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Diagnostic Differentiation of Mild Cognitive Impairment Due to Alzheimer's Disease Using a Hippocampus-Dependent Test of Spatial Memory

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ABSTRACT: The hippocampus is one of the earliest brain regions affected in Alzheimer's disease (AD) and tests of hippocampal function have the potential to detect AD in its earliest stages. Given that the hippocampus is critically involved in allocentric spatial memory, this study applied a short test of spatial memory, the 4 Mountains Test (4MT), to determine whether test performance can differentiate mild cognitive impairment (MCI) patients with and without CSF biomarker evidence of underlying AD and whether the test can distinguish patients with MCI and mild AD dementia when applied in different cultural settings. Healthy controls (HC), patients with MCI, and mild AD dementia were recruited from study sites in UK and Italy. Study numbers were: HC (UK 20, Italy 10), MCI (UK 21, Italy 14), and AD (UK 11, Italy 9). Nineteen UK MCI patients were grouped into CSF biomarker-positive (MCI+, $n = 10$) and biomarker-negative (MCI–, $n = 9$) subgroups. Behavioral data were correlated with hippocampal volume and cortical thickness of the precuneus and posterior cingulate gyrus. Spatial memory was impaired in both UK and Italy MCI and AD patients. Test performance additionally differentiated between MCI+ and MCI– subgroups ($P = 0.001$). A 4MT score of $\leq$8/15 was associated with 100% sensitivity and 90% specificity for detection of early AD (MCI+ and mild AD dementia) in the UK population, and with 100% sensitivity and 50% specificity for detection of MCI and AD in the Italy sample. 4MT performance correlated with hippocampal volume in the UK population and cortical thickness of the precuneus in both study populations. In conclusion, performance on a hippocampus-sensitive test of spatial memory differentiates MCI due to AD with high diagnostic sensitivity and specificity. The observation that similar diagnostic sensitivity was obtained in two separate study populations, allied to the scalability and usability of the test in community memory clinics, supports future application of the 4MT in the diagnosis of pre-dementia due to AD.

KEY WORDS: Alzheimer's disease; mild cognitive impairment; spatial memory; hippocampus; precuneus

INTRODUCTION

Alzheimer's disease (AD) is the commonest cause of dementia and its management represents one of the highest priorities for health systems worldwide. It is now recognized that the AD pathological process begins many years before the onset of dementia and this is reflected in the replacement of the 1984 NINDS-ADRDA diagnostic criteria for AD by new criteria that encompass the concept of prodromal AD (Dubois et al., 2010) and that of mild cognitive impairment (MCI) as a pre-dementia stage of AD (Albert et al., 2011). However, MCI due to underlying AD may be clinically indistinguishable from MCI due to other causes, including non-neurodegenerative disorders such as anxiety. Furthermore, memory tests commonly used in clinical psychometric testing, such as the Rey Auditory Verbal Learning Test (RAVLT), the Logical Memory test of the Wechsler Memory Scale, or the various versions of the paired associate learning test (PAL) (Wechsler, 1945) lack diagnostic specificity for AD (Fowler et al., 2002).

Differentiation of MCI due to AD has major prognostic implications. However, while testing for AD biomarkers, in the form of amyloid-PET scanning or CSF studies of amyloid and tau, has discriminatory value their usage in routine clinical diagnostic practice is limited by their invasive nature, high cost, and restricted availability, all of which preclude their application to the wider population of patients with MCI that are diagnostic not in university hospitals but in community clinics.

An alternative strategy for identification of MCI due to AD involves the use of a theory-driven approach based on the knowledge that the hippocampus and related medial temporal lobe structures are affected from the earliest stages of AD. Evidence that the hippocampus is critically involved in spatial memory originates from the initial demonstration of place-

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related firing activity of hippocampal neurons in freely moving rats (O'Keefe and Dostrovsky, 1971), which led to the "cognitive map" theory of hippocampal function (O'Keefe and Nadel, 1978). Subsequent work has shown that the human hippocampus is also involved in spatial cognition, as part of a network of brain regions including the precuneus and posterior cingulate gyrus (Maguire et al., 1998; Burgess et al., 2001; Iaria et al., 2007).

The 4 Mountains Test (4MT) is a brief behavioral test of spatial memory designed to reflect hippocampal function (Hartley et al., 2007). Landscapes containing four mountains in differing configurations are computer-generated, with subsequent presentation of same- and rotated-view landscapes permitting assessment of allocentric (viewpoint-independent) spatial perception and memory.

The initial design and testing of the 4MT paradigm encompassed testing of spatial and nonspatial perception and memory, the latter two conditions involving alterations of conditions such as lighting levels and vegetation color. In an initial study, patients with focal hippocampal damage exhibited impairment of spatial memory but preservation of spatial perception, nonspatial perception, and nonspatial memory (Hartley et al., 2007). Given the early involvement of the hippocampus in AD and its relative sparing in non-AD dementias, and the clinical importance of differential diagnosis of dementia, two subsequent studies applied the 4MT to groups of patients with dementia. Bird et al. (2010) showed that performance on the 4MT spatial memory test was impaired in patients with early AD and discriminated these patients from those with frontotemporal dementia (FTD), representing a non-AD dementia. Pengas et al. (2010) used the 4MT as one of several behavioral tasks of spatial memory, with similar observations that spatial memory testing differentiated between AD and clinical subtypes of FTD (Pengas et al., 2010).

This study builds on the results from these previous patient studies and critically the focus shifts from differential diagnosis of established dementia to that of MCI. In view of the substantial neuropathological evidence of hippocampal damage in AD occurring prior to the onset of dementia (Braak and Braak, 1991; Arriagada et al., 1992; Price et al., 2009) the central study hypothesis was that spatial memory performance (as tested using the 4MT) is impaired in prodromal AD, manifest as MCI. As proof of hypothesis would have significant implications for the use of this test in clinical diagnostic practice, and in view of the importance attached worldwide to the detection of AD prior to the onset of dementia, several study objectives were defined. The primary objective was to determine whether testing of spatial memory would differentiate MCI due to AD from MCI without biomarker evidence of underlying AD, using CSF AD biomarker profiles to distinguish the two groups of MCI patients. The second objective was to determine whether performance on the 4MT correlated with structural measurements of brain regions involved in spatial processing, specifically the hippocampus, precuneus, and posterior cingulate gyrus. The third objective was to evaluate the discriminative ability of the 4MT when applied to patients recruited from countries with different clinical diagnostic practices. To this effect, patients with MCI and early AD were recruited in two parallel studies involving memory clinics in the UK and Italy, with patient data in each instance compared locally with those from matched control subjects.

METHODS AND MATERIALS

Subjects

Patients with MCI and mild AD dementia were recruited at two sites. At both sites, MCI and AD were diagnosed, respectively, according to Petersen (Petersen, 2004) and McKhann criteria (McKhann et al., 2011). For patients with AD dementia, mild dementia was determined by Mini-Mental State Examination (MMSE) (Folstein et al., 1975) scores >22 and a Clinical Dementia Rating (CDR) (Morris, 1993) of one, the latter score representing the overall CDR, rather than CDR—Sum of Boxes, as a global measure of the severity of cognitive impairment.

All MCI patients had MMSE scores ≥ 26 (UK) or ≥ 25 (Italy) with CDR ≤ 0.5. MCI was diagnosed in clinic on the basis of a history of change in cognitive performance from baseline, corroborated by an informant, with objective evidence of cognitive decline, in the absence of dementia and presence of largely intact functional activities. For UK-based patients objective cognitive decline was established using either the Addenbrooke's Cognitive Examination—Revised (Mioshi et al., 2006) or the Queen Square Screening Test for Cognitive Deficits (©EK Warrington 2003) plus MMSE. UK MCI patients were not stratified further into amnestic/non-amnestic/multi-domain subsets. For Italy-based patients, objective cognitive decline was established using the MMSE and short story recall test (Novelli et al., 1986; Caffarra et al., 2002) and only patients with amnestic MCI (single- or multi-domain) were recruited for the study, in line with the clinical practice at this Italian site of stratifying MCI patients to assess risk of conversion to AD, patients with amnestic MCI being considered to have a higher risk of converting to AD compared to patients with non-amnestic MCI (Petersen, 2004).

The exclusion criteria include (i) evidence of significant vascular lesion load on imaging, (ii) Hachinski Ischemic Score $>$ 4 (Moroney et al., 1997). "Significant vascular lesion load" was defined as the presence of cortical infarcts, extensive, and/or confluent white matter hyperintensities (WMH) and WMH $>$ 10 mm diameter. These guidelines for determining the diagnostic significance of WMH are comparable to those listed in the positioning paper by Wardlaw et al. (2013) on neuroimaging standards for research into small vessel disease and also to the imaging criteria outlined in the Sachdev et al. (2014) recommendations for the diagnosis of vascular cognitive disorder.

UK-based patients were recruited from the Cognitive Disorders Clinic, Hurstwood Park Neurological Centre, Hayward Heath, West Sussex, and consisted of 21 MCI and

TABLE 1.

Demographics of UK and Italy Participants

	UK study population			
	HC $n = 20$	MCI $n = 21$	AD $n = 11$	*P*
Gender, M:F	7:13	15:6	5:6	0.06
Age, years	62.6 (6.1)	68.1 (8.9)	66.2 (8.9)	0.10
Education, years	12.1 (1.7)	11.7 (1.9)	12.4 (2.2)	0.6

	Italy study population			
	HC $n = 10$	MCI $n = 14$	AD $n = 9$	*P*
Gender, M:F	7:3	6:8	3:6	0.3
Age, years	71.3 (4.0)	73.6 (6.9)	74.3 (5.1)	0.5
Education, years	12.0 (2.8)	9.4 (3.9)	9.4 (4.0)	0.2

(top) All UK participants and (bottom) Italy participants.
HC = healthy controls, MCI = mild cognitive impairment, AD = Alzheimer's disease dementia.

11 AD patients; as part of their diagnostic workup 19 MCI patients testing for CSF AD biomarkers using the CSF collection protocol and ELISA assay kits (Innotest, Innogenetics, Ghent, Belgium) as outlined in the CSF substudy of the Alzheimer's Disease Neuroimaging Initiative (Shaw et al., 2009). Patients were divided into MCI biomarker-positive (MCI+), indicative of prodromal AD in line with the criteria of Dubois et al. (2010) and Albert et al. (2011), and MCI biomarker-negative (MCI−) groups on the basis of abnormal CSF β-amyloid$_{1–42}$ and tau levels according to updated normal ranges for these indices (Mulder et al., 2010). These were as follows: CSF β-amyloid$_{1–42}$>550pg/mL, CSF tau <375pg/mL, and tau:amyloid ratio <0.8. MCI+ patients were classified accordingly on the basis of CSF β-amyloid$_{1–42}$ < 550pg/mL and CSF tau > 375pg/mL, with tau:amyloid ratio > 0.8. For the MCI− group, all but three patients had CSF amyloid and tau levels in the normal range, with correspondingly normal CSF tau:amyloid ratios; the remaining three patients had high tau levels but had normal range amyloid levels (>900pg/mL in all cases) and additional had a history of stable cognitive function over a minimum 24-month follow-up period and as such were diagnosed clinically as having stable MCI.

Italy-based patients were recruited from the specialist dementia clinic at the Istituto Neurologico "Carlo Besta", Milan, and consisted of 14 MCI and 9 AD patients. MCI patients recruited at this site did not undergo amyloid-PET or CSF biomarker testing as part of their diagnostic workup, reflecting the clinical practice at this site. One patient was not included in the final analyses due to lack of engagement with the task.

At both sites, all patients underwent clinical and laboratory assessments (including blood tests for thyroid function, vitamin B12 status) to exclude potentially treatable causes of cognitive decline. All subjects observed to have a significant vascular lesion load on initial brain scanning were excluded from the study.

At both study sites age-matched healthy control (HC) subjects without a history of cognitive impairment were recruited (UK $n = 20$, Italy $n = 10$). Separate approval was obtained from the UK Research Ethics Committee South East Coast—Brighton and Sussex (references 10/H1107/23 and 13/LO/0277) and from the human subjects ethics committee of the Fondazione IRCCS Istituto Neurologico "Carlo Besta" (reference fMRI-AD). At both sites, the study was performed in accordance with the Declaration of Helsinki. All participants gave written informed consent.

Demographics

There were no significant differences between HC, MCI, and AD groups in terms of age, gender, and years of education when the UK and Italy cohorts were compared separately (Tables 1 and 2). A comparison of the UK and Italy control subjects revealed that the latter were significantly older (UK: age 62.6 ± 6.2 years, Italy age 71.3 ± 4.0 years, $t(28) = 4.1$, $P < 0.001$).

No significant differences in these demographics were noted on comparison of the UK MCI+ and MCI− subgroups, who were also matched for disease duration (Table 3).

Behavioral Studies

General neuropsychological assessment

UK and Italy subjects underwent a battery of neuropsychological tests. The following domains were tested, with the tests used in parentheses (where not otherwise specified, these were common to both centers): (1) episodic memory [UK: Rey Auditory Verbal Learning Test, RAVLT (Rey, 1941; Van der Elst et al., 2005); Italy: short story recall and Rey figure recall (Spinnler and Tognoni, 1987; Caffarra et al., 2002)], (2) attention and Executive function [Trail Making Test A and B (Reitan, 1958; Giovagnoli et al., 1996); Italy only: FAB (Appollonio et al., 2005)], (3) executive function [Lexical and semantic fluency (Benton et al., 1994; Novelli et al., 1986; Tombaugh et al., 1999)], (4) working memory [Digit span

TABLE 2.

Demographics of UK and Italy Participants

	UK MCI sub-groups		
	MCI−	MCI+	*P*
Gender, M:F	7:2	8:2	0.7
Age, years	65 (9.5)	68.1 (6.2)	0.4
Education, years	11.6 (1.9)	12.1 (2.1)	0.6
Disease duration, years	3.8 (0.4)	3.7 (0.8)	0.8

UK MCI patients grouped according to CSF AD biomarker status.
HC = healthy controls, MCI = mild cognitive impairment, AD = Alzheimer's disease dementia.

TABLE 3.

Neuropsychometric Results for UK MCI Patients, Grouped According to CSF AD Biomarker Status (Alpha = 0.004, Adjusted for Multiple Comparisons)

	MCI−	MCI+	*t*(df)	Uncorrected *P*
NART	116.3 (8.0)	109.1 (11.1)	1.5 (16)	0.2
MMSE	27.6 (0.7)	27.4 (1.3)	0.3 (17)	0.8
VOSP	17 (1.7)	16.4 (2.3)	0.6 (16)	0.5
RAVLT-DR	2.8 (2.7)	2.7 (1.8)	0.1 (16)	1.0
RAVLT-RP	0.6 (0.2)	0.6 (0.2)	−0.1 (16)	0.9
Lexical Fluency	42.9 (9.2)	36.9 (10.6)	1.3 (16)	0.2
Semantic Fluency	28.6 (3.9)	27.9 (6.7)	0.3 (16)	0.8
Trails A	37.3 (8.3)	43.8 (16.2)	−1.0 (16)	0.3
Trails B	82.6 (24.6)	125.0 (39.0)	−2.7 (16)	0.02
Digit Span	6.9 (1.5)	6.3 (0.8)	1.1 (16)	0.3

NART: National Adult Reading Test; MMSE: Mini-Mental State Examination; VOSP: Visual Object and Space Perception (Object decision); RAVLT-DR: delayed recall; RAVLT-RP: recognition performance.

(Blackburn and Benton, 1957; Spinnler and Tognoni, 1987); Italy only: Corsi block-tapping task (Spinnler and Tognoni, 1987)], (5) higher visual processing [Object decision (James and Warrington, 1991)], (6) Premorbid IQ [UK only: National Adult Reading Test (NART) estimated IQ (Nelson and Willison, 1991)].

With regard to assessment of episodic memory, differences in the tests used at the two study sites reflected local differences in clinical practice. Other differences in test administration between sites related to scoring of the Trail making B test, with UK and Italy participants who were unable to complete the test given scores of 300 and 600, respectively, in reflection of local practice, and administration of the semantic fluency test, with two noun categories administered in the UK while an additional category was assessed in Italy. Again in keeping with local clinical diagnostic practice, UK neuropsychometric data are presented as raw scores whereas Italy data are corrected for age and education, with the exception of the VOSP data which are presented as raw scores due to the lack of an age/education correction algorithm for this particular test.

In the UK, the test battery outlined above was not undertaken in three HC subjects, who opted out of these tests, and two MCI patients (one with no CSF biomarker data, one CSF biomarker negative) who declined testing due to anxiety. The NART was not performed in one MCI patient who did not undergo CSF studies.

The 4 mountains test

A fuller description of the 4MT is provided in the article by Hartley et al. (2007).

To maintain consistency with the terminology used in previous work involving application of the 4MT (Hartley et al., 2007; Bird et al., 2010; Pengas et al., 2010), the allocentric spatial perception and memory subtests of the 4MT are referred to as place perception (PP) and place memory (PM) tests, and abbreviated accordingly in the tables and figures. Testing was preceded by the presentation of three training slides to aid familiarization with the task. In brief, the task involves presentation of computer-generated landscapes containing four mountains with a semicircular mountain range in the background. Participants are shown a sample landscape along with a panel of four landscapes, consisting of the original landscape seen from another viewpoint and three foils. For the perceptual task, this panel is presented at the same time as the target image, whereas for the memory task the panel is presented after a 2s delay. The three foils for each test item were generated from the target image as follows. For the "spatial" foil the position of one mountain is shifted but the order of the four mountains around the center of the image is preserved. For the "ordinal" foil the ordering of the mountains about the origin is altered by exchanging the location of two or more of the mountains. In the "elemental" foil, the shape and/or size of one mountain is changed, whereas spatial layout is preserved. The design and usage of these foils helped to ensure that generation of an allocentric representation of the presented image would be required to distinguish the target image from the foils while maintaining local visual similarities between target and foils.

In the PP task a maximum of 30s is given for a forced choice match-to-sample. In the PM task a 4MT landscape is shown for 10 s, followed by a 2s interval during which the landscape is removed, with subsequent presentation of the original landscape seen from another viewpoint and three foils (Fig. 1), with a maximum of 30s given for the forced choice delayed match-to-sample.

Non-spatial features (e.g., lighting level, extent of vegetation cover) varied between presentation and testing to ensure that correct matching to sample could not be made on the basis of non-spatial aspects of the task.

All landscapes are shown in printed form on A4 sized pages within a ring-bound booklet such that, for the PP task, the target image is shown on one page and the four match-to-sample choices simultaneously on a separate page. For the PM task, after presentation of the target image, participants are shown a blank white page for 2s before being presented with the four match-to-sample choices on a subsequent page. Total test duration was approximately 20 min.

In the Bird et al. (2010) and Pengas et al. (2010) studies, 15 PP and 15 PM scenes were presented, reflecting the fact that a common aim of both studies related to the comparison of spatial perception and spatial memory performance. In contrast Hartley and Harlow (2012) omitted the PP subtest altogether, in light of the study aim of determining an association between 4MT PM performance and hippocampal volume.

In this study, some of the UK patients were initially tested on the 4MT protocol including a 15 item PP; the remaining 16 UK participants (5 controls, 10 MCI, 1 AD) recruited subsequently and the Italy-based participants were tested on a shortened 6 item PP in view of the lack of study hypothesis associated with the PP component of the 4MT and to shorten

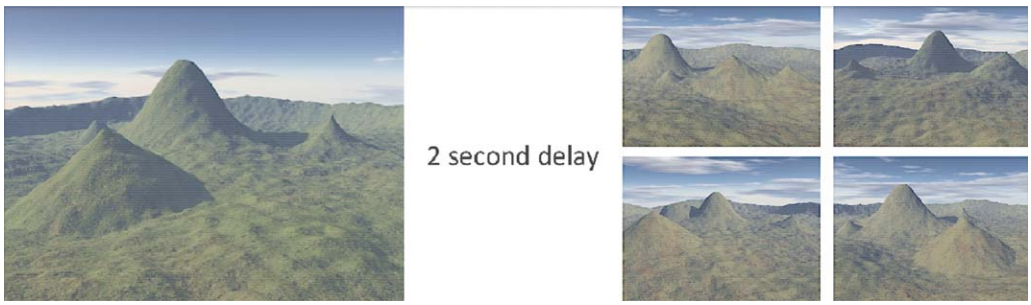

FIGURE 1. Sample 4MT place memory testing. A "4 Mountains" landscape (left panel) is initially presented for 8 s and then removed and a blank white page is shown for 2 s. After this 2 s delay participants are shown the initially viewed landscape, but from a rotated viewpoint, with three additional "foil" landscapes (right panel), as part of a delayed match-to-sample paradigm (correct response: bottom right landscape). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

test duration. Use of 15 or 6 item PP had no effect on the associated PM scores in the same individuals (e.g., MCI patients tested with 15 PP items, PM scores 7.3 ± 3.6; MCI patients tested with 6 PP items, PM scores 7.8 ± 1.9. $P = 0.7$).

Volumetric MRI Studies

UK

UK-based subjects underwent MRI on a 1.5 T scanner (Avanto, Siemens AG, Erlangen DE) at the Clinical Imaging Sciences Centre, Brighton and Sussex Medical School. Two AD patients were unable to tolerate MRI scanning. T1-weighted 3D volumetric MRI data were acquired by means of a magnetization-prepared rapid-acquisition gradient-echo (MPRAGE) sequence, having $1 \times 1 \times 1\text{mm}^3$ voxel size, TI = 600ms, TE = 4ms, TR = 1,160ms. Because of the logistical reasons, four patients from MCI+ group could not have a scan, structural correlations are therefore reported for the remaining 17 cases.

Italy

Italy-based subjects underwent MRI on a 3.0 T scanner (Achieva TX, Philips Medical Systems NV, Best NL). T1-weighted 3D volumetric data were acquired by means of a turbo field-echo sequence, having $1 \times 1 \times 1\text{mm}^3$ voxel size, TI = 1,223ms, TE = 4.6ms, TR = 9.9ms. All Italy subjects completed scanning but quantitative data could not be extracted from one MCI subject due to severe motion artifact, structural correlations are therefore reported for the remaining 22 cases.

Cortical thickness was measuring using the FreeSurfer workflow (Massachusetts General Hospital, Harvard University, Boston, MA), which, as detailed elsewhere (Fischl, 2012), involves iterative reconstruction of the white-gray matter interface and pial surface, and subsequent labeling with non-linear morphing to a probabilistic brain atlas. The Desikan probabilistic brain atlas was used (Desikan et al., 2006), with the posterior cingulate gyrus and precuneus chosen as regions of interest (ROIs) for quantitative analysis. All segmentations were manually cleaned up and refined by a specialized operator blinded to disease status.

Hippocampal volumes were measured using the FSL/FIRST tool (FMRIB, Oxford Centre for Functional Magnetic Resonance Imaging of the Brain, Oxford, UK) (Patenaude et al., 2011). This additional segmentation was undertaken in view of the current lack of consensus regarding the different semi-automated tools used to analyze hippocampal volume (Morey et al., 2009; Sánchez-Benavides et al., 2010; Mulder et al., 2014); on our images, preliminary expert evaluation revealed that FreeSurfer tended to include parts of other medial temporal structures such as the parahippocampal gyrus and amygdala.

These ROIs were specifically chosen to encompass regions that are affected early in AD and represent components of the brain network considered to underpin memory functions (Greicius et al., 2003; Buckner et al., 2008).

Statistical Analysis

For HC, MCI, and AD group data, ANOVA was used to determine between-group differences for the demographic and neuropsychometric data. Post hoc pair-wise comparisons were undertaken using the conservative Scheffé test, which controls for family wise error rate across all planned contrasts. Two-tailed *t*-tests were used for comparison of MCI+ and MCI− subgroups; the alpha threshold was Bonferroni adjusted for multiple comparisons (12 comparisons inclusive of general and 4MT psychometric measures; alpha = 0.004). To allow comparison between patients who were tested with 15 and 6 PP scenes, the former PP scores were rescaled to scores in the range of 0–6.

Place memory scores were correlated with total (i.e., combined left and right) hippocampal volumes. Additional correlations were undertaken with total cortical thickness of the precuneus and posterior cingulate gyrus, in view of previous studies that have suggested a role for these brain regions in spatial memory (Pengas et al., 2012). Age was inserted as covariate for both analyses, having excluded effects of sex. Total

TABLE 4.

4MT Place Perception (PP; Scored Out of 6) and Place Memory (PM; Scored Out of 15) Scores for all UK Participants (Top) and Italy Participants (Bottom)

	HC	MCI	AD	ANOVA	HC versus MCI	HC versus AD	MCI versus AD
All UK participants							
PP	4.9 (0.9)	4.3 (1.2)	2.8 (0.8)	$F(2,49) = 16.0$ $P < 0.001$	$P = 0.1$	$P < 0.001$	$P = 0.001$
PM	11.1 (2.1)	7.6 (2.7)	4.6 (1.3)	$F(2,49) = 32.0$ $P < 0.001$	$P < 0.001$	$P < 0.001$	$P = 0.004$
Italy participants							
PP	4.0 (0.8)	3.3 (1.0)	2.7 (1.0)	$F(2,30) = 4.6$ $P = 0.02$	$P = 0.3$	$P = 0.02$	$P = 0.3$
PM	9.0 (2.3)	5.8 (1.5)	4.8 (2.2)	$F(2,30) = 12.7$ $P < 0.001$	$P = 0.002$	$P < 0.001$	$P = 0.5$

HC = healthy controls; MCI = mild cognitive impairment; AD = Alzheimer's disease.

intracranial volume from Freesurfer segmentation was included as an additional covariate in hippocampal volume–place memory correlation analyses.

All correlations were undertaken using patient data only, with exclusion of control data to avoid biasing the correlations as a result of the strong group differences. A univariate general linear model was used to assess differences between HC, MCI, and AD quantitative MRI group data and between UK MCI +ve and MCI −ve subgroup data, age inserted as a covariate for comparisons involving the PCG and precuneus, age and TIV inserted as a covariates for hippocampal comparisons; Bonferroni adjusted for multiple comparisons; alpha = 0.02).

RESULTS

Behavioral Studies

General neuropsychometric assessment

Consistent with their diagnostic classification, MCI patients were impaired on tests of delayed recall and executive function whereas AD patients were impaired in all tested cognitive domains. The full breakdown of test scores, with the UK and Italy study populations tabulated separately, are provided in Supporting Information Tables S1 and S2.

There were no significant differences in the test scores obtained by the MCI− and MCI+ patients (Table 3).

4 Mountains Test

Place perception. For the UK study population, ANOVA revealed group differences in test performance ($P < 0.001$, Tables 4 and 5). Pairwise comparisons, corrected for multiple comparisons, revealed that the difference in scores was significant between HC and AD groups ($P < 0.001$) and between MCI and AD groups ($P = 0.001$). Further analyses revealed a significant difference between the MCI biomarker negative and AD groups only ($P < 0.001$). No significant differences were observed between the MCI subgroups or between MCI subgroups and HC.

For the Italy study population, ANOVA revealed group differences in test performance ($P = 0.02$, Tables 4 and 5). Pairwise comparisons, corrected for multiple comparisons,

TABLE 5.

MT Place Perception (PP; Scored Out of 6) and Place Memory (PM; Scored Out of 15) Scores for UK MCI Patients Grouped According to CSF AD Biomarker Status

	HC	MCI−	MCI+	AD	ANOVA	HC versus MCI−	HC versus MCI+	HC versus AD	MCI− versus MCI+	MCI− versus AD	MCI+ versus AD
PP	4.9 (0.9)	4.9 (1.2)	3.9 (0.9)	2.8 (0.8)	$F(3,46) = 13.8$ $P < 0.001$	$P = 1.0$	$P = 0.06$	$P < 0.001$	$P = 0.2$	$P < 0.001$	$P = 0.09$
PM	11.1 (2.1)	9.6 (1.6)	5.8 (2.3)	4.6 (1.3)	$F(3,46) = 34.3$ $P < 0.001$	$P = 0.3$	$P < 0.001$	$P < 0.001$	$P = 0.002$	$P < 0.001$	$P = 0.6$

HC = healthy controls; MCI − = MCI without CSF biomarker evidence of AD; MCI + = MCI with CSF biomarker evidence of AD; AD = Alzheimer's disease.

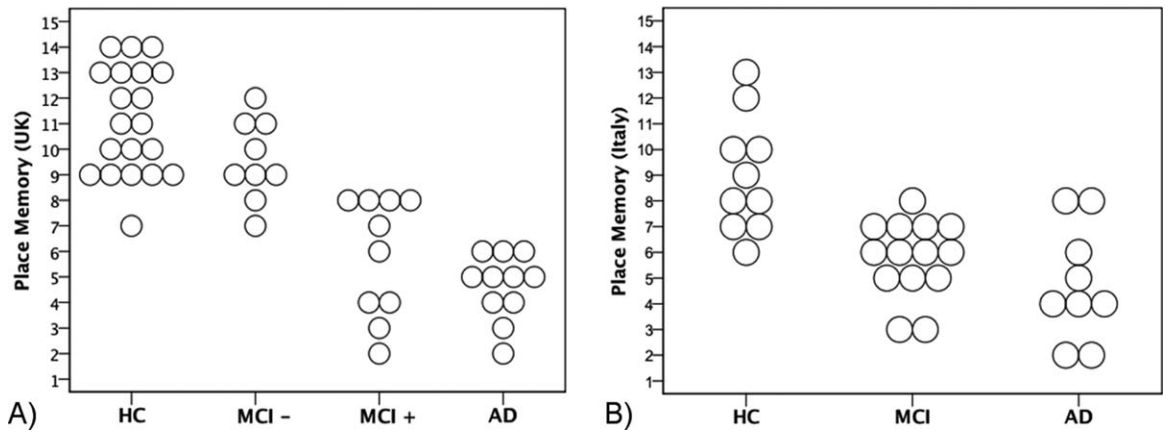

FIGURE 2. 4MT place memory test scores. (Top) UK study population, with MCI patients grouped by CSF AD biomarker status; (Bottom) Italy study population.

revealed a significant difference in PP performance between HC and AD groups ($P = 0.02$).

Place memory. For the UK study population, ANOVA revealed group differences in test performance ($P < 0.001$, Tables 4 and 5). Pairwise comparisons, corrected for multiple comparisons, revealed that the difference in scores was significant between HC and MCI groups ($P < 0.001$), between HC and AD groups ($P < 0.001$), and between MCI and AD groups ($P = 0.004$). Further analyses revealed significant differences in PM scores for the following pairwise group comparisons: HC versus MCI+ ($P < 0.001$), HC versus AD ($P < 0.001$), MCI− versus MCI+ ($P = 0.002$), and MCI− versus AD ($P < 0.001$). By comparison no significance difference in PM test scores was observed for the comparison between HC and MCI− ($P = 0.3$) or between MCI+ and AD ($P = 0.6$).

For the Italy study population, ANOVA revealed group differences in test performance ($P < 0.001$, Tables 4 and 5). Corrected pairwise comparisons revealed that significant differences in scores were observed for HC versus MCI ($P = 0.002$) and HC versus AD ($P < 0.001$) but not for MCI versus AD ($P = 0.5$).

Figure 2 shows the individual PM scores and the differences in score between participant groups, with data from UK and Italy participants represented separately.

Receiver Operating Characteristic Curves

The discriminative ability of 4MT place memory testing is illustrated by use of receiver operating characteristics (ROC) curves (Fig. 3). For the UK population, test performance is associated with an area under the curve of 0.98 (differentiating MCI+ and AD patients from controls and MCI− patients) and of 0.90 for the Italy population (differentiating MCI and AD patients from controls). PM scores of 8 or below were associated with 100% sensitivity and specificities of 90% and 50% for the UK and Italy study populations, respectively.

Correlations between spatial memory performance and quantitative MRI data

Partial correlations undertaken for the UK patient population (MCI and AD), corrected for age and total intracranial volume (hippocampal volume only), revealed, after averaging between left and right hemisphere, significant associations between 4MT PM score, hippocampal volume ($r = 0.42$, $P = 0.03$, not surviving the corrected alpha threshold of 0.02) and cortical thickness of the precuneus ($r = 0.55$, $P = 0.003$) but not the posterior cingulate gyrus ($r = 0.19$, $P = 0.4$). For the Italy patient population (MCI and AD) a significant association was observed with cortical thickness of the precuneus($r = 0.58$, $P = 0.006$) but not with hippocampal volume ($r = 0.09$, $P = 0.7$) or with cortical thickness of the posterior cingulate gyrus ($r = 0.34$, $P = 0.1$). Scatterplot representations of the correlations between behavioral data and measures of hippocampal volume and cortical thickness of the precuneus and posterior cingulate gyrus are provided in Figure 4.

Considering each hemisphere in isolation, no statistically significant effects were obtained.

Vertex level comparisons, applied to the pooled UK and Italy study data, revealed an association between PM and cortical thickness of the precuneus, lateral parietal, and supramarginal regions (Fig. 5).

DISCUSSION

Spatial memory performance, as evaluated using the brief 4MT, is impaired in patients presenting with mild cognitive impairment (MCI) with biomarker evidence of underlying Alzheimer's disease (AD). Performance on the 4MT place memory testing (PM) was significantly impaired in patients with MCI and AD compared to age- and gender-matched control subjects, in keeping with previously published results (Bird

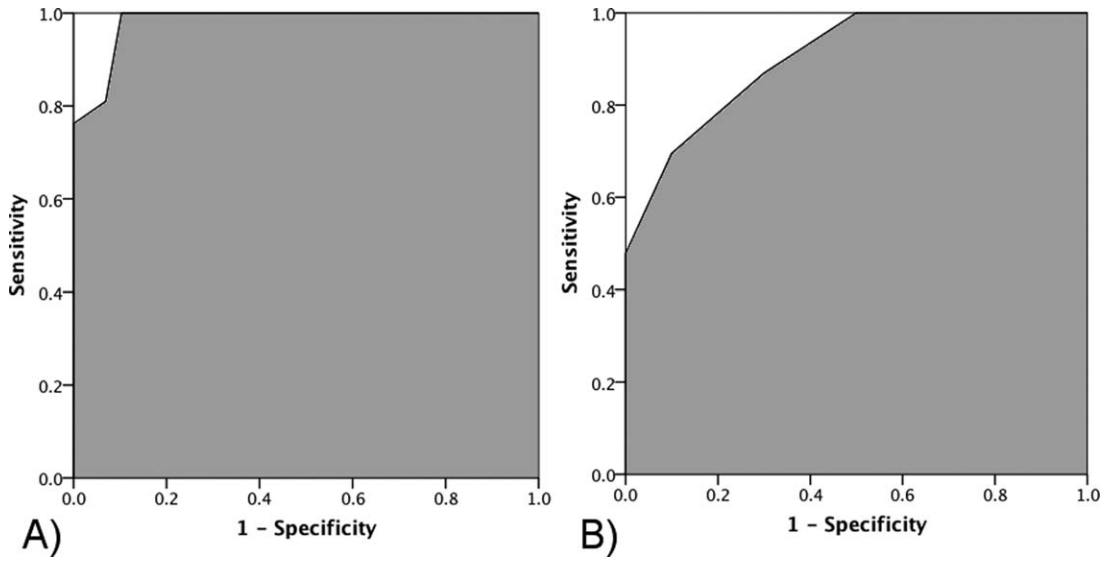

FIGURE 3. ROC curves. (Top) UK: discrimination of patients with evidence of AD (MCI+ plus AD dementia) from controls and MCI− patients. Area under ROC curve 0.98. (Bottom) Italy: discrimination of patients (MCI and AD) from controls. Area under ROC curve 0.90.

et al., 2010; Pengas et al., 2010). When the UK MCI patients were grouped according to CSF AD biomarker status, 4MT PM scores differed significantly between MCI patients with and without CSF biomarker evidence of AD, in stiking contrast to the lack of difference between groups in terms of demographics, symptom duration, premorbid IQ, and performance on general neuropsychometric testing. Of particular note was the observation that MCI subgroups did not differ in the scores obtained on the Rey Auditory Verbal Learning Test and the Trail Making Test part B, given that both tests that have been shown to have high diagnostic sensitivity for early AD and as such are widely used in clinical and research practice (Chapman et al., 2011; Ewers et al., 2012; Gainotti et al., 2014).

To explore the diagnostic ability of the 4MT in different clinical and cultural settings testing was undertaken in parallel on patients recruited from two memory clinics in the UK and in Italy, with patient data at each site compared with data obtained from age- and gender-matched control subjects with no history of cognitive impairment. For both UK and Italy study populations, the PM scores obtained from both MCI and AD patient groups were significantly lower that the corresponding control scores; in both study populations no significant difference was observed between MCI and AD scores, in keeping with previous findings (Bird et al., 2010). Comparison of data from the two study sites revealed that control PM scores were lower in the Italy control subjects but similar for the two AD groups. When comparison is made across the Italy and UK MCI patients, with the latter grouped according to CSF biomarker status, the mean PM score of the Italy patients was identical to that of the UK MCI biomarker positive subgroup (5.8) but significantly different to that of the UK MCI biomarker negative subgroup (mean score 9.6). This may reflect the selection at the Italy site of patients with a diagnosis of amnestic MCI who are considered more likely to have underlying AD, and as such are more in keeping with the UK MCI biomarker positive subgroup.

The ability of 4MT PM testing to detect the presence of disease is illustrated by the determination of test sensitivity and specificity and calculation of the area under the ROC curve (AUC). For the UK population, the AUC was 0.98 for patients with early AD (i.e., MCI+ and mild AD dementia), with a score of 8 or below yielding 100% sensitivity and 90% specificity for the detection of early AD. For the patients recruited from an Italy memory clinic, in whom CSF AD biomarker testing was not undertaken as part of the clinical diagnostic process, the AUC was 0.9, with a score of 8 or below yielding 100% sensitivity and 50% specificity for detection of a clinically defined disease state (MCI and AD). Further scrutiny of these latter data indicates that the lower specificity of the 4MT in the Italy population results primarily from the lower scores obtained by the control subjects (UK HC 11.1 $\pm$ 2.1; Italy HC 9.0 $\pm$ 2.3; $t(28) = 2.52$; $P = 0.02$). When the two study sites are considered together, a PM score of 8 or below was associated with a positive predictive value between 82 and 88% and a negative predictive value of 100%. These findings indicate that the 4MT has high diagnostic sensitivity for early AD in different countries, while the diagnostic specificity associated with a PM score of 8/15 varied according to clinical practice, with higher specificity observed when clinical diagnosis was supplemented by testing for AD biomarkers.

Previous work (Hartley et al., 2007; Bird et al., 2010) has shown that there is relative preservation of place perception in the context of hippocampal damage and that 4MT PM, but not PP, scores differentiated AD from other dementias. As such the decision was made a priori to shorten the PP test battery

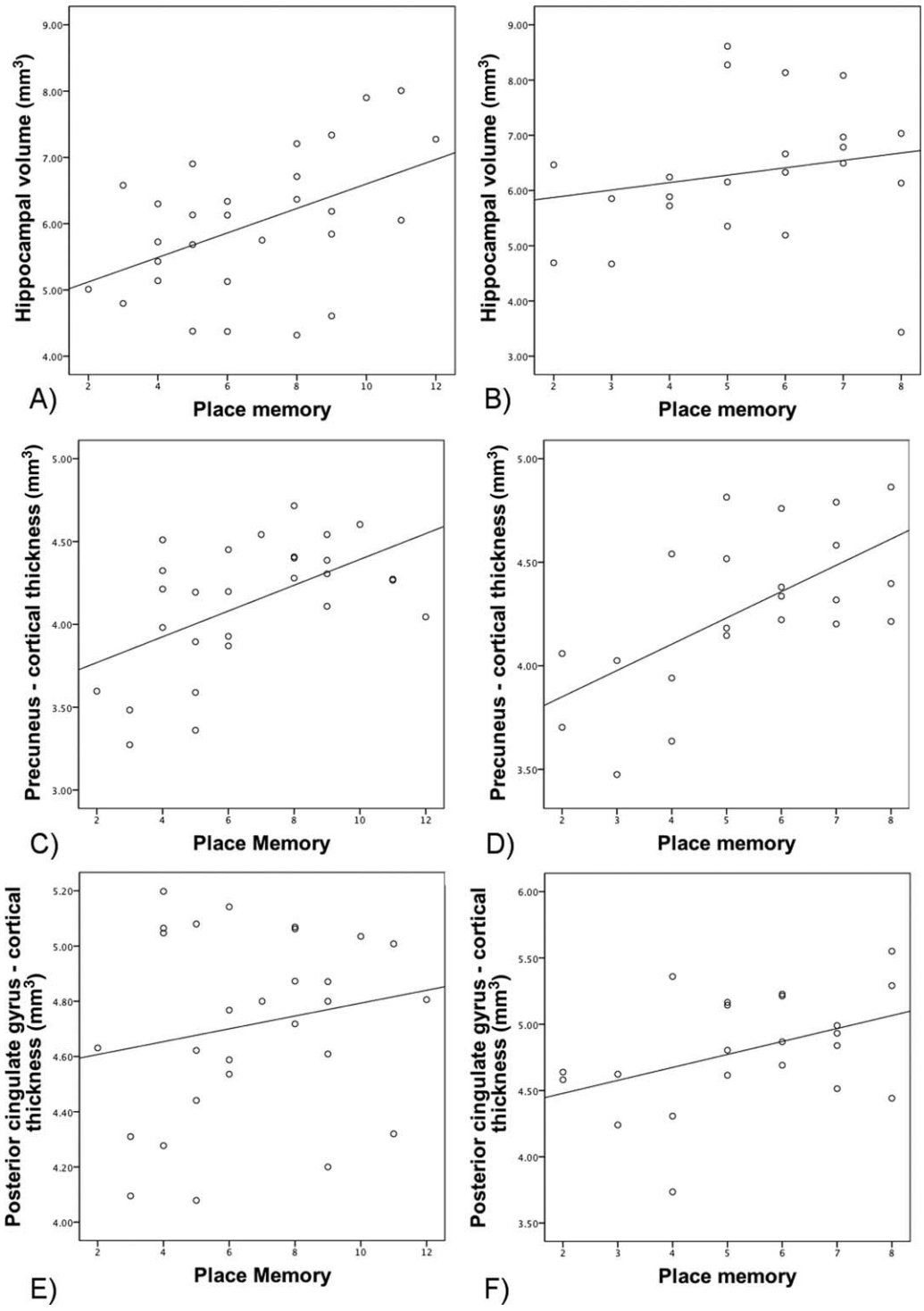

FIGURE 4. Scatterplots demonstrating correlation between 4MT place memory score and hippocampal volume (top), cortical thickness of the precuneus (middle), and cortical thickness of the posterior cingulate gyrus (bottom) for UK (A,C,E) and Italy (B,D,F) patients.

from 15 to 6 items to reduce the test time, in light of the potential future application of the 4MT as a test for use in clinical practice. A comparison of the data acquired from subjects tested with either 15 to 6 PP items revealed no effect on the subsequent PM scores and overall the PP scores did not discriminate between controls and MCI patients in either UK or Italy study populations, or between MCI+ and MCI− subgroups. PP scores were significantly lower in patients with AD

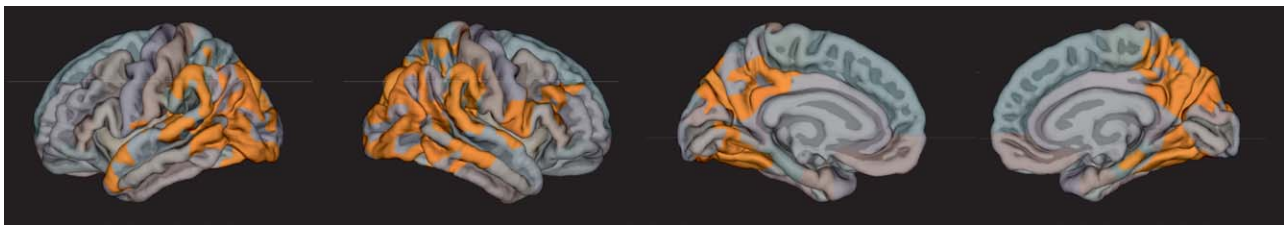

FIGURE 5. Vertex level correlation between place memory and cortical thickness (Monte Carlo simulation, threshold = 0.5, fwhm = 10, $P < 0.001$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

dementia, consistent with the spread of pathology into cortical regions in more advanced disease.

Quantitative MRI analyses revealed that hippocampal volume, and the cortical thickness of the precuneus and posterior cingulate gyrus were reduced in patients with MCI, and that this atrophy was more severe and extensive in patients with AD dementia. These observations were consistent across both UK and Italy study populations and are in keeping with a number of previous MRI studies conducted in MCI and AD (Du et al., 2001; Hämäläinen et al., 2007; Fennema-Notestine et al., 2009). However, and in contrast to the place memory test performances, no differences in these ROI structural measurements were observed between MCI+ and MCI− subgroups.

PM scores correlated with total hippocampal volume in the UK patient group and with the cortical thickness of the precuneus in both UK and Italy patient populations but not with cortical thickness of the posterior cingulate gyrus. The correlation with hippocampal volume in the UK patient population is in keeping with the central study hypothesis with regard to impairment of hippocampal function in early AD, and as such it is proposed that this relationship is causal, and not merely associative, in nature. Two factors may explain the absence of any observed correlation between PM scores and hippocampal volume in the Italy patient population; first, the smaller sample size at this study site and second, the reduced dynamic range as a consequence of the high degree of overlap between MCI and AD patient scores (see Fig. 2).

The correlation between PM score and cortical thickness of the precuneus can be interpreted in two main ways. The first of these is that this correlation is associative rather than causal, as a reflection of the known early involvement of the precuneus in AD (Braak and Braak, 1991; Mirra et al., 1991; Thal et al., 2002). However, this is inconsistent with the failure to observe any correlation with the cortical thickness of the posterior cingulate gyrus, given that this brain region is similarly early in AD.

The second interpretation is that the precuneus, along with the hippocampus, is directly implicated in allocentric spatial memory. Evidence from non-human primates (Selemon and Goldman-Rakic, 1988) and from human studies (reviewed by Cavanna and Trimble, 2006) suggests that the precuneus is involved in spatially related behaviors. These study findings may therefore be consistent with the viewpoint that in humans allocentric spatial memory is subserved by a functional network that encompasses the hippocampus and the precuneus. Task-free fMRI studies show that the hippocampus and precuneus represent highly interconnected hubs within a "default mode network" underpinning spatial and episodic memory (Greicius et al., 2004; Vincent et al., 2006) and the vulnerability of this network to early AD (Rombouts et al., 2005) is of note in the context of this study.

Several aspects of this study warrant further discussion in light of the potential future application of the 4MT as a clinical diagnostic tool. First of all, this study did not aim to assess the effect of gender on 4MT place memory performance. Although previous work has suggested the presence of sexual dimorphism in spatial cognition (Maguire et al., 1999) no significant difference in 4MT performance between men and women was observed in the recent study by Hartley and Harlow (2012). However, unpublished results from a large study undertaken in healthy individuals suggest a small but significant gender effect with lower scores obtained from women on a 30-item test, with mean scores of 20 and 18.6 for men and women, respectively (T. Hartley, C. Bird, H. Spiers, personal communication). The issue of gender effect on 4MT performance needs further clarification and this issue is being explored within current studies involving much larger numbers of young and older cognitively normal subjects.

The second issue relates to the lower place memory scores obtained by the Italy-based control subjects and the potential negative implications for diagnostic discrimination. However, while these lower control scores are reflected in lower diagnostic specificity in this study population (50% as opposed to 90% in the UK study population) a PM score of 8/15 or below was still associated with 100% sensitivity. In terms of the explanation for the lower control scores, it is perhaps relevant that the Italy-based control subjects were significantly older than their UK counterparts ($P < 0.001$). As is the norm for dementia research studies of this kind, in this study the primary criterion for recruitment of control subjects was an absence of reported cognitive symptoms. Testing for AD biomarkers, in the form of amyloid-PET scanning or CSF examination, was not undertaken in any control subjects in either Italy or the UK. Given that the incidence of AD rises with age, one possible explanation for the lower Italy control scores

that cannot be discounted, and which would be a major confounding factor, is the presence of presymptomatic AD in the older control group.

The second aspect relates to the choice of 4MT for testing spatial memory. In the study conducted by Pengas et al. (2010) AD patients were found to be impaired on a variety of spatial memory tests and of these the virtual route learning test (VRLT) was found to be slightly superior to the 4MT in terms of diagnostic accuracy (differentiation of AD from semantic dementia AUC 0.93 for VRLT vs. AUC 0.85 for 4MT). However operational issues favored the choice of the 4MT over the VRLT in this study. In the Pengas et al. (2010) study, 2/32 (6%) of MCI patients were unable to complete the VRLT due to nausea from perceived motion, whereas all MCI (and all AD) patients tolerated the 4MT. Furthermore, the need to use a computer-based platform for the VRLT, allied with the requirement for extensive (and thus time-consuming) pretesting task familiarization, limits the potential future usage of the VRLT outside academic centers. By comparison the 4MT may be applied in paper as well as electronic forms and this, along with a short test duration, would favor future usage of the 4MT over the VRLT as a diagnostic tool in routine clinical practice. These study findings therefore have impact for both academic and clinical practice. The diagnostic benefits of a theory-driven test of hippocampal function are demonstrated; no less importantly, the use of a test that fulfils both diagnostic requirements with regard to sensitivity and specificity and operational requirements with regard to scalability and usability is of particular relevance given the high prevalence of memory impairment in the ageing population and the fact that the majority of patients with MCI are evaluated in community memory clinics rather than academic centers.

CONCLUSION

Performance on the "4 Mountains Test" of spatial memory differentiates mild cognitive impairment due to Alzheimer's disease with high diagnostic sensitivity and specificity. High diagnostic accuracy was observed in two separate study populations recruited from different countries. The correlation of test performance with structural measures of the hippocampus and precuneus is consistent with the role of these brain regions in spatial cognition and with their early involvement in the AD pathological process.

These findings indicate the value of spatial memory testing in the diagnosis of pre-dementia AD and of the 4MT as a diagnostic tool suitable for widespread use in routine clinical practice.

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