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**Locations of Objects are Better Remembered Than Their Identities in Naturalistic Scenes:
An Eye-Tracking Experiment in Mild Cognitive Impairment**

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Abstract

Objective: Retaining the identity or location of decontextualized objects in visual short-term working memory (VWM) is impaired by healthy and pathological ageing, but research remains inconclusive on whether these two features are equally impacted by it. Moreover, it is unclear whether similar impairments would manifest in naturalistic visual contexts.

Method: 30 people with MCI and 32 age-matched control participants (CP) were eye-tracked within a change detection paradigm. They viewed 120 naturalistic scenes, and after a retention interval (1 second) asked whether a critical object in the scene had (or not) changed on either: *identity* (became a different object), *location* (same object but changed location) or *both* (changed in location and identity).

Results: MCIs performed worse than CP but there was no interaction with the type of change. Changes in *both* were easiest while changes in identity alone were hardest. The latency to first fixation and first-pass duration to the critical object during successful recognition was not different between MCIs and CPs. Objects that changed in *both* features took longer to be fixated for the first time but required a shorter first-pass compared to changes in identity alone which displayed the opposite pattern.

Conclusions: Locations of objects are better remembered than their identities; memory for changes is best when involving both features. These mechanisms are spared by pathological ageing as indicated by the similarity between groups besides trivial differences in overall performance. These findings demonstrate that VWM mechanisms in the context of naturalistic scene information are preserved in people with MCI.

Keywords: change detection; visual working memory; mild cognitive impairment; naturalistic scenes; eye movements

Introduction

People with mild cognitive impairments (MCIs) are more likely to progress to full-blown dementia (e.g., Alzheimer's Disease - AD) than healthy people of the same age (Petersen et al., 2013; Gauthier et al., 2006). Impairments in memory processes are important indicators of this potential conversion, observed for example with classic verbal learning tasks (Lonie et al., 2010; Zhao et al., 2012) or selective reminding paradigms (Grande et al., 2018; Grober et al., 1987). Short-term visual memory mechanisms of recognition and retention are also compromised in MCIs. Compared to matched control participants (CPs), MCIs are markedly worse on immediate, and especially delayed recognition of images, explicitly or incidentally learned as associated pairs (Barbeau et al., 2004; Didic et al., 2013; van Geldorp et al., 2015). Moreover, when asked to temporarily retain arrays of shapes-colours combinations in memory (e.g., 1 second) and tested on the detection of changes in colour, shape, or both (binding condition), independently of their location (see Parra et al., 2009, 2010; Della Sala et al., 2018 for validation of the task) their capacity in the binding condition appears to be reduced (see Martínez et al., 2019, for a recent review).

These tasks rely on temporary memory about *identity* information of objects, i.e., features constituting them (e.g., colour or shape). However, a visual object also occupies a spatial *location* within the context, and this information is neuro-anatomically processed by a different neural pathway (see Mishkin et al., 1983 for classic evidence about the 'what' and 'where' distinction, or Milner & Goodale, 2008, for a review) although the two pathways are grossly interconnected (Schenk & McIntosh, 2010), also in early dementia (Deng et al., 2016).

Surprisingly, temporary memory for object location has been little investigated in older people suffering from neuropathology with most research comparing instead younger and healthy older adults and presenting a mix of evidence. Some studies showed it to decline with age (e.g., Chalfonte & Johnson, 1996; Muffato et al., 2019), especially when sequential order of presentation was assessed (Kessels et al., 2007) or when the location of objects had to be remembered together with their identity (Dai et al., 2018). Other studies instead found a preserved ability to bind objects to locations in healthy ageing. Olson et al., (2004), for example, showed that younger and healthy older adults equally remembered locations of coloured squares, and their memory was similarly impacted by interference. Similarly, Pertzov et al., (2015) showed comparable abilities to associate identity and location of objects. Of the studies we are aware of, recognition memory for object-location was more impaired in MCIs than CPs (e.g., Hampstead et al., 2011; Troyer et al., 2008). Moreover, ADs underperform in recalling the identity and location of objects compared to MCIs (Kessels et al., 2010).

Impairments in short-term visual memory processes may also stem from disrupted attentional mechanisms (Perry & Hodges, 1999, for a classic review). MCIs, and people with AD (ADs), need longer exposure to visual stimuli to perform as good as CPs in recognition memory (e.g., Bublak et al., 2011) or in comparative, same/different, tasks (e.g., Bonney et al., 2006) and can process fewer elements simultaneously (Ruiz-Rizzo et al., 2017). MCIs and ADs have also greater difficulties in detecting changes when distracted by an attentional task between the study phase and the recognition phase (Alescio-Lautier et al., 2007). Attentional deficits in older people suffering from neuropathology seem to extend to its overt manifestation, i.e., eye-movement responses (see Freitas Pereira et al., 2014 or Molitor et al., 2015 for reviews). The most evident changes are observed in low-level oculomotor control, whereby MCIs or ADs display more saccades and eye blinks than CPs (Müller et al., 1991), have difficulties pursuing moving targets (Hutton et al., 1984), or take significantly longer to respond to exogenous cueing in anti-saccade tasks (Wilcockson et al., 2019). Even if less reported, other eye-movement measures show signs of impairment such as shorter gaze duration (Fernández et al., 2018) or limited visual exploration (Nakashima et al., 2010) in ADs.

In sum, there is ample evidence of impaired memory processes in MCIs, with literature pointing at temporary mechanisms to hold information in short-term memory as early indexes for it, and to the potential impairment of attention too, also in its overt manifestation.

However, most of the research just reviewed has operationalised featural information about identity and location of objects in artificial stimuli (e.g., arrays of geometrical objects) and used different arrangements to display it in the visual context (e.g., free-floating or in grids). In ecological contexts (e.g., photographs), cognitive processes may, instead, manifest differently (Willems & Peelen, 2021) and so the mechanisms to perceive, recognize and memorize objects will operate on a structured and predictable world (Kaiser et al., 2019). The capacity of short-term visual working memory, for example, appears to be substantially different when tested in 3D virtual environments (Draschkow et al., 2021). Naturalistic contexts could also facilitate the memory integration of objects, with their location and identity, within the scene (see Hollingworth, 2007 for a comparison between object arrays and 3D rendered scenes) and provide compensatory information that could normalize age differences (e.g., Diamond et al., 2020; Mitchell & Cusack, 2018; Schnitzspahn et al., 2011).

In a study using methods and procedures similar to those reported here (D’Innocenzo et al., 2022), we precisely investigated the role that naturalistic (photographic) visual contexts play on temporary memory for identity and location of objects in healthy ageing. In a nutshell, we observed the same patterns of change detection performance between younger and healthy older adults: changes in object location were easier to detect than identity changes, and performance was best

when the object changed in both identity and location, especially for younger adults. A qualitative comparison with literature adopting non-naturalistic contexts and manipulating similar features of identity and location suggested that memory mechanisms may benefit from the richer context provided by the naturalistic scenes, and so enable their preservation in healthy cognitive ageing. The ensuing question is whether such a benefit would extend to MCIs.

The main goal of the current study is to compare MCIs with CPs on their capacity to successfully form temporary bindings¹ of identity and locations of objects in short-term visual memory when such cognitive operations take place in naturalistic visual contexts². We aim to contribute to a neglected topic while shedding new light on the ongoing debate about evidence of their potential impairments. We also examine oculomotor responses, as there is evidence in the literature that attention may be impacted by MCI and investigate whether they truly differ when visual short-term memory representations are successfully retrieved.

On the change detection accuracy, it is not theoretically relevant whether the performance of MCIs is overall worse than CPs, but rather if it systematically differs due to the feature change and is suggestive of specific deficits to temporarily retain better (or worse) a certain feature (e.g., identity vs. location). We expect MCIs to generally underperform compared to CPs. However, the focus of the experiment is to investigate whether they experience more difficulties on object location as predicted by previous literature (e.g., Alescio-Lautier et al., 2007; Troyer et al., 2008) or more difficulties in object identity (as predicted by our study on healthy ageing; D’Innocenzo et al., 2022). As already argued, a naturalistic context may provide a rich context, such as relational information about the objects in it (e.g., see Hollingworth, 2006, for an insightful discussion), which could make the detection performance of MCIs comparable to CPs. In sum, if we replicate our previous results on healthy ageing, we should observe a better detection performance for a change in object location, and even more so, if it also changed in identity, but no evidence of interaction between type of changes and group.

On eye-movement responses, we focus on data acquired during the recognition phase of correct trials, and measures related to the critical object. We do not focus also on the data collected during the study phase because it is only in the recognition phase that we can directly associate eye-movement strategies with the successful detection of changes. We are not arguing that eye-movement strategies employed during the study phase may not importantly impact on the

¹ As the concept of binding classically referred to low-level visual features of objects (e.g., colour, shape, etc.), it does not strictly apply to naturalistic scenes, whose objects have far richer information and more complex relationships with the context itself. We use *temporary binding* to refer to the cognitive operation that makes it possible to hold featural information about an object (e.g., its identity) within the scene context in visual short-term memory.

² In this study we do not compare VWM on naturalistic scenes and object arrays directly and so interpretative comparisons between these two contexts, whenever done, remain qualitative and based on critical analysis of previous literature on the topic.

recognition phase (see Hilton et al., 2020 for an example comparing younger and older adults). However, our interest here is to investigate how changes in the identity, location, or both features relate to the allocation of overt attention while successful processes of short-term memory retrieval are on-going, and especially whether differences may emerge between MCIs and CPs. We examined two measures often used in the analysis of visual search tasks (see, Zelinsky 2001, for discussing similarities with change detection tasks): (a) the latency of the first fixation to the critical object, which reflects how quickly was overt attention oriented to the critical object, and (b) the sum of all fixations during the first-pass on the critical object, which points to the processing effort needed to drive a successful detection of the change. Searching for targets discriminable through their feature conjunction takes longer than for a single feature especially in older adults (e.g., Whiting et al., 2005). So, during recognition, we expect longer latencies of the first fixation when an object changed in identity and location (double change) than when it only changed in identity (single change). This expectation will also align with what was found in D’Innocenzo et al. (2022). However, if MCI disrupts mechanisms of attentional orienting, then people in this group should find the conjunctive change harder to maintain in VWM and hence display a significantly longer latency of the first fixation in this condition. Once the object is first fixated, and in line with our sibling work, we would expect it to be inspected less when it changes in both location and identity, as it is sufficient to verify only one of the two features to drive a successful detection. Most importantly, if attentional mechanisms confirm to be preserved in a naturalistic visual context, we will not expect any difference between the two groups. On the contrary, if we base our expectations on findings obtained using object arrays (e.g., Fernández et al., 2018), we expect, for example, longer first-passes on the critical object when it changed in both features than when it only changed in identity but be shorter in MCIs due to potential inefficiency in the mechanisms of object-scene integration.

Table 1:

Neuropsychological Test	Type	CP	MCI	p-value
MMSE		29.41 (0.84)	27.35 (1.69)	< .001
Logical memory	immediate	12.84 (4.78)	8.2 (5.55)	< .001
Object naming		39.36 (0.95)	39.48 (1.5)	0.75
Verbal fluency	semantic	19.23 (5.11)	14.04 (4.62)	< .001
	phonetic	10.03 (5.13)	7.6 (3.08)	0.03
Trail Making Test	A	56.69 (18.95)	105 (46.48)	< .001
	B	147.83 (77.64)	242.09 (93.79)	< .001
	incomplete letters	19.19 (0.82)	17.08 (3.35)	< .001
VOSP	dot	19.38 (0.87)	16.12 (4.43)	< .001
	number	8.97 (2.36)	7.23 (3.67)	0.04
Digit Symbol ³		-	20.48 (8.65)	-
Digit Span	forward	-	4.62 (1.36)	-
	backward	-	3.35 (0.85)	-
CVLT		-	35.05 (11.11)	-
Demographics	-			
Age	-	65.03 (8.59)	69.16 ± 8.37	0.06
Years in Education	-	8.06 (4.42)	8.63 (3.72)	0.6
Gender	-	21 F; 11 M	19 F; 11 M	-

Table 1: Raw scores (mean and standard deviation) for the neuropsychological battery of tests administered to the MCI participants and healthy age-matched controls (CP) which span general cognitive capacity (Mini-Mental State Examination, MMSE) and five different cognitive domains: attention and processing speed (Digit Symbol; Trail Making Test A, normed in Portuguese by Cavaco, et al, 2013a; Digit Span Forward from Wechsler Memory Scale, WMS), memory & learning (Logical Memory from WMS translated by Guerreiro, 1998, immediate recall only); California Verbal Learning Test, CVLT, – List A Learning Trials), executive function (Digit Span Backwards, Trail Making Test B), language (Object naming, based on drawings of Snodgrass & Vanderwart, 1980; semantic and phonemic fluency, normed in Portuguese by Cavaco, et al., 2013b) and basic visual perception (incomplete letters, position discrimination and number location from Visual Object and Space Perception Battery, VOSP; Warrington & James, 1991). The table also includes demographics of age, sex and years of education of the two groups. The p-value is obtained by comparing the two groups using a Welch two-sample t-test.

³ We only observe three MCI participants who scored below 2 SD on the digit symbol test compared to the relevant norms. Therefore, we trust that this would not have an impact on the generality of the results.

Methods

Participants

Thirty-nine participants⁴ with a neuropsychological diagnosis of MCI and thirty-four healthy age-matched CPs, all European native speakers of Portuguese, were recruited from the Language Research Laboratory at the Faculty of Medicine, University of Lisbon. These patients were referred for cognitive evaluation from the Neurology Outpatients clinic at Centro Hospitalar Universitario Lisboa Norte, Hospital de Santa Maria, Lisboa, (Portugal).

The diagnosis of MCI was structured following international guidelines (Arnáiz et al., 2004; Gauthier et al., 2006; Petersen, 2016; Winblad et al., 2004) and included: a Mini-Mental State Examination raw score ≥ 24 (see Morgado et al., 2010 for Portuguese norms), a subjective history of cognitive decline reported by the patient, or a carer, and objective neuropsychological impairment on two or more cognitive domains with cut-off set at $> \pm 1.5$ standard deviations from normative values of a healthy Portuguese population matched by age and education (refer to Table 1 for the descriptive statistics of the neuropsychological examination and the statistical comparison between MCIs and CPs that contributed to the analyses reported in this study). Other inclusion criteria were: 1) age between 50 and 90 years; 2) no less than 3 years of formal education; 3) normal or corrected-to-normal vision with no history of eye surgery (e.g., LASIK); 4) no history of neurological and/or psychiatric disorders (other than memory disturbances); 5) no lifetime history of alcohol or substance abuse and/or use of medications (e.g., anti-epileptic or benzodiazepines) and 6) ability to understand the instructions and perform the task.

Nine MCIs and 2 CPs were excluded from the analyses because their overall performance on the change detection task was at chance⁵, assessed using a binomial test. The remaining 30 MCIs (19 women) and 32 CPs (21 women), matched on age (MCI = 69.16 ± 8.37 ; CP = 65.03 ± 8.59)[$t(59) = -1.91$, $p = 0.06$] and years in education (MCI = 8.63 ± 3.72 ; CP = 8.06 ± 4.42)[$t(59) = -0.55$, $p = 0.6$], contributed to the analyses of the change detection performance.

According to their composite cognitive profiles (i.e., average z-scores on tests belonging to the same domain), MCIs were classified as amnesic single-domain (9, 30%) amnesic multiple domains (17, 56.7%) and non-amnesic MCI (4, 13.3%).

The quality of the eye-tracking data of these participants was further examined. We excluded 5 MCIs and 4 CPs because we could not obtain reliable tracking (e.g., droopy eyelids, had

⁴ Post-hoc simulation analyses using the method by Green & Macleod, 2016, which is designed to assess generalised linear mixed effects models shows that our sample is sufficient to detect reasonable effect sizes (Cohen's $d = .2$, p -values $< .05$), refer to Supplementary Material, S3, for an explanation of these analyses, the full output of the simulations as well as the observed power of our study.

⁵ An analysis of response accuracy which includes all participants, and considers all their trials, confirms an identical pattern of results to those reported below. In this study, however, we maintain our selection criteria, i.e., participants must perform above chance, as including those performing below chance may shadow genuine effects related to the experimental conditions due to their performance being at floor.

trouble staying on the chin rest, etc.) and had a severe data loss in their eye-tracking record⁶. For each remaining participant, we calculated the average visual angle deviation of both eyes between the 9-points calibration accepted at the start of the session, and a 9-point verification performed at the end of the eye-tracking session. The data from 4 MCIs and 4 CPs showed an end of task average deviation greater than 2 degrees of visual angle across all fixation points (i.e., approximately the size of the fovea), hence they were discarded from the eye-movement analysis as it indicated poor tracking. 21 MCIs and 24 CPs contributed to the analyses of the eye-movement data.

Participants were naive to the study and its stimuli, voluntarily took part in it (i.e., no monetary reward) and signed informed consent at the start of the session. The Joint Ethical Committee of the Faculty of Medicine and Centro Hospitalar Universitário Lisboa Norte provided ethical assessment and clearance for the study before starting the data collection.

Figure 1:

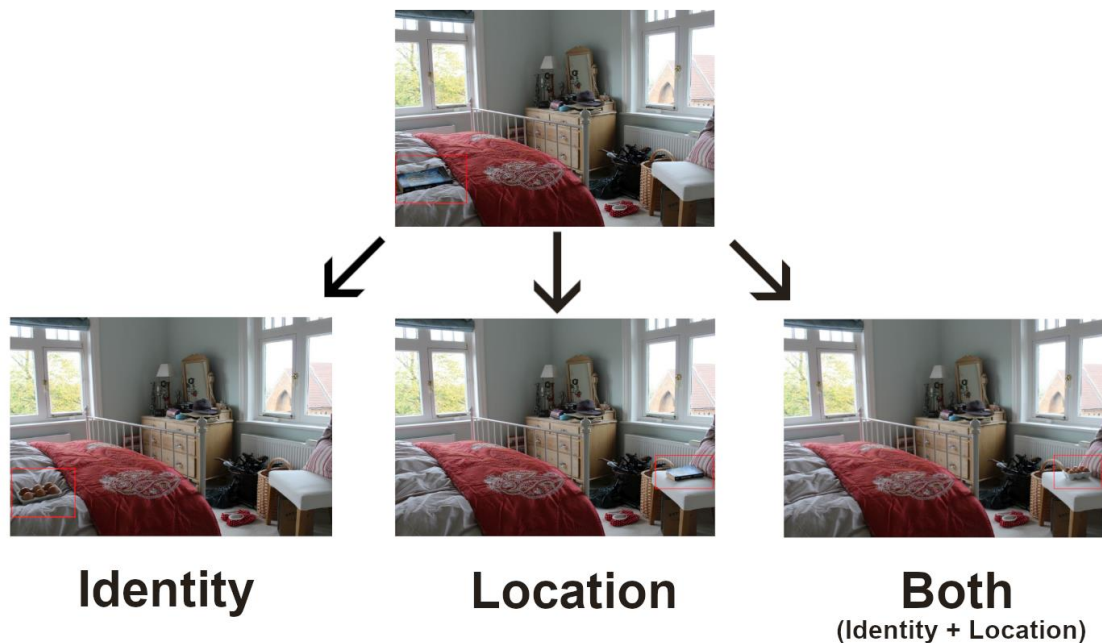


Figure 1: Types of change implemented in an example scene. The red bounding box indicates the critical object of this scene as well as the area of interest considered to compute the eye-movement measures reported in the study. The bounding box was not visible to the participants, it is overlaid only for illustration. Three types of change were implemented: *Identity* (the object becomes another object, consistent or inconsistent with the scene), *Location* (the object moves from right to left, or vice-versa), and *Both* (the object moves and becomes another object). The main author of the manuscript holds the copyright of these example images and all other images used in this study.

⁶ We used a threshold of > 30% invalid samples per trial as a cut-off criterion for exclusion.

Design

We examined short-term visual memory for identities and locations of objects embedded in naturalistic scenes using a change detection paradigm, in which participants had to spot whether they noticed (or not) a change happening to a critical object in the scene. Three types of change could occur between the study phase and the recognition phase of change trials: (a) **Identity**, the critical object remained in the same spatial position, but it became a different object, which was either consistent or inconsistent with the scene context (e.g., the *book* becomes *a box of eggs*), (b) **Location**, the critical object moved from one side to the other of the scene (e.g., the *book* moves from the right to the left of the scene) and (c) **Both**, the critical object became a different object and changed side in the scene. Thus, we implemented two single and one double feature change, the latter was conceived to operationalise in the context of naturalistic scenes, a conjunctive condition, and conceptually approximate what classically done in object arrays with low-level features, e.g., a change in colour and shape (please refer to Figure 1 for an example of the changes implemented). The types of change were equally distributed and fully counterbalanced across scene items for each participant to avoid the development of systematic strategies to resolve the change detection task.

Materials

The stimuli consisted of 304 photographic images of indoor scenarios (e.g., bedrooms, bathrooms, etc.) of which: (a) 60 experimental (change items) in 4 possible versions (i.e., 240 scenes in total) containing a critical object, placed either to the left or to the right of the scene, which was either semantically consistent or inconsistent with its context, (b) 60 fillers (no-change items), also balanced in position and object consistency, and (c) 4 practices (2 change and 2 no-change scenes). Scenes were selected from a database used in other studies of our lab (Coco, et al., 2020, D’Innocenzo et al., 2022); we refer readers to Supplementary Material (S1) for miniatures of all scenes used in this study.

Apparatus

A Tobii T120 was used to record eye movements binocularly at a 120 Hz sample rate and display visual stimuli on an integrated monitor (57.3 cm width and ~50 cm height) at a resolution of 1280 × 1024 pixels. The monitor had a vertical refresh rate of 75 Hz, and the eye-tracking spatial resolution was .3 root mean square (RMS) degrees of visual angle with an accuracy of .5 (Tobii, 2011). Participants sat at ~60 cm from the screen display, and a headrest was used to stabilize their position. The experiment was implemented on OpenSesame (Version 3.0.7, Mathôt et al., 2012) and the PyGaze Python plug-in used to acquire the eye-tracking data (Dalmaijer et al., 2014).

Procedure

Each participant was calibrated on a 9-points grid at the beginning of each experimental session, and the visual angle deviation error of both eyes (mean and standard deviation) accepted for the two groups was: $1.09^\circ \pm 0.22^\circ$ on the x-axis and $1.29^\circ \pm 0.24^\circ$ on the y-axis for the healthy adults, and $1.53^\circ \pm 1.26^\circ$ on the x-axis and $1.15^\circ \pm 0.19^\circ$ on the y-axis for the MCIs.

Each trial started with the presentation of a scene that the participant was asked to study. The presentation time of each scene was estimated from a different sample of healthy older British speakers (D’Innocenzo et al., 2022 and refer to Coco, et. al., 2020 for the younger adults) performing the same task (and stimuli) where we used a gaze-contingency mechanism linking the first fixation into the critical object (threshold of 150 ms fixation within the invisible bounding box) to the offset of the scene presented in the study phase, which occurred 2 seconds \pm 200 ms jitter uniformly distributed after such a fixation⁷. In practice, this paradigm ensured that the critical object was looked at in most trials, and after first viewed, participants had approximately the same amount of time to inspect the scene before the retention interval. Our current purpose was to tailor the presentation timings of each scene based on what was just described to prevent arbitrary decisions of a fixed preview for all scenes (e.g., 10 seconds⁸). Thus, the presentation time of each of the 300 scenes during the study phase of the current study was estimated using the data collected on healthy older adults in our previous work (D’Innocenzo et al., 2022). We selected the median gaze-contingent time observed across all older participants that had viewed each scene in our previous study ($N = 9.33 \pm 7.0$, where N refers to the number of participants that had studied the scene). On average, scenes were studied for 3.99 ± 1.24 (SD) seconds, which is enough time to preview the scene and attend to the critical object while being under the pressure of a realistic timeout to the retention interval. A fixation point was presented in the centre of the display for 1 second during the retention interval, then the study scene was presented again with (or without) one of the three changes described above for the recognition phase. Half of the trials presented a change whereas the other half did not present any change. Participants were told that during the recognition phase an object would change in the scene but did not know which one beforehand, as they had to deduce it based on a memory comparison with the scene they had studied. Participants had 20 seconds to verbalize whether they noticed a change in the scene and if so, they had to describe which object had changed. Thus, we asked them to provide a verbal response, rather than press on a keyboard, also to reduce a potential dual-task engagement, i.e., watch the scene and prepare a motor action.

⁷ No fixation onto the critical object for 10 seconds automatically triggered the scene offset (timeout).

⁸ We could not establish a stable, moment-by-moment, gaze-contingency mechanism with low-resolution 120 Hz data of the T120 Tobii device that was available to develop the current study, and so we opted not to implement it here.

The experimenter pressed y (*yes*, change detected) or n (*no*, change not detected) on the keyboard to record the choice of the participant. Verbal responses were recorded using a standard computer microphone, and a subset of the recordings (~10%) screened post-hoc to double-check that the experimenter had logged the verbal responses correctly. The keyboard press triggered the presentation of the next trial. If participants did not manage to respond within the 20 second time limit, a null response was recorded, and the next trial began. Each participant completed 4 practise trials followed by 60 change trials and 60 no-change trials, presented in random order. A Latin Square rotation was used to counterbalance and equally distribute experimental conditions across 12 randomization lists.

The task was explained aurally, and participants were also given written instructions to read at the beginning of the session. They could repeat practice trials more than once to familiarize themselves with the task, and when comfortable with it, begin the experimental session. Together with the neuropsychological assessment, the experimental session lasted for about an hour.

Data analysis

Data processing

Our analyses focused on the 3,720 change trials (i.e., 62 participants \times 60 scenes), of which, we excluded 61 trials (1.6%) that timed out (i.e., missing, or ambiguous verbal response), 245 trials of 4 scene items which had a change detection performance at chance level (6.58%) and 55 trials with a response time slower than 99% of all trials (1.47%), as computed independently for each participant. Thus, change detection accuracy was analysed on 1,735 trials for the healthy controls, with a by-participant average of 43.93 ± 21.34 , and 1,617 for the MCI group, with a by-participant average of 45.2 ± 20.41 .

As for the eye-movement responses, we only considered trials in which changes were correctly detected and focused on data from the recognition phase. In this way, we compared oculomotor responses associated with successful VWM processes between groups, and so unveiled underlying similarities (or differences) in their oculomotor strategies. Of the 2,700 change trials (i.e., 45 participants \times 60 scenes, refer to the *Participant* section for greater details about the excluded participants), we excluded trials that had no eye-movement data (i.e., machine error, 25, 0.92%), those discarded because of time-out, detection performance on the scene at the chance level, and response time slower than 99% (e.g., 275, 10.18%), 798 incorrect trials (29.55%), and a further 215 trials (7.96%) in which the critical object was not fixated. Thus, eye-movement responses were analysed on 817 trials for the healthy controls, with a by-participant average of 34.04 ± 9.97 , and 570 trials for the MCI group, with a by-participant average of 27.14 ± 12.05 . We

utilised the I2MC algorithm to parse the eye-tracking samples into fixations and saccades as it is robust to low-frequency data (Hessels et al., 2017) and used MATLAB 2021a to run it.

Dependent measures

The change detection performance was examined as *response accuracy* (a binomial variable with values of 1 for correct and 0 for incorrect responses). Two simple eye-movement measures were computed relative to the critical object, which was subjected to the change manipulation (please refer to Figure 1 for a visualisation of the types of change and an example of the bounding box surrounding the critical object): (a) the *latency to the first fixation*, which is the time taken to fixate the critical object for the first time after scene onset (in milliseconds) and reflects the amount of exploration required to orient overt attention towards the changed object; and (b) the sum of all fixations during its first inspection (*first-pass duration* in milliseconds) which points at the processing effort required to verify the changed object. As a sanity check, we z-scored both measures to account for the general slowing effect associated with ageing (Faust et al., 1999), and confirm that the pattern of results is nearly identical to raw scores (the reader is referred to Supplementary Material (S2) for plots and model outputs obtained using z-scores).

Statistical modelling

Generalised and linear-mixed effects modelling (G/LMM) was used to infer the statistical significance of our data as implemented by the lme4, R package, (Bates et al., 2015). The centred predictors (or fixed effects) introduced as main effects and in interaction (i.e., a full fixed-effect structure) were: **Type of Change** (Location, Both and Identity, which was also the reference level) and the between-participant **Group** variable (CP = -.5 and MCI = .5). The random effects were **Participant** (62 for the response accuracy model, and 45 for the analyses of latency to first fixation and first-pass duration) and **Scene** (56), which were introduced as intercepts only. In the tables, we reported all predictors, i.e., fixed effects, (significant or not) along with their beta coefficients, t-values (LMM) or z-values (GLMM), p-values and confidence intervals computed using the sjPlot package by Lüdtke, 2021. The level of significance was calculated from an F-test based on the Satterthwaite approximation to the effective degrees of freedom (Satterthwaite, 1946), whereas p-values in GLMMs were based on asymptotic Wald tests. Tables also include the R^2 of the model fit, which was also computed using the sjPlot package.

The current study abides to the transparency and openness promotion guideline. Thus data, and R script to replicate the results of this manuscript are available on the Open Science Framework

Table 2:

Dependent Variable	Predictor	β	SE	CI	z-value	Pr ($> z $)
Response Accuracy	Intercept	0.8	0.14	(0.53; 1.09)	5.62	< 0.001
	Group	-0.79	0.24	(-1.27; -0.33)	-3.31	< 0.001
	Both	0.49	0.11	(0.26; 0.72)	2.55	< 0.001
	Location	0.29	0.11	(0.07; 0.52)	2.54	0.01
	Group:Both	-0.19	0.23	(-0.66; 0.26)	-0.85	0.4
	Group:Location	0.16	0.23	(-0.29; 0.61)	0.69	0.5

N = 3,352; Marginal $R^2 = 0.05$; Conditional $R^2 = 0.3$

Table 2: Generalized and linear mixed-effects model with a binomial link for the *response accuracy* of detecting a change.

Note. Predictors centred were: Group (Control = -.5 and MCI = .5) and Type of Change (Location, Both – Identity as reference level). We report the β , the standard error, the confidence intervals the z-value and the p-value of those predictors that were significant in the model. The random-effects introduced as intercepts were Participants (62) and the unique identifier of Scene item (56).

at: <https://osf.io/ny6gu/>. Other information relevant to the replication of the study will be made available upon reasonable request to the corresponding author of the work.

Results

On the change detection accuracy, CPs had a significantly better performance than MCIs (please refer to Figure 2 for a visualisation of the response accuracy and Table 2 for the model coefficients). When looking at the type of changes, the detection was more accurate when the critical object changed in position, and especially when it also changed in identity (i.e., both features), as compared to a change in identity only. Crucially, we did not observe any significant interaction between group and type of changes.

Figure 2:

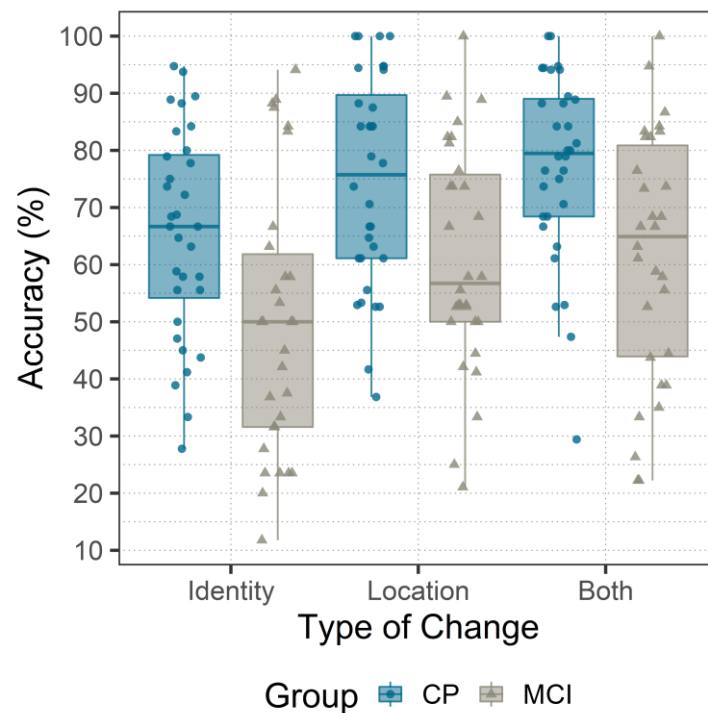


Figure 2: Change detection accuracy (in percentage) plotted on the y-axis as a function of the different types of change (Identity, Location and Both). The two groups of participants are compared within each panel: healthy controls (CP) in azure colour, MCIs in grey. The hinges of the boxplots represent the 25th and 75th percentiles of the measure (lower and upper quartiles) with the horizontal line representing the median of the distribution. Each dot is the by-participant average for that factor.

Figure 3:

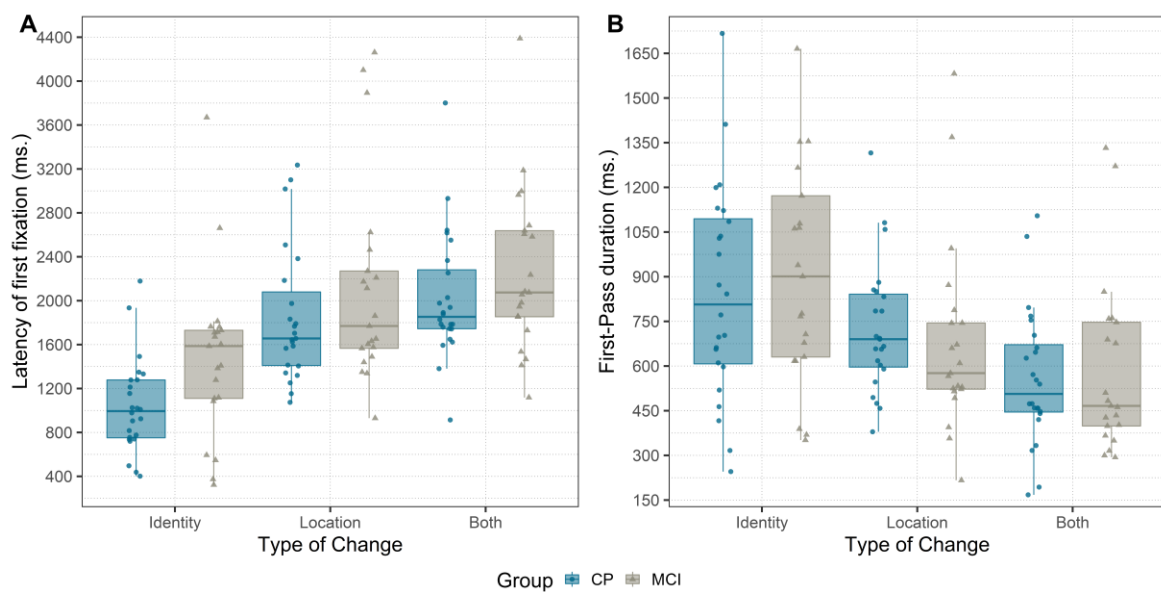


Figure 3: Eye-movement measures on the critical object: (A) Latency of the first fixation on the target in milliseconds and (C) the sum of all fixations on the critical object before exiting it for the first time also in milliseconds (First-Pass). The two groups of participants are compared within each panel: healthy controls (CP) in azure colour, MCIs in grey. The hinges of the boxplots represent the 25th and 75th percentiles of the measure (lower and upper quartiles) with the horizontal line representing the median of the distribution. Each dot is the by-participant average for that factor.

Table 3:

Dependent Variable	Predictor	β	SE	CI	t-value	Pr ($> z $)
Latency of First Fixation (ms.)	Intercept	1,788.7	86.6	(1,618.7; 1,958.6)	20.65	< 0.001
	Group	275.2	142.1	(-3.6; 554.1)	1.93	0.06
	Both	792.4	126	(545.3; 1,039.6)	6.3	< 0.001
	Location	371.9	122.5	(131.6; 612.3)	3.03	0.002
	Group:Both	-62.2	255	(-562.9; 438.47)	-0.24	0.8
	Group:Location	-43.1	249.2	(-532.1; 445.8)	-0.17	0.9

N = 1342; Marginal $R^2 = 0.06$; Conditional $R^2 = 0.16$

First-Pass Duration (ms.)	Intercept	722.9	37.2	(650; 795.7)	19.44	< 0.001
	Group	21.1	63.7	(-103.7; 146)	0.3	0.7
	Both	-231.4	60.3	(-349.7; -113.1)	-3.83	< 0.001
	Location	-75.05	58.7	(-190.2; 40.1)	-1.27	0.2
	Group:Both	57.5	122.3	(-182.3; 297.3)	0.47	0.6
	Group:Location	-124.5	119.3	(-358.6; 109.6)	-1.04	0.3

N = 1342; Marginal $R^2 = 0.02$; Conditional $R^2 = 0.1$

Table 3: Linear mixed-effects model output for the eye-tracking measures of Latency to the first fixation and first pass duration on the critical object during recognition (correct trials only).

Note: Predictors centred and standardized entered were: Group (CP = -.5 and MCI = .5) and Type of Change (Location, Both – Identity as reference level). We report the β , the standard error, the t-value and the p-value of those predictors that were significant in the model. The random-effects introduced as intercepts were Participants (45) and the unique identifier of Scene item (56).

Turning to the eye-movement measures and looking at the latency to the first fixation, we found CPs to be marginally faster than MCIs to look at the critical object for the first time during the recognition phase, but this trend disappears when this measure is z-scored by group (see Supplementary Material, S2). Interestingly, all participants took longer to identify a critical object that moved location, and especially so when it also changed in identity (please refer to Figure 3 for a visualisation of the eye-movement measures and Table 3 for the significant predictors). Once the critical object was identified, all participants explored it (first-pass) less when it changed in both features, as compared to when it changed only in identity. We did not observe any other significant main effect or interaction.

Discussion

The ability to recall information from short-term memory is a key indicator of healthy cognitive ageing, and its impairment is often taken as an early index of neuropathology (e.g., Lonie et al., 2010). Difficulties to remember the *location* of objects, or conjunctive features about their *identity* (e.g., colour and shape) are often observed in people with MCI or AD (e.g., Kessels et al., 2010; Parra et al., 2010). Additional deficits in memory processes may be attributable to attentional dysfunctions (e.g., Rizzo et al., 2000) which could also manifest in abnormal eye-movement responses (e.g., Wilcockson et al., 2019). Most of this research has used simple objects (e.g., geometrical shapes or drawings) arranged on grids or free-floating. However, it is now evident that realistic contexts differently modulate ongoing processes (e.g., Draschkow et al., 2021), and so their use may be revelatory of preserved functions in healthy and pathologically aged populations (e.g., Diamond et al., 2020).

In the present study, we examined short-term memory binding mechanisms for identity, location, or both, of objects embedded in naturalistic scenes and investigated whether impairments in holding these temporary associations due to healthy and pathological ageing extends to this context. Thus, we compared the ability of CPs and MCIs to detect changes in these object features and examined the contribution of eye-movement responses in their successful retrieval from VWM.

On the accuracy to detect changes, MCIs were significantly worse than CPs, which confirms their impairment on short-term visual working memory tasks, amply demonstrated by previous literature (e.g., Barbeau et al., 2004). However, memory for object location was not disproportionately impaired in MCIs compared to CPs, as the study by Troyer et al., (2008) showed using object arrays. Moreover, memory about object location was overall better than memory for identity, which counters evidence that ageing affects the former type of memory more than the latter (Chalfonte & Johnson, 1996; Muffato et al., 2019) while it corroborates findings of preserved

object-location binding (Pertzov et al., 2015). Importantly, we did not observe any significant interaction between the type of change and the group, not even for feature conjunctions (i.e., when the object changed in location and identity), which some studies observed to be worse for healthy older than younger adults (Dai et al., 2018) and particularly so for people suffering from neurodegenerative disorders (e.g., Parra et al., 2009, 2010). Even though, we did not provide a direct comparison with a non-naturalistic visual context, we argue that the availability of a much richer, and relationally structured, visual context aided the successful encoding of objects within their surrounding local context in the scene (Rensink, 2000). It may be plausible to assume that scenes are stored in visual working memory as a coherent global ensemble of objects therein (Postma & van der Ham, 2017). So, a change in object location may have been processed as a local change in the configuration of the scene (Rensink, 2002), and hence better detected because the scene was perceived as globally different (see Nie et al., 2017 for an example using object arrays). This proposition would also align with the idea that observers first create a mental map of the absolute and relative positions occupied in the visual context, and then assign additional information of the objects (e.g., identity) to such indexed positions (Postma & Haan, 1996). An alternative explanation for this result is that a change involving two features increases the likelihood that, at least, one of the two features would be retrieved from VWM, and so drive the successful detection. This suggestion links to hierarchical models of working memory postulating an independent and differential processing of feature information of visual objects (e.g., Fougne & Alvarez, 2011; Brady et al., 2013). Nonetheless, our interpretations remain qualitative and to be further tested. The main reason is that the current design does not disentangle the additive effect of identity and location from the overall role played by global scene representation in detecting changes, which is a limitation of the current study. In ongoing research, we address this issue by holding the global configuration of the scene constant while the identity, location and both features of the critical object change. We do so by swapping the critical object with another object in the scene for changes involving its location and so maintain the same global configuration of the scene between the study and the recognition phase. Even though our study taps into memory mechanisms for identity and location of objects, which are known to be processed by neuro-anatomically distinct pathways (e.g., Mishkin et al., 1983) it has little relevance to the brain localization of the behaviour under investigation, especially because the interconnections of the dissociating neuroanatomical processing of these two features (Schenk & McIntosh, 2010) is particularly overt in the diffuse brain damage associated with early dementia (Deng et al., 2016).

Turning to the eye-movement analyses, we confirm the similarity between MCIs and CPs also in the oculomotor responses associated with successful detections. There was no significant

difference between the two groups in either the latency to the first fixation, or the first-pass duration onto the critical object, or any significant interaction with the type of changes. This result counters research pointing at impairments on oculomotor responses due to neuropathology (see Freitas Pereira et al., 2014 for a review). Notably, most impairments are observed on low-level oculomotor control (e.g., Müller et al., 1991; Hutton et al., 1984; Wilcockson et al., 2019), and we could not assess this in our study as our sampling rate was too low (120 Hz) to confidently detect such metrics, e.g., saccades. Nevertheless, our findings remain at odds with studies looking at measures related to the critical object, such as the gaze duration, especially for changes of feature conjunctions (i.e., a change in location and identity), which was expected to generate a clear differential between the two groups (Fernández et al., 2018). The evidence of persevered patterns of overt attention, instead, corroborates recent findings by Cimminella et al., 2021 showing that extra-foveal capture by object semantics is intact in people with AD. Regardless of the group, we observed significant differences in the eye-movement measures associated with the type of change. Critical objects that changed in location took longer to be looked at than changes only in identity. Moreover, this latency was even longer when objects changed both in identity and location. When a target changes only in identity, the global structure of the scene is preserved between the study and the recognition phase. So, if the critical object is successfully encoded at its location, it is also readily available at the recognition phase to be inspected. When instead the critical object changes in location, observers search for the new location of the object to confirm its re-positioning within the scene, hence taking longer. When changes occur in both location and identity, we observe an additional cost in the latency, and that could be due to the conjunctive nature of such a change, which is known to increase response times in search tasks (e.g., Whiting et al., 2005). Once the critical object is found, it is inspected for longer when it only changed in identity, and significantly less when it changes location, especially when also its identity changes. This pattern can be logically linked to the detection accuracy, and again to the idea of independent encoding of features in VWM. Changes only in identity were the hardest to spot while those involving both location and identity were the easiest; and so relatedly, the former required much more attentional effort than the latter to drive a successful detection. A change in identity and location could benefit by recognition of either feature; it is sufficient to verify only one of the two to be successful. These results call for future investigation into finer manipulations of identity and location of critical objects in naturalistic scenes, such as positional or semantic likelihood, the low-level perceptual characteristics (e.g., visual prototypicality) of the critical objects, as well as include outdoor scenes, which have a substantially different field of view (see Vö 2021, for an inspiring discussion about naturalistic scenes). Coco et al. (2021) for example used outdoor naturalistic scenes to demonstrate that effects

of semantic interference on long-term visual memory are substantially reduced in MCIs compared to CPs, and lead to different compensatory strategy in their overt allocation of attention. Research in this direction will enable a better understanding of the mechanisms substantiating effective integration of object-scene information in short and long-term visual memory and potentially uncover more subtle differences due to pathological ageing, which were not observed in the current study. It is also important to stress that the diagnosis of MCI was made on clinical, mostly cognitive grounds, but different pathologies may be represented in our sample (e.g., early AD or vascular cognitive impairment). The multifarious nature of our MCI population may shadow potential differences in their change detection performance because possibly linked to a specific type of impairment (e.g., amnesic vs. non-amnesic). Thus, future research should look more closely at differences in the aetiology of the impairment to better characterise the type of population that may (or not) display benefits on their short-term memory processes by being situated in naturalistic visual contexts, as well as more clearly qualify whether preservation of these visual short-term memory mechanisms would generalize in more specific segments of the MCI spectrum.

Finally, it is important to draw a comparison with our sibling study (D’Innocenzo et al., 2022) where we examined a different sample of younger and healthy older adults on the same task and stimuli. Across the board, we observe an identical pattern of results both on the accuracy to detect changes and on eye-movement responses to the critical object associated with a successful recognition, thus confirming the reliability and replicability of the current study. The only prominent difference was a greater advantage of younger adults compared to older adults to detect changes involving both identity and location of the critical object, which may lend further support to the independent encoding of object features in VWM, as indicating that to a certain degree cognitive ageing may reduce memory for object identity. A change in identity requires, in fact, participants to retrieve semantic information about the critical object from VWM and compare it with the available input, i.e., a different object, to successfully recognize the change.

When considering other limitations of the current study, we note that 2 CPs and especially 9 MCIs had to be excluded from the analyses as their performance was at the chance level. This may indicate that our task is possibly hard for this population. One solution for future research could be to test our experimental manipulations using a flicker change detection task, where the study and the recognition phase are alternated several times. This experimental approach may have two advantages. The first is that we can systematically modify the timing of presentation to guarantee change detection performances above chance, e.g., by using a gating approach. The other is that we could examine the time it takes to successfully resolve blindness to change on identity and location of objects.

In sum, the findings of the current study together with those of our sibling study (D’Innocenzo et al., 2022) suggest relatively preserved short-term memory mechanisms and attentional responses in healthy and pathological ageing for bindings of object identity and location in naturalistic visual contexts. This core finding highlights the need to move from artificial to more ecologically valid stimuli (e.g., Willems & Peelen, 2021, Draschkow et al., 2021) to better distinguish what is spared by healthy and pathological ageing (e.g., Schnitzspahn et al., 2011; Diamond et al., 2020) from what instead is compromised by it, and especially the contexts eliciting this distinction. This approach will enable us to devise strategies that can capitalise on preserved mechanisms to ameliorate the cognitive decline that arises due to healthy ageing, and especially when pathological.

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