

Spatial navigation deficits — overlooked cognitive marker for preclinical Alzheimer disease?

Gillian Coughlan¹, Jan Laczó^{2,3}, Jakub Hort^{2,3}, Anne-Marie Minihane¹ and Michael Hornberger^{1,4 *}

Abstract | Detection of incipient Alzheimer disease (AD) pathophysiology is critical to identify preclinical individuals and target potentially disease-modifying therapies towards them. Current neuroimaging and biomarker research is strongly focused in this direction, with the aim of establishing AD fingerprints to identify individuals at high risk of developing this disease. By contrast, cognitive fingerprints for incipient AD are virtually non-existent as diagnostics and outcomes measures are still focused on episodic memory deficits as the gold standard for AD, despite their low sensitivity and specificity for identifying at-risk individuals. This Review highlights a novel feature of cognitive evaluation for incipient AD by focusing on spatial navigation and orientation deficits, which are increasingly shown to be present in at-risk individuals. Importantly, the navigation system in the brain overlaps substantially with the regions affected by AD in both animal models and humans. Notably, spatial navigation has fewer verbal, cultural and educational biases than current cognitive tests and could enable a more uniform, global approach towards cognitive fingerprints of AD and better cognitive treatment outcome measures in future multicentre trials. The current Review appraises the available evidence for spatial navigation and/or orientation deficits in preclinical, prodromal and confirmed AD and identifies research gaps and future research priorities.

Alzheimer disease (AD) is the most common form of dementia, with increasing worldwide prevalence^{1,2}. Accurate early diagnosis is crucial as it provides the chance to intervene at an early stage before substantial neuronal death occurs. This approach is particularly relevant in an era in which research is focused on the efficacy of upcoming pharmacological^{3–5} and non-pharmacological prevention and treatment strategies⁶, which might allow intervention when neuronal loss is at its minimum to stop or delay disease progress.

Current ‘gold-standard’ clinical diagnostic and outcome measures for AD are strongly focused on episodic memory⁷. Episodic memory loss is one of the most common features of AD and is considered the most sensitive and specific cognitive marker of underlying AD pathophysiology⁸. However, it is becoming increasingly clear that decline in memory is so common in healthy ageing that early detection of incipient AD pathophysiology is difficult⁹, which in turn often delays diagnosis as clinicians schedule follow-up appointments in an attempt to confirm a progressive decline in memory performance. The situation is further complicated

by the fact that other brain diseases^{10–12}, such as fronto-temporal dementia (FTD), can manifest with substantial memory deficits despite having a different underlying pathology¹³.

Given this limited specificity of episodic memory deficits for incipient underlying AD pathophysiology, a new approach is required. Emerging data reveal that spatial navigation and orientation deficits have higher specificity than episodic memory in distinguishing AD from other dementias, particularly FTD^{14,15}. More specifically, in animal studies AD pathophysiology has been shown to affect navigation-specific brain areas before episodic memory areas are affected¹⁶. Further, healthy older adults do not experience topographical disorientation in well-known environments, which contrasts starkly with the spatial disorientation seen in early AD^{17,18}. Finally, analysis of spatial performance allows better translation of animal intervention studies to human clinical trials as the conceptualization of episodic memory is difficult to apply to non-human species¹⁹. Despite these highly promising findings, the utility of such spatial navigation deficits for diagnosis in preclinical individuals with a

¹Norwich Medical School, University of East Anglia, Norwich, UK.

²Memory Clinic, Department of Neurology, Charles University, Second Faculty of Medicine and Motol University Hospital, Prague, Czech Republic.

³International Clinical Research Center, St. Anne's University Hospital Brno, Brno, Czech Republic.

⁴Dementia and Complexity in Later Life, NHS Norfolk and Suffolk Foundation Trust, Norfolk, UK.

*e-mail: m.hornberger@uea.ac.uk

<https://doi.org/10.1038/s41582-018-0031-x>

Key points

- Episodic memory has limited utility as a diagnostic and outcome measure for preclinical Alzheimer disease (AD).
- Spatial navigation deficits have the potential to detect underlying pathophysiology in preclinical AD.
- The brain areas affected earliest by AD pathophysiology are key nodes in the spatial navigation network.
- Genetically at-risk individuals show altered spatial navigation patterns before any episodic memory symptom onset.
- Spatial navigation is emerging as a potential cost-effective cognitive biomarker to detect AD in the preclinical stages, which has important implications for future diagnostics and treatment approaches.
- Future spatial navigation benchmarks and standardization of spatial navigation tests are needed to realize this goal.

Episodic memory

One's memory of events represented by aspects of the past not present in other memories, such as the time, place or social context.

Mild cognitive impairment

(MCI). Prodromal or intermediate stage between the expected cognitive decline of normal ageing and the more serious decline of dementia.

high genetic risk of AD or with mild cognitive impairment (MCI) remains underexplored^{20,21}. The current Review appraises the available evidence for spatial navigation deficits in preclinical, prodromal and confirmed AD and identifies research gaps and future research priorities.

AD diagnosis and criteria

Diagnostic criteria. According to the National Institute on Aging, AD diagnostic criteria include a history of worsening amnesic and non-amnesic symptoms in the visuospatial, language and executive function domains that reflect amyloid- β (A β) burden and neurodegeneration in the brain²². Positive test results for cerebrospinal fluid (CSF) biomarkers and PET amyloid imaging increase confidence in the clinical diagnosis and predict AD progression from prodromal stages²³. Importantly, A β plaque deposition has been observed in post-mortem evaluations of individuals who were not judged to be symptomatic in their lifetime^{24,25}, highlighting the complexity of the underlying AD pathology and time lag to clinical manifestation. A further complication is that biomarkers are not brain region-specific and do not equate to clinical outcomes or have real-life symptom relevance for patients^{26,27}. Thus, the role of cognitive evaluations is important in the early diagnostic process and has great potential to complement established biomarkers. Given that the amnesic syndrome continues to appear as a 'core' criterion to support diagnosis of the most typical form of AD, we discuss the issues surrounding the use of memory tests in clinical settings below (for atypical AD, see elsewhere²⁸).

Neuropathology over the lifetime. At a biological level, AD clinical symptoms are associated with the accumulation of extracellular A β plaques and intracellular tau tangles, leading to neuronal apoptosis. The extracellular deposition of A β plaques usually occurs first in prefrontal brain regions but becomes widespread over the cortex even in healthy ageing (although with fewer tau tangles in healthy ageing). By contrast, the intraneuronal neurofibrillary tangles of tau protein show a highly specific spreading pattern through the brain in AD²⁹. Typically, tangles first develop in the most superficial cellular layer of the transentorhinal cortex (Braak and Del Tredici stage I), advancing to the entorhinal cortex and Ammon's horn in the hippocampus (stage II) and

later spreading to the amygdala, the anterodorsal thalamic nucleus and the rest of the hippocampal formation (stage III). Finally, tau tangles continue to spread to neighbouring regions within the cerebral cortex, causing neocortical atrophy²³ (stages IV–VI). The interaction of A β and tau leads to progressive neuronal loss, which in turn is believed to underlie AD symptomology, such as forgetfulness, disorientation and confusion²⁸. The reason for the pronounced directional expansion of the tau pathological process in typical AD is still unknown.

Limitations of episodic memory for AD diagnosis. Given that patients with AD present with profound symptoms of forgetfulness and substantial A β load in the medial temporal lobe (MTL), it is not surprising that episodic memory is currently the gold standard for diagnosing probable AD⁷. Indeed, patients with substantial memory problems are highly likely to have underlying AD pathology. However, the reliance on episodic memory deficits for diagnosis in the prodromal or even preclinical stages is problematic because episodic memory peaks in very early adulthood³⁰ and progressively declines with normal ageing. Indeed, diagnosis can be challenging in people >75 years of age, in whom memory and associated MTL structures show considerable age-related changes not due to pathophysiological processes³¹. As a result, cognitive decline in healthy older people aged >75 years might have been considerably underestimated by longitudinal studies³². Moreover, delayed recall ability, one of the current main cognitive diagnostic indicators of AD, progressively declines in healthy adults aged ≥ 65 years³³, highlighting the potential difficulties with the sensitivity of episodic memory to diagnose and predict AD pathophysiology in an older population. Similarly, as mentioned above, it is becoming increasingly recognized that patients with other forms of dementia can also show significant episodic memory problems. For example, FTD subtypes — such as the behavioural variant of FTD (bvFTD) — often manifest with similar deficits of episodic memory to AD, even for pathologically confirmed cases of bvFTD^{12,34–36}, which can make the differential diagnosis difficult^{9,13,15,37}. A differential diagnosis is important in order to determine the underlying pathology and thus choose the correct treatment strategy to manage symptoms. In patients with AD who exhibit neuropsychiatric symptoms, an early and differential diagnosis is particularly problematic given that it can be very difficult to clinically distinguish these patients from patients with bvFTD³⁷.

Unlike episodic memory impairments, spatial navigation or orientation problems are rarely reported in healthy older adults³⁸ or non-AD dementias, and experimental studies have shown that spatial navigational paradigms that are independent of mnemonic processes can differentiate patients with AD from individuals with other dementias and healthy control groups^{14,39}. This finding is not surprising given that the neuropathology of AD starts in the entorhinal areas, which are crucial for successful navigation^{16,40–43}. This evidence raises the question as to whether such symptoms might be more sensitive and specific to underlying AD pathophysiology, even at a preclinical (that is, pre-memory symptom onset) stage. In the following sections, we briefly

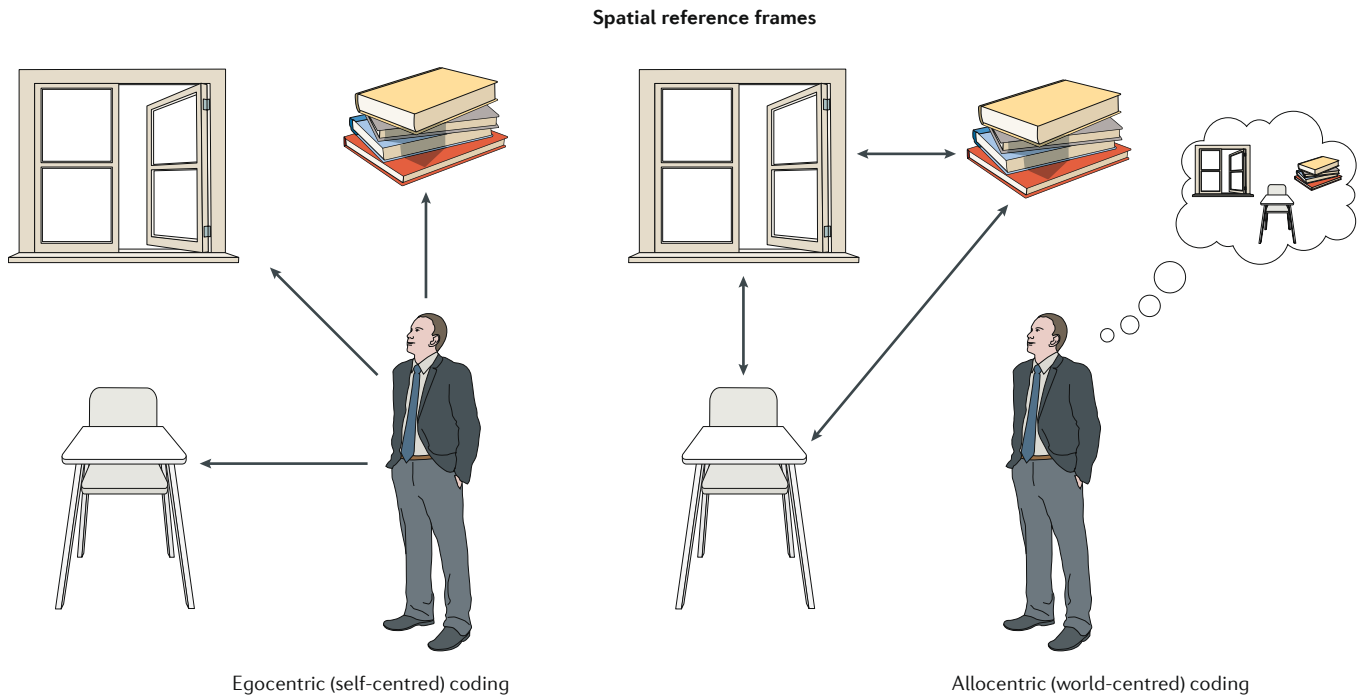


Fig. 1 | Egocentric and allocentric spatial coding. Egocentric self-centred navigation frames encode spatial information from the viewpoint of the navigator and are usually implemented when travelling a familiar route (left). Allocentric strategies are based on the navigator's perception of landmark positions relative to other landmarks and are usually implemented in a novel environment (right).

introduce current knowledge of navigation strategies and their neural correlates before reviewing the evidence in normal ageing and AD.

Spatial navigation

Navigation strategies. Spatial navigation is the process of determining and maintaining a trajectory between different points in our environment. Successful navigation relies on two co-dependent strategies: allocentric and egocentric navigation strategies. These strategies use different types of spatial reference frames but are highly correlated⁴⁴ (FIG. 1).

Egocentric navigation strategies are generally used when the same route is followed over and over again^{45,46}. These self-centred navigation frames encode spatial information from the viewpoint of the person navigating to form an internal representation that is based on a sequence of bodily movements. This sequence of movements allows the navigator to maintain their route-goal trajectory moderately free of conscious control. Perceptual processing is required as available visual input, bodily distance from landmarks, sensorimotor and vestibular knowledge of position in space and self-motion are all utilized as navigational cues. The temporal order in which environmental stimuli are encountered is important and facilitates the landmark-based behavioural responses that are stored in spatial memory (for example, turn left at the supermarket and right at the lights).

By contrast, when travelling a lesser known or novel route, spatial representations of sequential bodily movements are not available, and allocentric, world-centred strategies are employed instead. Allocentric navigation strategies are based on the navigator's perception of landmark

positions relative to other landmarks. These positions are memorized and estimated by the navigator, contributing to an internal representation or 'cognitive map' that enables an individual to plan shorter routes regardless of their starting point^{46,47}. Allocentric representations of self-location are updated by self-motion on the basis of visual, auditory, vestibular and proprioceptive information^{48,49} in a process known as path integration. This process has a pivotal role in an individual's ability to successfully maintain movement through the environment^{42,50}.

The ability to use environmental landmarks to navigate also relies on the translation of egocentric-to-allocentric information (for example, 'I am 20 m from the church' to 'the supermarket is to the left of the church') and vice versa. For example, when one's location in an environment has been determined, the navigation system calculates subsequent routes on the basis of a combination of egocentric and allocentric information. For instance, self-motion, distance travelled, head direction during the journey⁵¹ and temporal order of observed stimuli are combined across navigation frames. This strategic translation between allocentric and egocentric reference frames is a core determinant of one's navigational ability and might be of particular importance for detecting very early signs of disorientation by clinical examination.

Thus, egocentric and allocentric navigation strategies integrate for optimal performance in daily functioning and are associated with a network of brain regions that operate conjointly but can also be dissociated from each other⁵². Indeed, successful navigation can be achieved by employing just one of these navigation processes at a time. For example, employing only egocentric

Egocentric navigation strategies

Egocentric self-centred navigation frames encode spatial information from the viewpoint of the navigator.

Allocentric navigation strategies

Allocentric strategies are based on the navigator's perception of landmark positions relative to other landmarks.

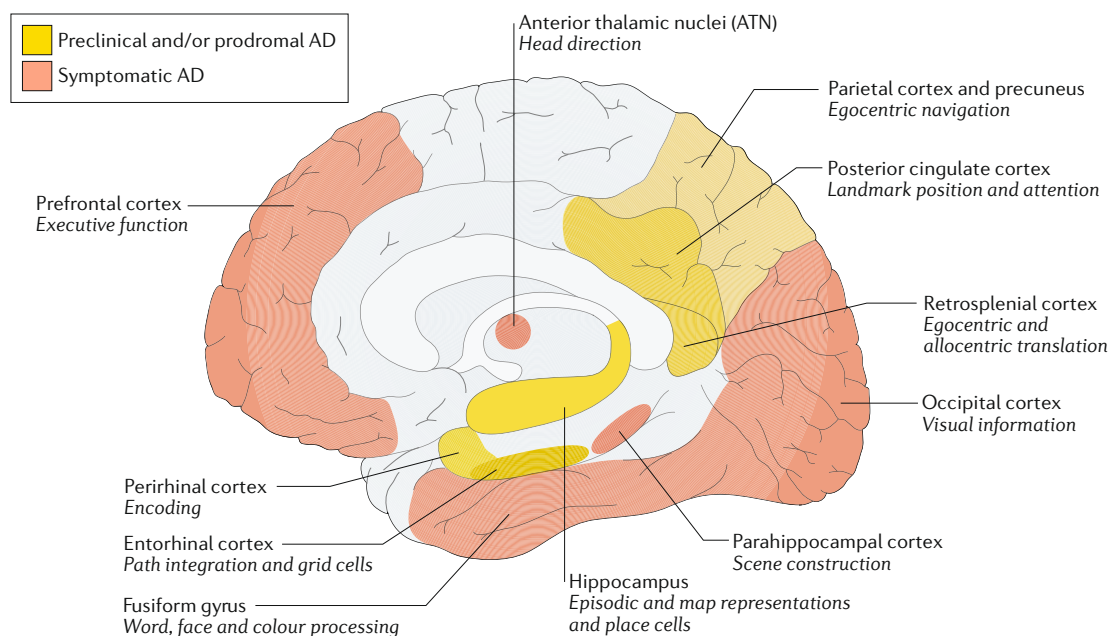


Fig. 2 | **Anatomical illustration of AD-related neuropathological changes.** Yellow areas are brain areas affected by Alzheimer disease (AD) pathophysiology in preclinical and prodromal stages of the disease; red areas are brain areas affected in symptomatic stages of the disease. Figure reproduced from REF¹⁵⁰, Macmillan Publishers Limited.

navigation, it is possible to go from one landmark to another without knowing the relationship between landmarks (allocentric information), as the overall path might be stored in a series of visual snapshots or scene memories^{53,54}. Similarly, egocentric navigation is also not required for allocentric navigation. When walking from one's house to the garden, the ability to measure bodily distance from landmarks (egocentric strategy) might not be necessary if a cognitive representation of the spatial trajectory already exists. Such a dissociation is often employed in experimental navigation tests by asking participants to remember locations on the basis of direction information while background cues are rotated or removed^{54–56}. Evidence also suggests interindividual differences for navigation preference, such that individuals preferentially choose specific strategies or reference frames when attempting to solve spatial tasks⁵². Outside the experimental paradigm, however, the human navigation system encourages the natural interaction (or strategic translation) of egocentric and allocentric strategies; therefore, it is important to identify translational impairment in the clinical setting.

Neural correlates of spatial navigation. Advances in the field have shown that a large network of brain regions, involving MTL regions (hippocampus, entorhinal cortex and parahippocampal cortex⁵⁷), parietal lobe regions (posterior cingulate, precuneus⁵⁸ and retrosplenial cortex (RSC)^{59,60}), frontal lobe regions⁶¹ and other subcortical structures (caudate nucleus⁴⁶ and thalamus^{62,63}), underlies our ability to navigate (FIG. 2). Electrophysiological recordings in freely moving rodents offered the original insights into spatially tuned neurons that independently code for various aspects of navigation such as place location, head direction, speed and environmental boundaries. Likewise, in humans these

sophisticated cells together form the neural architecture that underlies the navigation system.

Allocentric navigation strategies are thought to be represented by highly selective cell ensembles commonly found in the hippocampal CA1 and CA3 regions of the MTL. These so-called 'place cells' contribute to the formation of cognitive maps of the environment, providing local information about one's location within that environment. Both rodent and human models show that place cells become stable and more spatially restricted with repeated exposure to an environment (that is, as one becomes more familiar with the surrounding area). On the other hand, large-scale spatial information is provided by grid cells located primarily in the medial entorhinal cortex, which can encode grid-like representations of distinct positions in space (self-location) and calculate routes between locations^{41,43,64}. Grid cells represent a core component of the neural system that underlies path integration as they also seem to measure 'distance travelled' akin to an odometer^{64,65}.

In addition, head direction cells (which were first identified in the postsubiculum of the rat) encode orientation in space and are activated whenever one is facing a certain direction (the reference direction)⁶⁶. Since their first discovery in rats, these cells have been found in the posterior parietal cortex, RSC, dorsal pre-subiculum, postsubiculum and anterior thalamus in humans^{67,68}. Boundary vector cells⁶⁹ and cells coding specifically for self-motion (path integration)^{43,50,70} complement other spatial representations and together might be used to rapidly form goal-independent maps of the environment.

Previous work suggests that the posterior cingulate region, RSC and precuneus have major roles in the integration of egocentric and allocentric spatial information streams⁷¹. For example, the rodent posterior cingulate

cortex receives dense direct hippocampal connections from the subiculum and is thus considered an integrative hub for projections from the hippocampus and anterior thalamic nuclei⁷². Interactions between the egocentric parietal and allocentric MTL systems are mediated by the RSC^{51,73–75} as it projects to the parahippocampal gyrus and other areas, including the entorhinal cortex, presubiculum, thalamus and posterior parietal cortex^{76,77}. Moreover, the medial prefrontal cortex has been shown to receive information from the posterior parietal cortex and the hippocampus and might be involved in upstream processing of the spatial information generated^{78,79}.

Functional imaging studies in rodents and humans have shown that the RSC is a major contributor to navigational performance, especially accurate path integration in darkness⁸⁰, recognizing permanent environmental objects⁵⁹, binding together multiple cues within the environment⁷¹ and encoding and storing spatial information⁷². In healthy individuals, the RSC responds selectively to environmental objects with high permanence such as telephone booths or street lights^{59,81}. However, self-reported ‘poor navigators’ show reduced RSC activation in response to high-permanence landmarks and have increased difficulty estimating object permanency compared with self-reported ‘good navigators’ (REF. ⁶⁰). Moreover, the functional connectivity between the RSC and the anterior nuclei of the thalamus is reduced in poor navigators⁶⁰, consistent with the literature from rodent studies⁶³. The ability to recognize permanent objects in the environment is a general skill required to make appropriate decisions related to navigation, thus emphasizing the important role, within the wider posterior cingulate region, of the RSC in spatial navigation. Understanding spatial navigation performance in healthy individuals is a crucial starting point before inferences can be drawn about initial sites of functional abnormality in patients with AD or preclinical individuals.

Ageing and spatial navigation. The majority of research on spatial navigation in normal ageing supports a general consensus that human and mouse navigational ability, especially allocentric processing^{82,83}, declines with age^{18,84,85}. Reduced resting-state blood flow⁸⁶, long-term potentiation of mouse synaptic function⁸⁷ and decreased hippocampal volumes in humans⁸⁸ are some of the mechanisms that underpin this gradual decline. Along with these age-related neural changes, deficits in place learning⁸³, perception of self-motion⁸⁹ and retrieval of spatial memories⁹⁰ have been reported in humans. On the basis of rodent studies, such navigational errors are believed to be a consequence of computational changes within neural circuits of the medial prefrontal cortex and the CA1 and CA3 regions of the hippocampus⁹¹. These age-related changes give rise to deficits in spatial working memory as well as difficulties maintaining and retrieving allocentric representations^{91,92}. Interestingly, reduced allocentric processing, mostly related to spatial memory (that is, encoding and retrieval of route trajectories and environmental maps), is suggested to lead to a compensatory shift towards egocentric or

path integration navigational processes as they do not rely on memory per se^{84,93}. This idea is consistent with the finding that older adults between 60 and 80 years of age actually outperform younger adults on egocentric⁹⁴ and allocentric distance tasks (for example, manually adjusting the length of a line until its length matches the distance of a target)⁹⁵. The preservation of these memory-independent spatial processes in healthy ageing might therefore have important implications for the effective discrimination of age-related and AD-related decline in navigational ability⁹⁴ and may also have implications for navigational rehabilitation strategies for AD in the future.

Spatial navigation as a diagnostic tool

Early identification — on the basis of navigational difficulties — of individuals who are likely to develop AD is currently complicated by the challenges of measuring different features of spatial navigation in humans. Reliable tests of spatial navigation that are suitable for clinical settings across centres and different patient populations are still in development, as most experimental tests are not feasible for clinical evaluation. Validated, simple visuospatial tests such as the widely used Mental Rotation Test⁹⁶ and the Money Road Map Test⁹⁷ have been shown to be poor predictors of navigational abilities^{98,99} and cognitive decline¹⁰⁰. Newly developed virtual reality or real-world tests of spatial cognition have proved more sensitive in identifying spatial navigation deficits in patient populations. In particular, virtual reality testing can be applied as an alternative to real-world reality tests (which are difficult to administer with space constraints in clinical settings) to measure navigational abilities in younger and older age groups¹⁰¹ and in patients with MCI and early AD¹⁰². These computer-generated virtual environments provide tightly controlled testing conditions and enable manipulation of navigational parameters, such as landmark availability and navigation complexity. The adoption of tablet computers by clinical services for cognitive testing will make the testing of spatial navigation deficits more sophisticated and sensitive in everyday clinical practice. Furthermore, extraction of critical features from these virtual reality tests might enable development of further pencil and paper or bedside assessments.

Early AD. Previous studies using virtual reality techniques have shown that spatial disorientation in patients with AD typically includes both egocentric and allocentric impairments linked to widespread neurodegeneration in medial temporal, parietal and frontal brain regions^{17,103–106} (FIG. 2). In accordance with these findings, both types of navigational strategy have been found to be impaired in early AD dementia, alongside impairments in the translation of both reference frames¹⁰⁵ and the ability to construct novel scenes from spatial and contextual information, which is dependent on posterior parietal regions such as the supramarginal and angular gyrus¹⁰⁶. Virtual reality studies found that patients with early AD were unable to store an allocentric viewpoint-independent representation and to synchronize this representation with the allocentric viewpoint-dependent

representation (for example, memorize the position of a plant and retrieve the plant starting from a different location)¹⁷, probably as a result of reduced hippocampal neuronal density, particularly in the CA1 and CA3 subregions¹⁰⁷. Egocentric impairments are also present, mainly as a result of hypometabolism and structural medial parietal changes, which are signature features of AD¹⁰⁸. Surprisingly, these medial parietal changes and associated egocentric impairments have been much less investigated in AD than episodic memory deficits, despite having potentially much higher specificity for AD pathology. Indeed, retrosplenial (Brodmann areas 29 and 30) volumetric changes have been shown to efficiently distinguish AD from FTD, even in patients with similar hippocampal atrophy^{14,109}.

As noted above, patients with AD also experience difficulty translating between allocentric and egocentric reference frames, a function that strongly correlates with RSC and posterior cingulate dysfunction and has been shown to distinguish AD from FTD^{14,105}. Given the role of the RSC in integrating different navigational frames, orientation and visual information from the occipital lobes, its dysfunction in early AD is in agreement with deficits in translation between allocentric and egocentric representations that occur at early clinical stages of the disease and are highly specific to underlying AD pathophysiology¹¹⁰. For this reason, the RSC is often considered an initial site of functional abnormality in patients with AD or in preclinical individuals.

Prodromal AD and MCI. Similar to early AD, patients with MCI often show spatial navigation impairments¹¹¹. Although the exact trajectory from MCI to AD is still under discussion¹¹², a large number of studies show functional and structural changes in the MTL and parietal cortex in patients with MCI^{18,108,113–116}. Investigations of egocentric and allocentric memory in individuals with amnesic MCI (aMCI) indicate that these patients have substantial volume reductions in the hippocampus, the right-sided precuneus and the inferior parietal cortex and are severely impaired at learning both allocentric and egocentric tasks¹⁰⁸. Indeed, path integration in spatial navigation tests is substantially impaired among prodromal cohorts and might represent a cognitive marker for AD¹¹⁷. Furthermore, a study employing a human real-life version of the Morris water maze found that patients with AD had problems navigating and using both allocentric and egocentric orientation; aMCI groups were more severely impaired on allocentric trials¹¹¹, probably owing to the stronger emphasis on memory in these trials¹¹⁸.

Interestingly, genetic vulnerability interacts with aMCI to influence spatial navigation performance. The apolipoprotein E $\epsilon 4$ allele (*APOE** $\epsilon 4$), which is a known genetic risk factor for AD, has high prevalence but low penetrance in the general population, with a threefold increased risk of developing AD in *APOE** $\epsilon 3/\epsilon 4$ heterozygotes and a tenfold increased risk in *APOE** $\epsilon 4/\epsilon 4$ homozygotes compared with *APOE** $\epsilon 4$ non-carriers (reviewed elsewhere¹¹⁹). On a computerized human analogue of the Morris water maze test (Hidden Goal Task), aMCI *APOE** $\epsilon 4$ homozygous carriers scored lower on

all spatial navigation subtasks, including allocentric (hippocampus-dependent) and egocentric subtasks, than aMCI *APOE** $\epsilon 4$ heterozygous carriers¹¹⁵.

Despite the strong focus on MTL contributions to navigational deficits in AD, findings suggest an increasingly important role for the posterior cingulate cortex and RSC; these areas are affected early in the course of AD¹²⁰ and in patients at early MCI stages^{121,122}, especially those who then progress to AD^{116,121,123,124}. However, questions around the contributions of the RSC and associated posterior cingulate areas to spatial navigation deficits in early AD remain unanswered. In addition, whether changes in the RSC reflect a compensatory mechanism that occurs as a result of early AD pathology in the transentorhinal cortex and hippocampus at the microscopic level remains unclear. Such a finding would not be surprising, however, as the entorhinal cortex has a strong anatomical connection with the RSC¹²⁵.

Preclinical AD. Although evidence is emerging that spatial navigation is impaired in early AD and MCI, its integrity in preclinical populations is less well understood. Various attempts have been made to determine spatial neural and cognitive biomarkers in individuals as young as 45 years of age who have an elevated sporadic or genetic risk of progressing to AD¹²⁶. Preclinical investigations have reported functional MRI abnormalities in the resting-state default-mode network, including reduced functional connectivity in the posterior cingulate cortex and precuneus regions^{127,128}, both of which underlie egocentric ability and egocentric-to-allocentric translation.

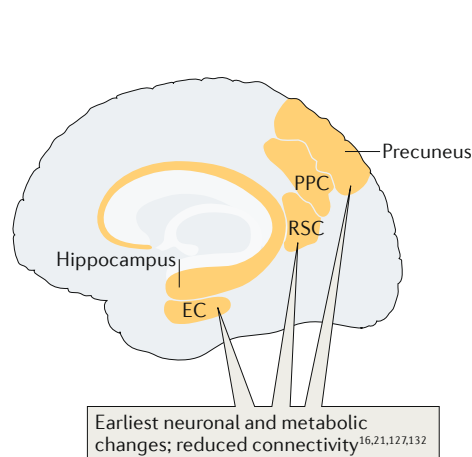
Studies in sporadic preclinical AD have partially relied on CSF A β levels. For example, a study from 2016 (REF.²⁰) investigated spatial navigation as a marker for AD using two non-immersive desktop virtual maze environments for allocentric and egocentric conditions. Individuals were considered preclinical if they had low CSF A β levels (<500 pg/ml)¹²⁹ with no cognitive deficits. Selective deficits in allocentric strategy among preclinical individuals were reported relative to individuals with a normal A β level in the CSF (>500 pg/ml). Despite allocentric acquisition impairments, the preclinical group retained sufficient information to solve the wayfinding task. However, the exact contribution of decreased CSF A β levels to the impairment of allocentric and egocentric processing is uncertain, as increasing evidence suggests that the tau protein has a critical role in the generation of cognitive deficits^{130,131}. Experiments in aged transgenic mice expressing human tau suggest that the interaction of reduced excitatory grid-cell firing in the dorsal medial entorhinal cortex and increased activity of inhibitory cells in response to enhanced theta oscillations results in the spatial memory deficits seen in early AD¹⁶. This finding links the destabilization of grid-cell fields (which code for route trajectories and update spatial information) with the earliest stage of tau pathology. However, the importance of this finding in relation to preclinical AD remains to be determined (see FIG. 3).

In human studies, preclinical individuals carrying mutations in the presenilin 1 and amyloid precursor

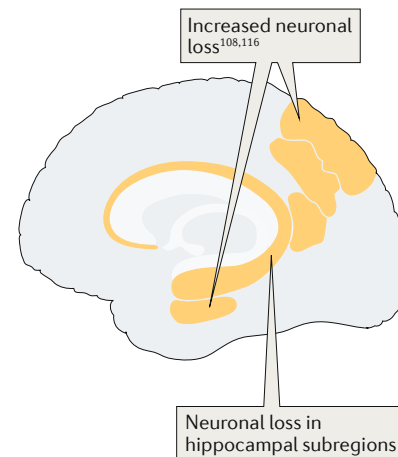
Morris water maze

A test of spatial learning examining rodent ability to navigate from different starting locations around an open swimming arena to locate a submerged escape platform using only distal cues. For more information, see elsewhere¹⁴⁹.

a Preclinical AD



b Prodromal AD (MCI)



c Early AD

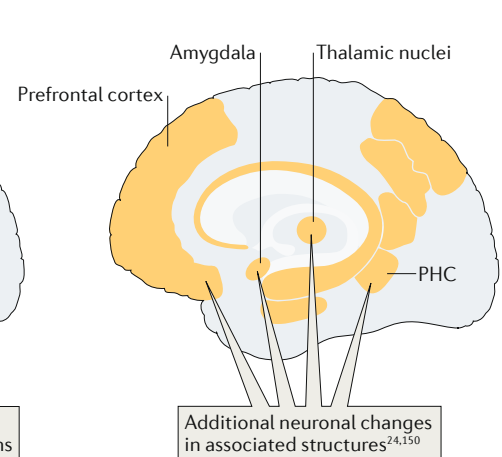


Fig. 3 | The progressive pathophysiological changes that underlie navigational impairment in AD. **a** | Grid-cell dysfunction leads to an altered navigation pattern at the preclinical stage. Cortical thinning in the egocentric-mediated precuneus and retrosplenial cortex (RSC) is also evident in the preclinical stage. **b** | Early volumetric decline in the medial temporal lobe (MTL) and parietal lobes gives rise to select allocentric and egocentric disturbances in prodromal Alzheimer disease (AD). **c** | In early AD, neurodegeneration continues to progress throughout the MTL and frontal lobe regions, rendering the neural navigation system severely impaired at this stage. EC, entorhinal cortex; MCI, mild cognitive impairment; PHC, parahippocampal cortex; PPC, posterior parietal cortex.

protein genes show entorhinal and posterior cingulate cortical thickness changes up to 8 years before disease onset¹³². However, to our knowledge, spatial navigational ability has not been investigated in these particular pre-clinical patients. These predictive MRI findings underscore the strong need for longitudinal investigations to examine the sensitivity of cortical thickness changes as neural markers for AD and the manifestation of spatial navigation disparities for predicting later conversion to MCI and early AD.

Most navigation studies in cohorts of patients with genetic risk factors for AD have been conducted with *APOE*-genotyped individuals. The association between the *APOE** ϵ 4 allele and AD risk has spurred a growing number of studies investigating the cognitive and neurophysiological effect of *APOE** ϵ 4 in younger (18–24 year olds)^{133,134}, middle-aged (40–60 year olds)^{135–138} and elderly (60–90 year olds) individuals¹³⁹ and in relation to spatial performance and hippocampal volume¹¹⁵.

A study examined a possible link between *APOE** ϵ 4 and spatial navigation in genetically at-risk young healthy adults. Reduced grid-cell-like representation was observed in *APOE** ϵ 3/ ϵ 4 carriers compared with *APOE** ϵ 3/ ϵ 3 individuals, suggesting functional (but no structural) differences between young *APOE** ϵ 4 carriers and non-carriers. Grid-cell representations were temporally unstable in young-adult carriers as functional connectivity between the right entorhinal cortex and hippocampus was impaired, leading to a behavioural preference to navigate along the border of the virtual environment. The authors proposed that the hippocampus was able to compensate for neuronal loss in the entorhinal cortex and reduced grid-cell representations, enabling young-adult carriers to navigate successfully and complete the task^{21,140}. Clearly, preclinical cohorts are of great interest for future

navigation research in AD pathophysiology, not only for individuals at genetic risk but also for sporadic high-risk groups.

An alternative approach is to investigate preclinical cognitive forms of AD via healthy elderly participants who have significant memory concerns (SMCs) but do not reach cut-offs for objective memory impairment on standard neuropsychological measures. Such SMCs are a potential harbinger of AD pathology¹⁴¹. However, it should be emphasized that no gold-standard tool currently exists to identify SMCs, and no threshold values to suggest clinically relevant SMCs have been established. Unsurprisingly, few studies have explored spatial navigation in SMC cohorts¹¹¹. However, evidence does suggest a positive association between amyloid pathology, genetic risk of AD, entorhinal cortex integrity and SMCs^{142,143}, which might ignite new interest in whether SMCs and navigational difficulties are comorbid among genetically at-risk cohorts.

Conclusions

This Review underscores the presence of spatial navigation impairments in early AD and its prodromal and preclinical forms. The evidence reviewed clearly highlights the great potential of spatial navigation and orientation deficits as diagnostic measures and predictors of incipient AD pathophysiology. The findings should not be surprising as MTL and posterior parietal regions, which constitute the core network for navigation, are highly susceptible to AD pathophysiology even in the prodromal and preclinical stages of the disease. An urgent need exists to revisit the notion that episodic memory should be the gold standard for early AD diagnosis and outcome intervention studies. Specifically, the literature indicates that spatial navigation deficits can identify individuals at risk of

Significant memory concerns

(SMCs). Self-experienced persistent declines in cognitive abilities in comparison with a prior normal status; occur in the absence of objective impairment on standardized neuropsychological tests.

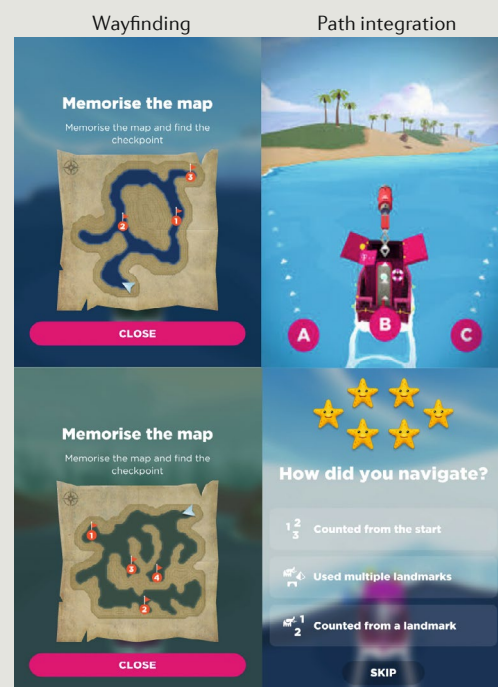
Box 1 | Sea Hero Quest

Sea Hero Quest (SHQ) is a mobile app-based cognitive task that enables the collection of spatial navigation data on a population level. SHQ has been downloaded by 3.7 million people in 193 different countries worldwide. As people advance in the game, they face challenges in different navigation domains, including visuospatial skills, path integration, spatial short-term memory and allocentric and/or egocentric navigational strategy.

Game performance can be divided into two main domains: wayfinding and egocentric path integration. In wayfinding levels, players are initially presented with a map indicating start location and the location of several checkpoints to find in a set order. The two variables of interest are trajectory distance and time taken to complete each level. In path integration levels, participants navigate along a river with bends to find a flare gun and then choose the correct direction back to the starting point from a choice of three options. Depending on their accuracy, players receive one, two or three stars. The game also controls for video-gaming proficiency, which might otherwise bias performance by giving players familiar with similar games an advantage.

Current preliminary findings for the population-level navigation data can be found elsewhere¹⁴⁶.

Image courtesy of H. Spiers and M. Hornberger. Top right and bottom left panels reproduced from ref[146], CC-BY-4.0.



developing AD, which has obvious implications for clinical practice. For example, routine assessment of spatial navigation complaints should be considered a priority in memory clinics³⁸. If subjective complaints are present, particularly when accompanied by behavioural symptoms that manifest as everyday difficulties navigating previously familiar routes and/or using public transport, the patient should be considered at high risk of developing AD. Identification of incipient AD might provide an earlier opportunity to begin potentially disease-modifying treatment before more substantial and deadly brain changes occur.

Spatial navigation parameters could also have an important role in animal-to-human translational research. Drug development for AD has been hampered by the failure to replicate success in animal models (tested with spatial navigation measures) in phase II or III clinical trials. A 3-month open-label study has shown that a computerized human analogue of the Morris water maze has the potential to measure the effects of donepezil in mild AD¹⁴⁴. Subsequent research has shown that the disruptive effect of scopolamine on place navigation can be reversed by donepezil, a finding that was demonstrated using both rodent and human versions of the Morris water maze¹⁴⁵.

The past few years have seen a considerable shift in interest towards patients with prodromal AD, and some of the conventional neuropsychological tests for AD might be subject to a ceiling effect in these patients. Only a few subtests of current measures have the potential to show differences in the effects of drugs and placebo in patients with prodromal AD or MCI. Therefore, spatial navigation, as a sensitive and specific marker of AD, presents a window of opportunity in

these patients. Furthermore, in the era of cross-cultural clinical trials, tests that are independent of language and culture (such as those for spatial navigation) facilitate comparison across research sites.

From a social-care perspective, the findings presented offer important information for dementia care organizations. Disorientation leads to patients getting lost in everyday environments, resulting in distress for patients and family members and often the involvement of emergency services and in extreme cases leading to death from exposure. Thus, the identification of individuals with spatial navigation deficits might enable better safeguarding to be put in place for those individuals.

Despite clear clinical applications of the research, spatial navigation has several limitations as a diagnostic tool for AD. One major question is whether spatial deficits occur before episodic memory deficits or whether both deficits manifest concurrently in humans. Navigation and orientation tests can be considered superior to episodic memory tests only if they are shown to be more sensitive and specific for AD pathology. However, given that the normal ageing process will probably give rise to complaints around memory of past events, as opposed to the ability to navigate and orientate oneself in space, disorientation should be further investigated as a potentially more valuable (specific) marker to distinguish pathological ageing from normal ageing. This rationale leads to a pressing need to develop a standardized and validated diagnostic spatial test battery that does not rely on topographical memory. These tests might also be used as a clinical diagnostic tool and outcome marker in upcoming treatment efficacy trials, as current navigation tools are limited and not standardized across research centres. Given the multifactorial nature of the navigation

system, such a battery of tests should consider not only mnemonic processes but also higher mental functions mediated by the frontal lobe such as planning, motivation and maintenance of spatial representations that influence navigational ability. This approach is especially important when considering a differential diagnosis (for example, between AD and FTD syndromes).

Importantly, spatial navigation studies in AD might be limited in their comparability, as many of the studies predate the publication of robust diagnostic criteria for AD⁷. As a result, the potential for mixed or other forms of dementia to confound an established cohort of patients with AD cannot be ruled out. It is also difficult to say with certainty that cut-off points for disease staging (preclinical, early MCI and late MCI) are consistent across studies published before the 2014 guidelines⁷. In addition, heterogeneity in the definition of patient cohorts and differences in spatial navigation paradigms and testing procedures have created inconsistencies across studies.

The current lack of epidemiological data from healthy populations for spatial navigation is a further obstacle. Interindividual differences in spatial navigation remain elusive, with no population-level data available to rectify conflicting ideas around, for example, sex differences in

navigational abilities. One notable exception is the launch of *Sea Hero Quest*, an online mobile game to measure spatial navigation (BOX 1). To date (April 2018), *Sea Hero Quest* has been played by more than 3.7 million people in 193 countries between the ages of 19 and 95 years¹⁴⁶. Initial results from *Sea Hero Quest* show that not only age but also gender and cultural background have a substantial effect on navigation behaviour, which clearly needs to be investigated further¹⁴⁶. Data from the game could be used to create the first population benchmarks for healthy navigation abilities across ages, gender and countries. In turn, these benchmark scores could enable the development of easy-to-administer, sensitive spatial navigation tools that are validated against population-level benchmarked scores and related to real-life navigation problems that patients might encounter¹⁴⁷. Furthermore, benchmarking from the *Sea Hero Quest* data set has enabled investigations of the earliest navigation changes in preclinical groups defined as genetically at risk of AD (*APOE***ε4* allele carriers)¹⁴⁸. Taken together, the presented evidence highlights the potential of spatial navigation for use in AD diagnosis, which in turn could have a major impact on clinicians, patients and their families.

Published online 6 July 2018

1. Blennow, K., de Leon, M. J. & Zetterberg, H. Alzheimer's disease. *Lancet* **368**, 387–403 (2006).
2. Alzheimer's Association. 2015 Alzheimer's disease facts and figures. *Alzheimers Dement.* **11**, 459–509 (2015).
3. Habchi, J. et al. An anticancer drug suppresses the primary nucleation reaction that initiates the production of the toxic Aβ42 aggregates linked with Alzheimer's disease. *Sci. Adv.* **2**, e1501244–e1501244 (2016).
4. Sevigny, J. et al. The antibody aducanumab reduces Aβ plaques in Alzheimer's disease. *Nature* **537**, 50–56 (2016).
5. Yang, T. et al. Small molecule, non-peptide p75 ligands inhibit Abeta-induced neurodegeneration and synaptic impairment. *PLoS ONE* **3**, e3604 (2008).
6. Vauzour, D. et al. Nutrition for the ageing brain: towards evidence for an optimal diet. *Ageing Res. Rev.* **35**, 222–240 (2017).
7. Dubois, B. et al. Advancing research diagnostic criteria for Alzheimer's disease: the IWG-2 criteria. *Lancet Neurol.* **13**, 614–629 (2014).
8. Rajah, M. N. et al. Family history and APOE4 risk for Alzheimer's disease impact the neural correlates of episodic memory by early midlife. *NeuroImage Clin.* **14**, 760–774 (2017).
9. Bellassen, V., Igloi, K., de Souza, L. C., Dubois, B. & Rondi-Reig, L. Temporal order memory assessed during spatiotemporal navigation as a behavioral cognitive marker for differential Alzheimer's disease diagnosis. *J. Neurosci.* **32**, 1942–1952 (2012).
10. Birrer, R. B. & Vemuri, S. P. Depression in later life: a diagnostic and therapeutic challenge. *Am. Fam. Physician* **69**, 2375–2382 (2004).
11. Bronnick, K., Emre, M., Tekin, S., Haugen, S. B. & Aarsland, D. Cognitive correlates of visual hallucinations in dementia associated with Parkinson's disease. *Mov. Disord.* **26**, 824–829 (2011).
12. Pennington, C., Hodges, J. R. & Hornberger, M. Neural correlates of episodic memory in behavioral variant frontotemporal dementia. *J. Alzheimers Dis.* **24**, 261–268 (2011).
13. Flanagan, E. C. et al. False recognition in behavioral variant frontotemporal dementia and Alzheimer's disease-disinhibition or amnesia? *Front. Aging Neurosci.* **8**, 1–11 (2016).
14. Tu, S. et al. Lost in spatial translation - a novel tool to objectively assess spatial disorientation in Alzheimer's disease and frontotemporal dementia. *Cortex* **67**, 83–94 (2015).
15. Yew, B., Alladi, S., Shailaja, M., Hodges, J. R. & Hornberger, M. Lost and forgotten? Orientation versus memory in Alzheimer's disease and frontotemporal dementia. *J. Alzheimers Dis.* **33**, 473–481 (2013).
16. Fu, H. et al. Tau pathology induces excitatory neuron loss, grid cell dysfunction, and spatial memory deficits reminiscent of early Alzheimer's Disease. *Neuron* **93**, 533–541 (2017).
17. Serino, S., Morganti, F., Di Stefano, F. & Riva, G. Detecting early egocentric and allocentric impairments deficits in Alzheimer's disease: an experimental study with virtual reality. *Front. Aging Neurosci.* **7**, 1–10 (2015).
18. Lihfous, S., Dufour, A. & Després, O. Spatial navigation in normal aging and the prodromal stage of Alzheimer's disease: insights from imaging and behavioral studies. *Ageing Res. Rev.* **12**, 201–213 (2013).
19. Templer, V. & Hampton, R. Episodic memory in nonhuman animals. *Curr. Biol.* **23**, 801–806 (2013).
20. Allison, S. L., Fagan, A. M., Morris, J. C. & Head, D. Spatial navigation in preclinical Alzheimer's disease. *J. Alzheimers Dis.* **52**, 77–90 (2016).
21. Kunz, L. et al. Reduced grid-cell-like representations in adults at genetic risk for Alzheimer's disease. *Science* **350**, 430–433 (2015).
22. Jack Jr, C. R. et al. Introduction to revised criteria for the diagnosis of Alzheimer's disease: National Institute on Aging and the Alzheimer Association Workgroups. *Alzheimers Dement.* **7**, 257–262 (2011).
23. Medina, M. & Avila, J. New perspectives on the role of tau in Alzheimer's disease. Implications for therapy. *Biochem. Pharmacol.* **88**, 540–547 (2014).
24. Nelson, P. T. et al. Correlation of Alzheimer disease neuropathologic changes with cognitive status: a review of the literature. *J. Neuropathol. Exp. Neurol.* **71**, 362–381 (2012).
25. Knopman, D. S. et al. Neuropathology of cognitively normal elderly. *J. Neuropathol. Exp. Neurol.* **62**, 1087–1095 (2003).
26. Chételat, G. et al. Amyloid imaging in cognitively normal individuals, at-risk populations and preclinical Alzheimer's disease. *NeuroImage Clin.* **2**, 356–365 (2013).
27. Morris, G. P., Clark, I. A. & Vissel, B. Inconsistencies and controversies surrounding the amyloid hypothesis of Alzheimer's Disease. *Acta Neuropathol. Commun.* **2**, 1–21 (2014).
28. Galton, C. J., Patterson, K., Xuereb, J. H. & Hodges, J. R. Atypical and typical presentations of Alzheimer's disease: a clinical, neuropsychological, neuroimaging and pathological study of 13 cases. *Brain* **123**, 484–498 (2000).
29. Braak, H. & Del Tredici, K. The preclinical phase of the pathological process underlying sporadic Alzheimer's disease. *Brain* **138**, 2814–2833 (2015).
30. Hartshorne, J. K. & Germine, L. T. When does cognitive functioning peak? The asynchron. rise fall different cognitive abilities across life span. *Psychol. Sci.* **26**, 433–443 (2015).
31. Park, H. L., O'Connell, J. E. & Thomson, R. G. A systematic review of cognitive decline in the general elderly population. *Int. J. Geriatr. Psychiatry* **18**, 1121–1134 (2003).
32. Brayne, C. et al. Estimating the true extent of cognitive decline in the old old. *J. Am. Geriatr. Soc.* **47**, 1283–1288 (1999).
33. Brailean, A. et al. Cohort differences in cognitive aging in the longitudinal aging study Amsterdam. *J. Gerontol. B Psychol. Sci. Soc. Sci.* <https://doi.org/10.1093/geronb/gbw129> (2016).
34. Bertoux, M. et al. Two distinct amnesic profiles in behavioral variant frontotemporal dementia. *Biol. Psychiatry* **75**, 582–588 (2014).
35. Hornberger, M., Piguet, O., Graham, A. J., Nestor, P. J. & Hodges, J. R. How preserved is episodic memory in behavioral variant frontotemporal dementia? *Neurology* **74**, 472–479 (2010).
36. Hornberger, M. & Piguet, O. Episodic memory in frontotemporal dementia: a critical review. *Brain* **135**, 678–692 (2012).
37. Wong, S., Flanagan, E., Savage, G., Hodges, J. R. & Hornberger, M. Contrasting prefrontal cortex contributions to episodic memory dysfunction in behavioural variant frontotemporal dementia and Alzheimer's disease. *PLoS ONE* **9**, e87778 (2014).
38. Cerman, J. et al. Subjective spatial navigation complaints - a frequent symptom reported by patients with subjective cognitive decline, mild cognitive impairment and Alzheimer's disease. *Curr. Alzheimer Res.* **15**, 219–228 (2017).
39. Tu, S., Spiers, H. J., Hodges, J. R., Piguet, O. & Hornberger, M. Egocentric versus allocentric spatial memory in behavioral variant frontotemporal dementia and Alzheimer's disease. *J. Alzheimers Dis.* **59**, 883–892 (2017).
40. Killian, N. J. & Buffalo, E. A. Grid cells map the visual world. *Nat. Neurosci.* **21**, 161–162 (2018).
41. Hafting, T., Fyhn, M., Molden, S., Moser, M.-B. & Moser, E. I. Microstructure of a spatial map in the entorhinal cortex. *Nature* **436**, 801–806 (2005).
42. McNaughton, B. L., Battaglia, F. P., Jensen, O., Moser, E. I. & Moser, M. B. Path integration and the neural basis of the 'cognitive map'. *Nat. Rev. Neurosci.* **7**, 663–678 (2006).

43. Fuhs, M. C. & Touretzky, D. S. A. Spin glass model of path integration in rat medial entorhinal cortex. *J. Neurosci.* **26**, 4266–4276 (2006).
44. Boccia, M., Nemmi, F. & Guariglia, C. Neuropsychology of environmental navigation in humans: review and meta-analysis of fMRI studies in healthy participants. *Neuropsychol. Rev.* **24**, 236–251 (2014).
45. Wolbers, T., Weiller, C. & Büchel, C. Neural foundations of emerging route knowledge in complex spatial environments. *Brain Res. Cogn. Brain Res.* **21**, 401–411 (2004).
46. Hartley, T., Maguire, E. A., Spiers, H. J. & Burgess, N. The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. *Neuron* **37**, 877–888 (2003).
47. O'Keefe, John & Nadel, L. *The Hippocampus as a Cognitive Map* (Oxford University Press, Oxford, 1978).
48. Loomis, J. M., Golledge, R. G. & Klatzky, R. L. Navigation system for the blind: auditory display modes and guidance. *Presence Teleoperators virtual Environments* **7**, 193–203 (1998).
49. Loomis, J. M. et al. Nonvisual navigation by blind and sighted: assessment of path integration ability. *J. Exp. Psychol. Gen.* **122**, 73–91 (1993).
50. Spiers, H. J. & Barry, C. Neural systems supporting navigation. *Curr. Opin. Behav. Sci.* **1**, 47–55 (2015).
51. Byrne, P., Becker, S. & Burgess, N. Remembering the past and imagining the future: a neural model of spatial memory and imagery. *Psychol. Rev.* **114**, 340–375 (2007).
52. Chiu, T. C. et al. Alpha modulation in parietal and retrosplenial cortex correlates with navigation performance. *Psychophysiology* **49**, 43–55 (2012).
53. Gaffan, D. Scene-specific memory for objects: a model of episodic memory impairment in monkeys with fornix transection. *J. Cogn. Neurosci.* **6**, 305–320 (1994).
54. King, J. A., Trinkl, I., Hartley, T., Vargha-Khadem, F. & Burgess, N. The hippocampal role in spatial memory and the familiarity–recollection distinction: a case study. *Neuropsychology* **18**, 405–417 (2004).
55. Feigenbaum, J. D. & Morris, R. G. Allocentric versus egocentric spatial memory after unilateral temporal lobectomy in humans. *Neuropsychology* **18**, 462–472 (2004).
56. Parslow, D. M. et al. Allocentric spatial memory activation of the hippocampal formation measured with fMRI. *Neuropsychology* **18**, 450–461 (2004).
57. Ekstrom, A. D. et al. Cellular networks underlying human spatial navigation. *Nature* **425**, 184–188 (2003).
58. Maguire, E. A. et al. Knowing where and getting there: a human navigation network. *Science* **280**, 921–924 (1998).
59. Auger, S. D., Mullally, S. L. & Maguire, E. A. Retrosplenial cortex codes for permanent landmarks. *PLoS ONE* **7**, e43620 (2012).
60. Auger, S. D. & Maguire, E. A. Assessing the mechanism of response in the retrosplenial cortex of good and poor navigators. *Cortex* **49**, 2904–2913 (2013).
61. Moffat, S. D., Kennedy, K. M., Rodrigue, K. M. & Raz, N. Extrahippocampal contributions to age differences in human spatial navigation. *Cereb. Cortex* **17**, 1274–1282 (2007).
62. Aggleton, J. P., Pralus, A., Nelson, A. J. D. & Hornberger, M. Thalamic pathology and memory loss in early Alzheimer's disease: moving the focus from the medial temporal lobe to Papez circuit. *Brain* **139**, 1877–1890 (2016).
63. Aggleton, J. P. & Nelson, A. J. D. Why do lesions in the rodent anterior thalamic nuclei cause such severe spatial deficits? *Neurosci. Biobehav. Rev.* **54**, 131–144 (2015).
64. Doeller, C. F., Barry, C. & Burgess, N. Evidence for grid cells in a human memory network. *Nature* **463**, 657–661 (2010).
65. Burgess, N., Barry, C. & O'Keefe, J. An oscillatory interference model of grid cell firing. *Hippocampus* **17**, 801–812 (2007).
66. Taube, J. S., Muller, R. U. & Ranck, J. B. Head-direction cells recorded from the postsubiculum in freely moving rats. II. Effects of environmental manipulations. *J. Neurosci.* **70**, 436–447 (1990).
67. Muller, R. U., Ranck Jr., J. B. & Taube, J. S. Head direction cells: properties and functional significance. *Curr. Opin. Neurobiol.* **6**, 196–206 (1996).
68. Shine, J. P., Valdes-Herrera, J. P., Hegarty, M. & Wolbers, T. The human retrosplenial cortex and thalamus code head direction in a global reference frame. *J. Neurosci.* **36**, 6371–6381 (2016).
69. Lever, C., Burton, S., Jeewajee, A., Keefe, J. O. & Burgess, N. Europe PMC funders group boundary vector cells in the subiculum of the hippocampal formation. *J. Neurosci.* **29**, 9771–9777 (2010).
70. Mahmood, O., Adamo, D., Briceno, E. & Moffat, S. D. Age differences in visual path integration. *Behav. Brain Res.* **205**, 88–95 (2009).
71. Alexander, A. S. & Nitz, D. A. Retrosplenial cortex maps the conjunction of internal and external spaces. *Nat. Neurosci.* **18**, 1143–1151 (2015).
72. Czajkowski, R. et al. Encoding and storage of spatial information in the retrosplenial cortex. *Proc. Natl Acad. Sci. USA* **111**, 8661–8666 (2014).
73. Bird, C. M., Keidel, J. L., Ing, L. P., Horner, A. J. & Burgess, N. Consolidation of complex events via reinstatement in posterior cingulate cortex. *J. Neurosci.* **35**, 14426–14434 (2015).
74. Dhindsa, K. et al. Examining the role of the temporo-parietal network in memory, imagery, and viewpoint transformations. *Front. Hum. Neurosci.* **8**, 1–13 (2014).
75. Vass, L. K. & Epstein, R. A. Abstract representations of location and facing direction in the human brain. *J. Neurosci.* **33**, 6133–6142 (2013).
76. Clark, B. J., Brown, J. E. & Taube, J. S. Head direction cell activity in the anterodorsal thalamus requires intact supragenual nuclei. *J. Neurophysiol.* **108**, 2767–2784 (2012).
77. Knight, R. & Hayman, R. Allocentric directional processing in the rodent and human retrosplenial cortex. *Front. Hum. Neurosci.* **8**, 1–5 (2014).
78. Chersi, F. & Pezzulo, G. Using hippocampal-striatal loops for spatial navigation and goal-directed decision-making. *Cogn. Process.* **13**, 125–129 (2012).
79. Sheynikhovich, D., Chavarriaga, R., Strössl, T., Arleo, A. & Gerstner, W. Is there a geometric module for spatial orientation? Insights from a rodent navigation model. *Psychol. Rev.* **116**, 540–566 (2009).
80. Elduayen, C. & Save, E. The retrosplenial cortex is necessary for path integration in the dark. *Behav. Brain Res.* **272**, 303–307 (2014).
81. Mullally, S. L. & Maguire, E. A. A new role for the parahippocampal cortex in representing space. *J. Neurosci.* **31**, 7441–7449 (2011).
82. Iaria, G., Palermo, L., Comitteri, G. & Barton, J. J. S. Age differences in the formation and use of cognitive maps. *Behav. Brain Res.* **196**, 187–191 (2009).
83. Moffat, S. D. et al. Effects of age on virtual environment place navigation and allocentric cognitive mapping. *Behav. Neurosci.* **116**, 851–859 (2002).
84. Gazova, I. et al. Spatial navigation in young versus older adults. *Front. Aging Neurosci.* **5**, 1–8 (2013).
85. Moffat, S. D. Aging and spatial navigation: what do we know and where do we go? *Neuropsychol. Rev.* **19**, 478–489 (2009).
86. Heo, S. et al. Resting hippocampal blood flow, spatial memory and aging. *Brain Res.* **1315**, 119–127 (2010).
87. Bach, M. E. et al. Age-related deficits in spatial memory are correlated with deficits in the late phase of hippocampal long-term potentiation in vitro and are attenuated by drugs that enhance the cAMP signaling pathway. *Proc. Natl Acad. Sci. USA* **96**, 5280–5285 (1999).
88. Driscoll, I. et al. Longitudinal pattern of regional brain volume change differentiates normal aging from MCI. *Neurology* **72**, 1906–1913 (2009).
89. Lalonde-Parsi, M.-J. & Lamontagne, A. Perception of self-motion and regulation of walking speed in young-old adults. *Motor Control* **19**, 191–206 (2015).
90. Holden, H. M. & Gilbert, P. E. Less efficient pattern separation may contribute to age-related spatial memory deficits. *Front. Aging Neurosci.* **4**, 1–6 (2012).
91. Lester, A. W., Moffat, S. D., Wiener, J. M., Barnes, C. A. & Wolbers, T. The aging navigational system. *Neuron* **95**, 1019–1035 (2017).
92. Carpenter, H. E., Kelly, K. B., Bizon, J. L. & Frazier, C. J. Age-related changes in tonic activation of presynaptic versus extrasynaptic γ -aminobutyric acid type B receptors in rat medial prefrontal cortex. *Neurobiol. Aging* **45**, 88–97 (2016).
93. Rodgers, M. K., Sindone, J. A. & Moffat, S. D. Effects of age on navigation strategy. *Neurobiol. Aging* **33**, 202.e15–202.e22 (2012).
94. Zheng Bian & George Andersen, J. Aging and the perception of egocentric distance. *Psychol. Aging* **28**, 813–825 (2013).
95. Norman, J. F., Adkins, O. C., Norman, H. F., Cox, A. G. & Rogers, C. E. Aging and the visual perception of exocentric distance. *Vision Res.* **109**, 52–58 (2015).
96. Vandenberg, S. G. & Kuse, A. R. Mental rotations, a group test of three-dimensional spatial visualization. *Percept. Mot. Skills* **47**, 599–604 (1978).
97. Money, J. et al. *A standardized road-map test of direction sense*; Manual (Johns Hopkins Press, Baltimore, MD, 1965).
98. Mitolo, M. et al. Relationship between spatial ability, visuospatial working memory and self-assessed spatial orientation ability: a study in older adults. *Cogn. Process.* **16**, 165–176 (2015).
99. Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F. & Epstein, R. A. Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus* **23**, 515–528 (2013).
100. Mapstone, M., Steffenella, T. M. & Duffy, C. J. A visuospatial variant of mild cognitive impairment: getting lost between aging and AD. *Neurology* **60**, 802–808 (2003).
101. Cushman, L. A. & Duffy, C. J. Virtual reality identifies navigational deficits in Alzheimer disease and cognitive aging. *Nat. Clin. Pract. Neurol.* **4**, 638–639 (2008).
102. Cogné, M. et al. The contribution of virtual reality to the diagnosis of spatial navigation disorders and to the study of the role of navigational aids: a systematic literature review. *Ann. Phys. Rehabil. Med.* **60**, 164–176 (2017).
103. Pengas, G. et al. The relationship of topographical memory performance to regional neurodegeneration in Alzheimer's disease. *Front. Aging Neurosci.* **4**, 1–10 (2012).
104. Jheng, S. S. & Pai, M. C. Cognitive map in patients with mild Alzheimer's disease: a computer-generated arena study. *Behav. Brain Res.* **200**, 42–47 (2009).
105. Serino, S. & Riva, G. Getting lost in Alzheimer's disease: a break in the mental frame syncing. *Med. Hypotheses* **80**, 416–421 (2013).
106. Irish, M. et al. Scene construction impairments in Alzheimer's disease - a unique role for the posterior cingulate cortex. *Cortex* **73**, 10–23 (2015).
107. Padurariu, M., Cioaba, A., Mavroudis, I., Fotiou, D. & Baloyannis, S. Hippocampal neuronal loss in the CA1 and CA3 areas of Alzheimer's disease patients. *Psychiatr. Danub.* **24**, 152–158 (2012).
108. Weniger, G., Rühleder, M., Lange, C., Wolf, S. & Irl, E. Egocentric and allocentric memory as assessed by virtual reality in individuals with amnesic mild cognitive impairment. *Neuropsychologia* **49**, 518–527 (2011).
109. Tan, R. H., Wong, S., Hodges, J. R., Halliday, G. M. & Hornberger, M. Retrosplenial cortex (BA 29) volumes in behavioral variant frontotemporal dementia and Alzheimer's disease. *Dement. Geriatr. Cogn. Disord.* **35**, 177–182 (2013).
110. Morganti, F., Stefanini, S. & Riva, G. From allo- to egocentric spatial ability in early Alzheimer's disease: a study with virtual reality spatial tasks. *Cogn. Neurosci.* **4**, 171–180 (2013).
111. Hort, J. et al. Spatial navigation deficit in amnesic mild cognitive impairment. *Proc. Natl Acad. Sci. USA* **104**, 4042–4047 (2007).
112. Jack, C. R. et al. Suspected non-Alzheimer disease pathophysiology—concept and controversy. *Nat. Rev. Neurol.* **12**, 117–124 (2016).
113. Delploly, A. R., Rankin, K. P., Mucke, L., Miller, B. L. & Gorno-Tempini, M. L. Spatial cognition and the human navigation network in AD and MCI. *Neurology* **69**, 986–997 (2007).
114. Dubois, B. & Albert, M. L. Amnesic MCI or prodromal Alzheimer's disease? *Lancet Neurol.* **3**, 246–248 (2004).
115. Laczó, J., Andel, R., Vyhalek, M. & Vlcek, K. APOE and spatial navigation in amnesic MCI: results from a computer-based test. *Neuropsychology* **28**, 676–684 (2014).
116. Julkunen, V. et al. Cortical thickness analysis to detect progressive mild cognitive impairment: a reference to Alzheimer's disease. *Dement. Geriatr. Cogn. Disord.* **28**, 404–412 (2009).
117. Mokrisova, I. et al. Real-space path integration is impaired in Alzheimer's disease and mild cognitive impairment. *Behav. Brain Res.* **307**, 150–158 (2016).
118. Laczó, J. et al. Spatial navigation testing discriminates two types of amnesic mild cognitive impairment. *Behav. Brain Res.* **202**, 252–259 (2009).
119. Genin, E. et al. APOE and Alzheimer disease: a major gene with semi-dominant inheritance. *Mol. Psychiatry* **16**, 903–907 (2011).
120. Scallil, R. I., Schott, J. M., Stevens, J. M., Rossor, M. N. & Fox, N. C. Mapping the evolution of regional atrophy in Alzheimer's disease: unbiased analysis of fluid-registered serial MRI. *Proc. Natl Acad. Sci. USA* **99**, 4703–4707 (2002).

121. Pengas, G., Hodges, J. R., Watson, P. & Nestor, P. J. Focal posterior cingulate atrophy in incipient Alzheimer's disease. *Neurobiol. Aging* **31**, 25–33 (2010).
122. Fennema-Notestine, C. et al. Structural MRI biomarkers for preclinical and mild Alzheimer's disease. *Hum. Brain Mapp.* **30**, 3238–3253 (2009).
123. Hämäläinen, A. et al. Voxel-based morphometry to detect brain atrophy in progressive mild cognitive impairment. *Neuroimage* **37**, 1122–1131 (2007).
124. Whitwell, J. L. et al. MRI correlates of neurofibrillary tangle pathology at autopsy: a voxel-based morphometry study. *Neurology* **71**, 743–749 (2008).
125. van Groen, T. & Michael Wyss, J. Connections of the retrosplenial granular a cortex in the rat. *J. Comp. Neurol.* **300**, 593–606 (1990).
126. Tan, C. C., Yu, J. T. & Tan, L. Biomarkers for preclinical Alzheimer's disease. *J. Alzheimers Dis.* **42**, 1051–1069 (2014).
127. Patel, K. T. et al. Default mode network activity and white matter integrity in healthy middle-aged ApoE4 carriers. *Brain Imaging Behav.* **7**, 60–67 (2013).
128. Pihlajamäki, M. et al. Evidence of altered posteromedial cortical fMRI activity in subjects at risk for Alzheimer disease. *Alzheimer Dis. Assoc. Disord.* **24**, 28–36 (2010).
129. Skoog, I. et al. Cerebrospinal fluid beta-amyloid 42 is reduced before the onset of sporadic dementia: a population-based study in 85-year-olds. *Dement. Geriatr. Cogn. Disord.* **15**, 169–176 (2003).
130. Villemagne, V. L., Fodero-Tavoletti, M. T., Masters, C. L. & Rowe, C. C. Tau imaging: early progress and future directions. *Lancet Neurol.* **14**, 114–124 (2015).
131. Johnson, K. A. et al. Tau positron emission tomographic imaging in aging and early Alzheimer disease. *Ann. Neurol.* **79**, 110–119 (2016).
132. Weston, P. S. J. et al. Presymptomatic cortical thinning in familial Alzheimer disease: a longitudinal MRI study. *Neurology* **87**, 2050–2057 (2016).
133. Yassen, A. L., Raber, J., Miller, J. K. & Piper, B. J. Sex, but not apolipoprotein E polymorphism, differences in spatial performance in young adults. *Arch. Sex. Behav.* **44**, 2219–2226 (2015).
134. Bunce, D. et al. APOE genotype and cognitive change in young, middle-aged, and older adults living in the community. *J. Gerontol. A Biol. Sci. Med. Sci.* **69**, 379–386 (2014).
135. Salvato, G., Patai, E. Z., McCloud, T. & Nobre, A. C. Apolipoprotein ε4 breaks the association between declarative long-term memory and memory-based orienting of spatial attention in middle-aged individuals. *Cortex* **82**, 206–216 (2016).
136. Greenwood, P. M., Lambert, C., Sunderland, T. & Parasuraman, R. Effects of apolipoprotein E genotype on spatial attention, working memory, and their interaction in healthy, middle-aged adults: results from the National Institute of Mental Health's BIOCARD Study. *Neuropsychology* **2**, 199–211 (2015).
137. Parasuraman, R., Greenwood, P. M. & Sunderland, T. The apolipoprotein E gene, attention, and brain function. *Neuropsychology* **16**, 254–274 (2002).
138. Evans, S. et al. Cognitive and neural signatures of the APOE E4 allele in mid-aged adults. *Neurobiol. Aging* **35**, 1615–1623 (2014).
139. Berteau-Pavy, F., Park, B. & Raber, J. Effects of sex and APOE epsilon 4 on object recognition and spatial navigation in the elderly. *Neuroscience* **147**, 6–17 (2007).
140. Bott, J.-B. et al. APOE sensitive cholinergic sprouting compensates for hippocampal dysfunctions due to reduced entorhinal input. *J. Neurosci.* **36**, 10472–10486 (2016).
141. Risacher, S. L. et al. APOE effect on Alzheimer's disease biomarkers in older adults with significant memory concern. *Alzheimers Dement.* **11**, 1417–1429 (2015).
142. Amariglio, R. E. et al. Specific SMC in older persons may indicate poor cognitive function. *J. Am. Geriatr. Soc.* **59**, 1612–1617 (2011).
143. Amariglio, R. E. et al. Subjective cognitive complaints and amyloid burden in cognitively normal older individuals. *Neuropsychologia* **50**, 2880–2886 (2012).
144. Hort, J. et al. Effect of donepezil in Alzheimer disease can be measured by a computerized human analog of the Morris water maze. *Neurodegener. Dis.* **13**, 192–196 (2014).
145. Laczó, J. et al. Scopolamine disrupts place navigation in rats and humans: a translational validation of the hidden goal task in the Morris water maze and a real maze for humans. *Psychopharmacol.* **234**, 535–547 (2016).
146. Coutrot, A. et al. Global determinants of navigation ability. Preprint at <https://www.biorxiv.org/content/early/2017/09/14/188870>.1 (2018).
147. Coutrot, A. et al. Virtual navigation tested on a mobile app (Sea Hero Quest) is predictive of real-world navigation performance: preliminary data. Preprint at <https://www.biorxiv.org/content/early/2018/04/22/305433> (2018).
148. Coughlan, G. et al. Impact of sex and APOE status on spatial navigation in pre-symptomatic Alzheimer's disease. Preprint at <https://www.biorxiv.org/content/early/2018/03/23/287722> (2018).
149. Vorhees, C. V. & Williams, M. T. Morris water maze: procedures for assessing spatial and related forms of learning and memory. *Nat. Protoc.* **1**, 848–858 (2006).
150. Vann, S. D., Aggleton, J. P. & Maguire, E. A. What does the retrosplenial cortex do? *Nat. Rev. Neurosci.* **10**, 792–802 (2009).

Author contributions

M.H. and G.C. contributed to all aspects of the manuscript. J.L. and J.H. contributed to reviewing and editing the manuscript before submission. A.-M.M. contributed to writing of the manuscript.

Competing interests

The authors declare no competing interests.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Reviewer information

Nature Reviews Neurology thanks T. Brandt, K. Possin and T. Wolbers for their contribution to the peer review of this work.

RELATED LINK

Sea Hero Quest: www.seaheroquest.com