM performance than in virtual environments).

Studies on the effects of retention intervals on navigational OLM performance aimed to elucidate how the time elapsed between learning and recall phases impacts the accuracy and efficiency of OLM. Such studies are crucial in revealing the temporal dynamics of memory consolidation and retrieval processes. These studies reveal that immediate recall yields better results than delayed recall [53,79], attributed to natural memory decay [88]. Complementarily, cues, as effective memory aids, can help maintain or reactivate OLM after a short delay, although this benefit may not extend to all populations [79]. In populations with severe memory impairments, cues during a delay did not improve OLM performance. Overall, these findings highlight the significant impact that retention intervals can have on OLM and the potential role of cues as compensatory mechanisms to support memory in such conditions. They also underscore the variability in how different populations, especially those with memory impairments, respond to these memory aids.

As expected, associations were observed between navigational OLM and other cognitive abilities, including spatial abilities, visuospatial and verbal learning and memory abilities, psychomotor speed and general cognition [37,39,42,48,49,62,79]. These associations reflect the intricate interplay among different cognitive functions. Notably, Janzen et al. [79] found no correlation between OLM performance and RBMT. This discrepancy may be partly explained by the passive video-visualization nature of the OLM task employed, potentially resulting in lower ecological validity for OLM assessment compared to more interactive tasks. This type of task may also have a weaker connection to the RBMT, designed to measure everyday memory. Conversely, the observation of superior performance in navigational compared to reaching OLM tasks [42] suggests a distinct cognitive processing or difficulty level between these types of OLM tasks.

OLM performances were associated with self-reported subjective cognitive complaints [39,62]. Additionally, higher levels of anxiety and stress were linked to poorer OLM outcomes [37,70], consistent with results from prior studies [89]. These findings highlight the intricate connections between cognitive strategies, subjective memory perceptions, emotional states and OLM performance. Understanding these relationships can provide a more comprehensive view of how memory functions in different emotional and cognitive contexts.

The application of neuroimaging techniques in the examined studies offers valuable insights into the neural underpinnings of OLM performance. These findings hold potential implications for clinical applications aimed at addressing neuropsychological disorders that manifest OLM memory impairment among their symptoms. The neuroimaging and electrophysiological findings collectively highlight the intricate and distributed neural network involved in OLM. The positive correlations observed between the volumes and activations in MTL regions, such as the hippocampus [40,58], entorhinal cortex [58] and parahippocampal gyrus [56,74], and the accuracy of responses highlight the pivotal role of these structures in OLM processes. Notably, variations in activations within different segments of the hippocampus and entorhinal cortex were linked to specific aspects of OLM task performance [40,58]. However, contrasting findings, where some studies found no significant relationship between MTL volumes or cortical atrophy and OLM performance, highlight the complexity of the neural mechanisms involved in OLM.

This review acknowledges certain limitations. A primary concern is the possible omission of specific research articles that, while assessing navigational OLM, might have chosen to describe their tasks using broader terms such as 'spatial memory,' resulting in their exclusion from this analysis. Secondly, the considerable heterogeneity in OLM assessment methods, including decision tasks and free-recall tasks with and without cues, coupled with the diverse array of environments and objects utilized across studies, makes it difficult to draw general conclusions about the functioning of OLM. However, the implications of this review for the understanding of the neuropsychological assessment of OLM are substantial.

This review makes a significant and innovative contribution to the existing body of work by providing an updated, comprehensive overview of the methods, devices, and factors that influence navigational OLM. By synthesizing findings from a diverse range of studies, we provide new insights into the assessment of spatial memory in both real and virtual environments and highlight key areas for future research and practical application.

We can conclude that there is a prevalent use of niVR devices for assessing OLM in navigational environments, often employing high-semantic value items. However, some studies incorporate iVR and real-world settings. The existing studies on navigational OLM predominantly focus on healthy young adults. This is a limitation in the generalizability of findings, emphasizing the need for more inclusive participant samples that span diverse age groups and clinical populations. The inclusion of individuals from different age groups provides insight into developmental aspects and cognitive changes. Future research should develop adaptive or scalable tasks that can be adjusted for different age groups and cognitive abilities to obtain a more precise assessment of OLM across the lifespan. This would help to minimize ceiling and floor effects. Crucially, the examination of OLM across both sexes is highlighted, showcasing associations between sex, landmarks, and OLM performance, with observed sex differences attributed to spatial and verbal representation. Environmental features, VR technologies, object characteristics, and active involvement in learning processes significantly impact OLM performance, along with the influence of retention intervals and cues. These factors should be carefully controlled or manipulated in assessments of OLM to ensure accurate and applicable results. Furthermore, the observed influence of cognitive strategies and emotional states on navigational OLM outcomes emphasizes the need for a holistic approach in neuropsychological assessments, considering both cognitive and emotional factors.

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Declaration of Competing Interest

None

Data availability

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

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