Neuropsychologia 211 (2025) 109117

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Differential eye movements and greater pupil size during mental scene construction in autobiographical recall

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ARTICLE INFO

Keywords:
Autobiographical memory
Cognition
Memory
Scene construction
Eye movements

ABSTRACT

There is growing evidence supporting a role for eye movements during autobiographical recall, but their potential functionality remains unclear. We hypothesise that the oculomotor system facilitates the process of mental scene construction, in which complex scenes associated with an autobiographical event are generated and maintained during recall. To explore this, we examined spontaneous eye movements during retrieval of cued autobiographical memories. Participants' verbal descriptions of each memory were recorded in synchronisation with their eye movements and pupil size during recall. For each memory participants described the place (details of the environment where the event took place) and the event (details of what happened). Narratives were analyzed using the Autobiographical Interview procedure, which separated internal spatial (place) and non-spatial (event, thoughts and emotion) details. Eye movements during recall of spatial details had significantly higher fixation duration and smaller saccade amplitude and peak velocity, and a higher number of consecutive unidirectional saccades, in comparison to recall of non-spatial details. Recurrence quantification analysis indicated longer sequences of refixations and more repetitions of the same fixation pattern when participants described spatial details. Recall of spatial details was also associated with significantly greater pupil area. Overall findings are consistent with the spontaneous production of more structured saccade patterns and greater cognitive load during the recall of internal spatial episodic scene details in comparison to episodic non-spatial details. These results are consistent with the oculomotor system facilitating the activation and correct positioning of elements of a complex scene relative to other imagined elements during autobiographical recall.

There is a growing evidence base supporting a functional role for the oculomotor system during the retrieval of autobiographical memories (El Haj, 2024). Concurrent eye movements have been shown to reduce image vividness and emotional valence for emotional autobiographical memories (Barrowcliff et al., 2004; Mertens et al., 2019; van den Hout et al., 2001; Andrade et al., 1997), while also just maintaining gaze fixation can reduce the vividness of autobiographical recall (Lenoble et al., 2019). Spontaneous eye movements recorded during autobiographical recall also differ significantly when compared to non-autobiographical control conditions (El Haj et al., 2014; El Haj, Nadrino, Antoine, Boucart and Lenoble, 2017).

While evidence for a significant association between eye movements and autobiographical recall is compelling, the potential functionality revealed by these eye movements is unclear. In recent years, several neuroimaging and neuropsychological studies have focused on understanding brain mechanisms associated with the process of *mental scene construction* (Hassabis and Maguire, 2007, 2009; Ladyka-Wojcik et al., 2022; Maguire and Mullally, 2013). Hassabis and Maguire define scene construction as "the process of mentally generating and maintaining a complex and coherent scene or event", (2007, p. 299). Scene construction is implicated not just during autobiographical recall, but also during the imagining of fictitious or future events (Palombo et al., 2018; Schacter et al., 2012). Patients with bilateral hippocampal lesions are significantly impaired for both autobiographical recall and imagined future thinking (Mullally et al., 2012; Race et al., 2011), and Maguire and Mullally (2013) have proposed that the mental construction of spatially coherent scenes is central to hippocampal information processing. Rubin argues this ability to mentally construct scenes is a stable individual difference that is predictive of the phenomenological qualities of autobiographical recall such as vividness, reliving, and emotional

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https://doi.org/10.1016/j.neuropsychologia.2025.109117
Received 8 July 2024; Received in revised form 9 February 2025; Accepted 5 March 2025
Available online 6 March 2025

intensity (Rubin, 2020). The extent to which autobiographical memories are experienced within a coherent spatial layout has been shown to correlate more strongly with phenomenological qualities of vividness and reliving than either non-spatial content or temporal specificity (Rubin et al., 2019).

The experience of visual mental imagery has long been recognised as a core element of autobiographical recall (Brewer, 1996; Conway and Pleydell-Pearce, 2000; Conway, 2009; Hassabis and Maguire, 2007). Donald Hebb was the first to propose that eye movements may play an organising function during the generation and exploration of mental images (Hebb, 1968). El Haj et al. (2014) found significantly reduced fixation duration and an increased number of saccades when comparing spontaneous eye movements during autobiographical recall against a control condition where participants counted out loud. They attributed these differences specifically to the greater involvement of visual mental imagery associated with autobiographical recall. Several studies examining visual pattern recognition have demonstrated spontaneous eye movements made while participants recall a previously viewed image depicting a scene significantly correlate with scan path patterns present during initial encoding (e.g. Bone et al., 2019; Brandt and Stark, 1997; Laeng and Teodorescu, 2002). Eye movements also reflect the spatial position of objects when participants are asked either to describe a previously viewed scene or simply listen to a spoken description of a scene (Johansson et al., 2010). Activity in the oculomotor system has been implicated during the storage and rehearsal of spatial information within visuo-spatial working memory (Ball et al., 2013; Bochynska and Laeng, 2015; McAteer et al., 2023; Pearson and Sahraie, 2003; Pearson et al., 2014). Directed saccades have also been argued to support visual recognition memory through sequences of saccadic eye-movement vectors that are based on the relevant feature layouts (Bicanski and Burgess, 2019).

Mental scene construction requires the retrieval and successful integration of spatial and sensory information relevant to the autobiographical event or fictitious scenario (Summerfield et al., 2010). Kosslyn (1994; Mast and Kosslyn, 2002) has argued that eye movements play a functional role during the construction of visual mental images, specifically by facilitating the activation of relevant stored memory representations and the correct positioning of elements of a scene relative to other parts. This view is consistent with the theory of autobiographical event memory proposed by Rubin and Umanath (2015), who argue it is the spatial layout of a retrieved autobiographical event that critically implicates visual imagery during scene construction rather than any related non-spatial content. A neuroimaging study conducted by Ladyka-Wojcik et al. (2022) contrasted free and restricted eye movement conditions while participants mentally constructed scenes in response to cued semantic scene categories such as casino or ski resort. They found that restricting eye movements significantly reduced the vividness of constructed scene imagery in comparison to allowing participants to make free eye movements. The authors argue this demonstrates a functional role for the oculomotor system during mental scene construction.

However, the study conducted by Ladyka-Wojcik et al. does not directly examine scene construction in the context of autobiographical recall. Previous studies that have investigated eye movements during autobiographical recall either compare characteristics of autobiographical memory under spontaneous eye movement and restricted/non-autobiographical control conditions (e.g. Armson et al., 2021; El Haj et al., 2014; Lenoble et al., 2019), or compare patterns of spontaneous eye movement across different categories of autobiographical memory (e.g., emotional and neutral autobiographical events, El Haj et al., 2017; covert or overt recall, Gautier and El Haj, 2023). To date, no study has examined spontaneous eye movement specifically during the mental scene construction of naturalistically encoded autobiographical events. This means it is unclear whether previously observed eye movement patterns reported in the literature are associated specifically with establishing the spatial layout of a recalled scene, or instead are associated more generally with visual imagery aspects of autobiographical recall (Armson et al., 2021; El Haj, 2024; Maguire and Mullally, 2013 Rubin, 2020; Rubin and Umanath, 2015).

The present study addressed this issue by examining participants' spontaneous eye movements during the retrieval of cued autobiographical memories. Participants' verbal descriptions of each memory were recorded in synchronisation with accompanying eye movements and pupil size during recall. Cued memories were divided into autobiographical events that had happened recently (within two weeks) or distantly (within two to three years). For each cued memory participants were asked to describe both the *place* (the details of the physical environment where the recalled event took place) and the *event* (the details of what happened in this environment). These verbal narratives were then subsequently segmented and categorised into separate recall periods using the Autobiographical Interview (AI) procedure (Levine et al., 2002). The AI is a standardized and widely used method for evoking and assessing autobiographical memory that has previously been used to examine eye movements during autobiographical recall (e.g. Armson et al., 2019, 2021; Davis et al., 2021). The AI procedure segments autobiographical narratives into internal (episodic) and external (non-episodic) details. Internal details reflect specific episodic recollection of an autobiographical event and are associated with brain structures and functions in networks that support episodic autobiographical memory (e.g. Gilboa and Moscovitch, 2021; Miller et al., 2020), while external details reflect non-episodic content including semantic knowledge and facts, unnecessary repetition, and general metacognitive statements and beliefs. In the current study we focused specifically on examining the spontaneous eye movements produced when participants recalled internal (but not external) details of their cued autobiographical memories (AMs). Metrics of interest for analyses included fixation duration, fixation pupil size, amplitude and peak velocity of saccades. These metrics were selected on the basis that they have previously been shown to reflect differences in autobiographical versus non-autobiographical recall (El Haj, 2024; El Haj et al., 2014, 2017; Wynn et al., 2019.), They are therefore suitable to explore whether eye movements differ during mental scene construction in comparison to autobiographical recall of non-spatial internal episodic details.

The novelty of the current procedure is that spontaneous eye movements produced during recall of internal spatial details of AMs (the layout and objects in the recalled environment) were compared against recall of internal non-spatial details such as the event (what happened, who was present, etc.) and associated thoughts and emotions. This approach affords greater granularity than previous studies which have compared recall of internal episodic and external non-episodic details, but not between spatial and non-spatial episodic features. For example, Armson et al. (2021) reported a significant relationship between eye fixation rate and the mean number of total internal details reported, but not external details. Similarly, Davis et al. (2021) found the degree of eye-movement synchrony observed for autobiographical memories of watching a movie was significantly related to the proportion of internal episodic details reported, but not the number of external details. Sheldon et al. (2019) did find a significant difference in eye fixations between scene and event-based mental representations, but in their procedure, events were framed as possible future scenarios rather than genuine AMs. Therefore, while findings such as these are supportive of a functional role for the oculomotor system during episodic autobiographical recall more generally, they do not allow a specific contribution to mental scene construction to be established.

If eye movements are associated with the generation and maintenance of coherent scenes during autobiographical recall, we expected to find differences in the spontaneous eye movements associated with the recall of *place* (the spatial layout and associated physical objects in the AM) in comparison to non-spatial *event* (what happened) and *thought/emotion* based internal episodic details. Fixation duration and amplitude/peak velocity of saccades were predicted to differ, as these metrics have been shown to vary during mental reinstatement and visual image generation (Bone et al., 2019; Johansson et al., 2010; Laeng and Teodorescu, 2002), and therefore should differ if eye movements make a specific contribution during mental scene construction. We predicted a difference in the number of consecutive saccades observed going in the same direction during spatial scene recall. This hypothesis was based on research demonstrating that when scanning complex scenes saccades are made more frequently in the same direction as their immediate predecessor (Hooge et al., 2005; Tatler and Vincent, 2008); We also predicted significant differences in pupil size, as pupil size has been shown to increase in association with both greater cognitive demands during AM recall (El Haj et al., 2019; Janssen et al., 2021) and during the construction of complex mental imagery (Laeng and Sulutvedt, 2014; Sulutvedt et al., 2018).

Finally, we predicted that eye movements during mental scene construction would be more structured and ordered than those observed during the recall of non-spatial episodic details, as a result of the eye movements facilitating the activation and correct positioning of elements in a complex imagined scene (Kosslyn, 1994; Mast and Kosslyn, 2002). Similar patterns have been observed for eye movement scanpaths during the recall of previously presented visual scenes (e.g. Bone et al., 2019; Brandt and Stark, 1997; Laeng and Teodorescu, 2002), but have not previously been explored in the context of naturalistic autobiographical recall. In line with this hypothesis regarding the temporal unfolding of fixations, we expected that during the description of spatial details, the spatial layout of fixations would be characterised by an increased number of refixations to the same region and the presence of characteristic repeated patterns of fixations in different spatial regions that are necessary to construct and maintain a complex mental image. Gurtner et al. (2021) have proposed that refixations in mental imagery may help to maintain the overall spatial structure of a constructed image.

1. Method

1.1. Participants

In this study, G*Power 3.1 software (Faul et al., 2009) was used to calculate the sample size required to achieve a power of 0.90 in a two-factor repeated measures analysis of variance with a medium effect size (e.g., El Haj et al., 2014; 2017; 2022). The data entered into the software were: two-tailed test with $\alpha = 0.05$, effect size $f = 0.25$, number of measurements = 3 (i.e., place, event and thought/emotion internal episodic details), correlation between repeated measures $r = 0.5$, and non-sphericity correction $\varepsilon = .75$ (i.e., intermediate violation of sphericity; with $k = 3$ measurements the value of $\varepsilon = 1$ is when the assumption of sphericity is met, whereas $\varepsilon = \frac{1}{k-1} = 0.5$ is the maximum possible violation of sphericity; Landis and Koch, 1977). A minimum of 44 participants was required.

We recruited 44 (24 females) participants from the University of Trieste (mean age = 23.84, SD = 1.70). All participants were students at the University of Trieste with Italian mother tongue language, had normal or corrected to normal vision, and received course credit for their contribution. The experiment was approved by the Ethic committee of the University of Trieste, and informed consent was obtained in accordance with the principles laid down by the Helsinki Declaration.

1.2. Apparatus

Descriptions of autobiographical memories were recorded with a Lavalier Microphone (Boya BY—LM20) and eye movements with a video-based eye tracker (EyeLink 1000 plus – SR Research – Desktop Mount). The eye tracker recorded only the dominant eye with a sampling rate of 500 Hz, and a spatial resolution of $<0.1^\circ$. The eye movement events are generated in real-time during recording, based on the default internal heuristic saccade detector that uses a velocity- and acceleration-based saccade detection method (thresholds: 30°/sec and 8000°/sec^2 respectively). The recording of the voice audio track and the eye-movements were synchronized. The stimuli were presented on a ViewSonic TD2220 22-inch monitor (47.8 cm horizontal x 26.9 cm vertical).

1.3. Stimuli

We used 6 different cue words to elicit description of autobiographical memories, one for each trial (see Table 1). To ensure participants were able to recall appropriate autobiographical memories in response to the cue words they were selected to refer to events likely to be commonly experienced by university students. In order to examine whether the age of the recalled event was a significant factor three cue words were associated to recent autobiographical events (within the last 2 weeks), and three to distant autobiographical events (from 2 to 3 years ago). To reduce the heterogeneity of the recalled AMs the duration of the distant condition was set to cover a period where participants were still at university, rather than their teenage or childhood experiences.

1.4. Procedure

The experiment took place in a dimly illuminated room. Participants sat in front of a screen, placed at a distance of 60 cm, with the forehead fixed. The eye tracker was placed just in front of the screen without occluding it. Eye movements and the voice were synchronously recorded while participants described the place and event associated with each memory.

Each trial started with the presentation of the cue word in the middle of the screen for 2 s, followed by the instructions to describe the event (or the place) - duration 1 s. Then, a blank screen signaled the beginning of a 90-s time window allocated for the description of the event (or the place) associated with each autobiographical memory. An acoustic tone signaled the end of the 90-s time window, followed by a new instruction on the screen, inviting the participant to describe the place (or the event) associated to the same autobiographical memory. Another 90-s time window was allocated for the description of the place (or the event). At the end of the trial there was a 60-s pause. A new calibration of the eye-tracker was acquired (see Fig. 1) every trial. We asked participants to keep the gaze within the outer border of the 22-inch blank screen during the description of the memories. Light grey (RGB: 211; 211; 211) was the background color during instruction, cue word presentation and blank screen.

The 3 distant cue words were presented always together in a randomized order; for each word in the sequence of 3 we asked participants to remember the place (or the event) first, then the event (or place). The same procedure was adopted for the 3 recent cue words. The temporal distance (distant vs. recent) and description (place vs. event) were counterbalanced.

1.5. Analysis

Given that the main aim of the study was to analyze and compare eye movements during the spatial description of autobiographical memory (AM) places – and all physical objects – versus the non-spatial description of thoughts, emotions and other non-visual memories associated

Table 1
Six different cue words used to elicit description of autobiographical memories.

Time Position: Distant (from 2 to 3 years ago)	Time Position: Recent (within the last 2 weeks)
graduation or birthday party	café or restaurant or canteen
natural area	university life event
art city or touristic city	shop

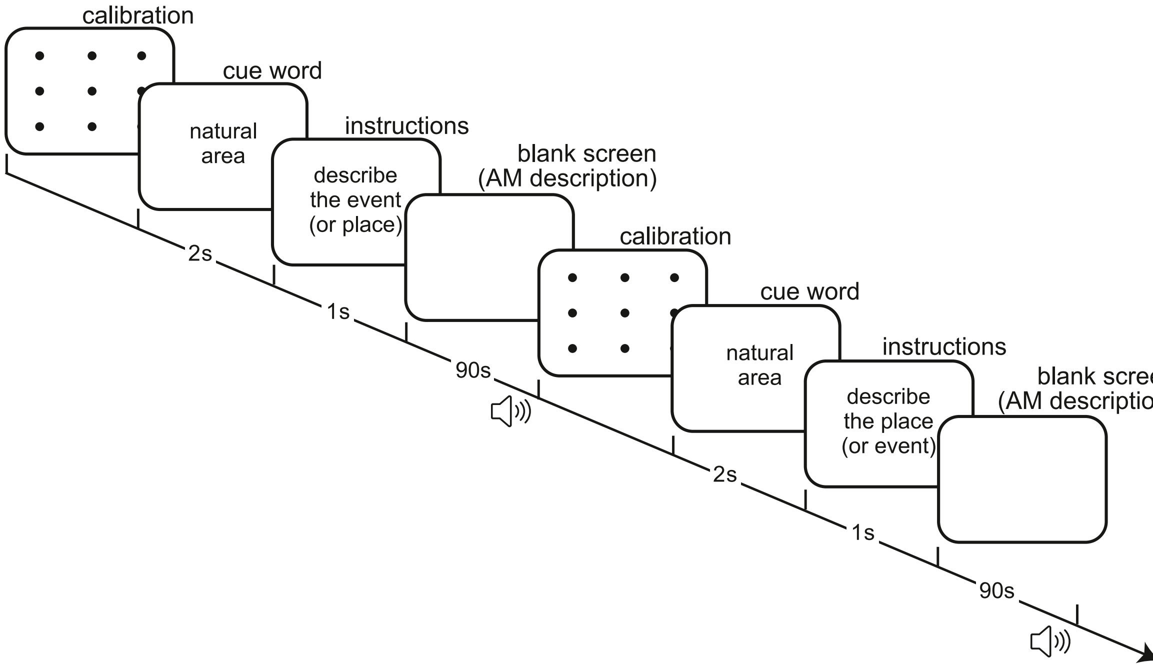

Fig. 1. Experimental procedure. In 90 s, sitting in front of a blank screen, participants retrieved the autobiographical memories (AM) of the place and event associated with each cue word.

with the autobiographical event, we used the Autobiographical Interview (Levine et al., 2002) to classify AM in recall periods.

The AI is a standardized and widely used method for evoking and assessing AM. Freely recalled memories were segmented into internal (episodic) and external (non-episodic) informational bits, or "details". Internal (but not external) details related to the main event of interest, reflect episodic recollection and are associated with brain structure and function in networks supporting episodic AM. External details largely reflect details tangential to the main event. Internal details are: Event; Time; Place; Perceptual; Thought/Emotion. External details are: Event; Semantic; Repetition; Other. Two extensively trained external scorers were independently involved in classification of autobiographical memories. They scored the narrative recall of autobiographical events separately using the Levine classification. Inter-rater reliability (IRR) calculated with Fleiss' Kappa index for unordered categories and interpreted using the heuristic benchmarks suggested by Landis and Koch (1977), could be classified as almost perfect (all categories IRR = 0.83; Event IRR = 0.78; Thought/Emotion IRR = .88; Place IRR = 0.79). In case of important discrepancies, differences were resolved by consensus.

Finally, onset and offset for all time intervals corresponding to the internal and external details were merged with raw eye-movement data by means of EyeLink Data Viewer Software (SR Research Ltd). The same software has been used to convert raw eye-movements in saccades, blinks, and fixations. Movements in which the velocity between two samples exceeded the threshold of 30° per second over a distance of 0.1° were considered saccades. A missing signal from the pupil lasting more than 3 samples was used to mark blinks. All other activity that wasn't saccades or blinks were considered fixations. Overall, the blink rate was 19.1% (SD = 10%), with an average duration of 136 ms (SD = 62 ms); the blinks were excluded from the analyses.

For the purposes of our experiment, we analyzed only the fixations and saccades that occurred in the time periods corresponding to the internal details of spatial recall (Place) and non-spatial recall (Event and Thought/Emotion). Eye movements were not recorded during the presentation of any external stimuli or events and the screen remained blank throughout. The dependent variables were the duration of fixations, pupil size (the blank screen lightning conditions were stable and constant through all eye movement recording sessions), the amplitude and peak velocity of saccades (which are related as peak velocity scales with saccade amplitude), and the number of saccades sequences in the same direction. Regarding this last index, each sequence of saccades corresponded to a series of at least two consecutive saccades in the same direction – leftward, or rightward, or downward, or upward. In our data we observed a maximum of 5 consecutive saccades in the same direction. If in the same time interval (for example in the Internal detail: place) we observed two consecutive saccades toward the left, followed by a fixation, and then 4 consecutive saccades toward the right, 2 saccade sequences were computed in this internal detail. These variables were analyzed with an analysis of variance with two within factors, i.e., temporal distance (distant, recent)); detail (place, event, thought/emotion). In case of statistically significant Mauchly's test of sphericity ($p < .05$), for the detail factor and temporal distance × detail interaction we used the p-value from the Greenhouse-Geisser correction of degree of freedom. Post-hoc comparisons were corrected with Holm post-hoc method, and effect size measures were reported as partial eta-squared and Cohen's *d*.

Given that eye movements unfold over time and the variables analyzed so far do not quantify the temporal structure of these movements, we also conducted an analysis of the temporal structure of eye fixation using recurrence quantification analysis (RQA). This type of analysis, originally conceived to be used with nonlinear systems that evolve over time, has been adapted by Anderson and colleagues (2013) to quantify eye fixations and refixation and to show recurrent patterns. In short, RQA is based on the recurrence plot (RP), which plots recurrences of a fixation sequence with itself over all possible time lags. To accomplish this, we merged all events that belonged to the same detail type across the whole memory description for each autobiographical event. Fixations were defined as recurrent if within 2° of visual angle of a previous fixation. We chose this value of the parameter to approximate the dimensions of the fovea (see Anderson et al., 2013).

The parameters are:

- the percentage of recurrent fixation, that is the number of times that a fixation recurs at the same (local) spatial position.

- the determinism, that is the percentage of gaze patterns (sequences of saccade-fixation) that are repeated in the same order. For example, this parameter increases as the viewer moves their gaze from a first to a second and then to a third spatial position, repeating the same pattern in the same order several times.
- the laminarity whichin the RP is the percentage of recurrence points forming vertical lines, corresponding to areas initially examined with a single fixation and later followed with consecutive fixations.
- the center of recurrent mass (CORM) indicates when refixations occur in time and describes the temporal unfolding of refixations. Small values of CORM indicate that refixations occur soon (early in time) with respect to the first fixation, and large values indicate that refixations occur late, after several intermediate fixations to other locations.
- the entropy, referring to the Shannon entropy (Shannon, 1948), that indicates the complexity of the deterministic structure in a system, in our case of eye movements patterns.

To calculate the RQA parameters (see detailed description in Anderson et al., 2013) we used routines written in Matlab® found here: http://barlab.psych.ubc.ca/research/

A Bayesian analysis was also performed calculating the alternative/null Bayes Factor (BF10), a continuous statistical index that quantifies the evidence in favor of the alternative over the null hypothesis. In particular, (a) BF10 > 3 and BF10 > 10 provide significant and strong evidence for the alternative hypothesis, respectively; (b) BF10 < .33 and BF10 < .10 provide substantial and strong support for the null hypothesis, respectively; and (c).33 < BF10 < 3, can be considered anecdotal for any hypothesis (Jarosz and Wiley, 2014). All analyses were performed using R Statistical Software (v4.1.2; R Core Team, 2021). We carried out repeated measure analysis of variance along with estimated marginal means comparisons using the R package *jmv* (v2.0; Selker et al., 2020). We computed Bayes Factor indices with the R package *BayesFactor* (v0.9.12–4.2; Morey and Rouder, 2018). Inter-rater reliability was assessed using the R package *irr* (Gamer et al., 2019). For all the aforementioned analyses, p-values reported were based on a two-tailed alternative hypothesis.

All data files are available at https://osf.io/je59c/?view_only=cc07ed9577f24b9c840ce087da1bc736.

2. Results

The first exploratory analysis of AM with the AI method revealed that the mean number of internal (episodic) and external details was 175.8 and 58.2 respectively. In the internal category the sum of the three details, place, event, and thought/emotion corresponded to the 82.1%. In Table 2 we can see the different occurrences of the three categories when describing the event and place. In addition, the distribution of durations and interquartile range of all details was very similar for each of the three main categories (Place, Event, and Thought/Emotion, see Fig. 2A), with a mean duration of 4.01 (Me = 3.02, SD = 4.54, IQR = [1.89, 4.65]), 3.55 (Me = 2.91, SD = 2.71, IQR = [1.98, 4.39]), and 4.09 (Me = 3.21, SD = 3.09, IQR = [2.05, 5.25]) seconds respectively. The combined remaining AMI categories (perceptual; repetition; semantic; time; other) accounted for only 17.8% of the total reported details. These categories provided an insufficient number of details to reliably associate with eye movements, and therefore were excluded from further analysis.

Table 2
Total number of details remembered during the description of the event and place. The category "all other details" is the sum of the categories: Perceptual; Repetition; Semantic; Time; Other.

details:	place	event	thought/ emotion	all other details	total internal details
Instructions:					
describe the event	547 (14.4%)	1605 (42.3%)	1091 (28.7%)	553 (14.3%)	3796 (100%)
describe the place	2244 (59.5%)	541 (14.4%)	191 (5.1%)	794 (21.1%)	3770 (100%)
total	2791 (36.9%)	2146 (28.4%)	1282 (16.9%)	1347 (17.8%)	6572 (100%)

The mean values and ANOVA results of the dependent variables are summarized in Tables 3–5. To deal with excess skewness and kurtosis (>1) we log-transformed the non-normal dependent variables prior to entering them into the repeated measure analysis of variance.

2.1. *Duration of fixations*

The ANOVA for the single fixation duration showed a statistically significant main effect of the detail factor ($F(2, 82) = 8.47$, $\eta^2 = .17$, $p < .001$; BF10 = 19.03). The post-hoc analysis highlighted a significantly higher fixation duration for the spatial Place details (M = 6.215 log(ms); SD = .444) in respect to non-spatial Event details (M = 6.151 log(ms); SD = .439; $t = 2.47$; df = 41; p = .036; $d = .38$; BF10 = 2.46) and Thought/Emotion details (M = 6.114 log(ms); SD = .410; $t = 3.79$; df = 41; p = .001; $d = .59$; BF10 = 58.22). No differences were found between the Event and Thought/Emotion conditions ($t = 1.70$; df = 41; p = .097; $d = .26$; BF10 = .62). The time distance factor and its interaction with the detail factor showed no statistically significant effects. See Fig. 2 and Table 4 for a complete list of results.

2.2. *Fixation pupil size*

The ANOVA for the pupil size showed a statistically significant main effect of the detail factor ($F(2, 82) = 18.78$, $\eta^2 = .31$, $p < .001$; BF10 = 17.51; see Table 4). The post-hoc analysis revealed significantly greater pupil area for spatial Place details (M = 7.269 log(area); SD = .373) with respect to non-spatial Event details (M = 7.250 log(area); SD = .374; $t = 3.17$; df = 41; p = .005; $d = .49$; BF10 = 11.73) and Thought/Emotion details (M = 7.230 log(area); SD = .374; $t = 5.67$; df = 41; p < .001; $d = .88$; BF10 > 1000). Differences were found also between the Event and Thought/Emotion conditions, with a significantly greater pupil area for the Event details ($t = 3.23$; df = 41; p = .005; $d = .50$; BF10 = 13.65; see Fig. 2). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

2.3. *Amplitude and peak velocity of saccades*

The ANOVA analyses for the amplitude of saccades showed a statistically significant main effect of the details factor ($F(1.64, 67.19) = 9.86$, $\eta^2 = .19$, $p < .001$; BF10 = 7.60; see Table 4). The post-hoc analyses revealed that in the spatial Place condition (M = .946 log(deg); SD = .554) saccadic amplitude was smaller with respect to non-spatial Event (M = 1.075 log(deg); SD = .566; $t = -3.52$; df = 41; p = .003; $d = .54$; BF10 = 27.93) and Thought/Emotion conditions (M = 1.101 log (deg); SD = .646; $t = -3.48$; df = 41; p = .003; $d = 0.54$; BF10 = 25.24). No differences were found between the Event and Thought/Emotion conditions ($t = -.89$; df = 41; p = .379; $d = .14$; BF10 = .24; see Fig. 2). Lastly, the time distance factor and its interaction with the detail factor showed no statistically significant effects.

As for the peak velocity of saccades (which would be expected to scale with amplitude), the ANOVA results showed a statistically significant main effect of the detail factor ($F(1.60, 65.41) = 6.79$, $\eta^2 = .14$, $p = .004$; BF10 = .79; see Table 4). The post-hoc analyses confirmed a smaller peak velocity for the spatial Place condition (M = 5.099 log (deg/s); SD = .391) with respect to the non-spatial Thought/Emotion conditions (M = 5.186 log(deg/s); SD = .430; $t = -2.96$; df = 41; p = .015; $d = 0.46$; BF10 = 7.17) and Event condition (M = 5.164 log(deg/s); SD = .372; $t = -2.64$; df = 41; p = .023; $d = 0.41$; BF10 = 3.50). No difference in saccadic peak velocity was found between the Event and

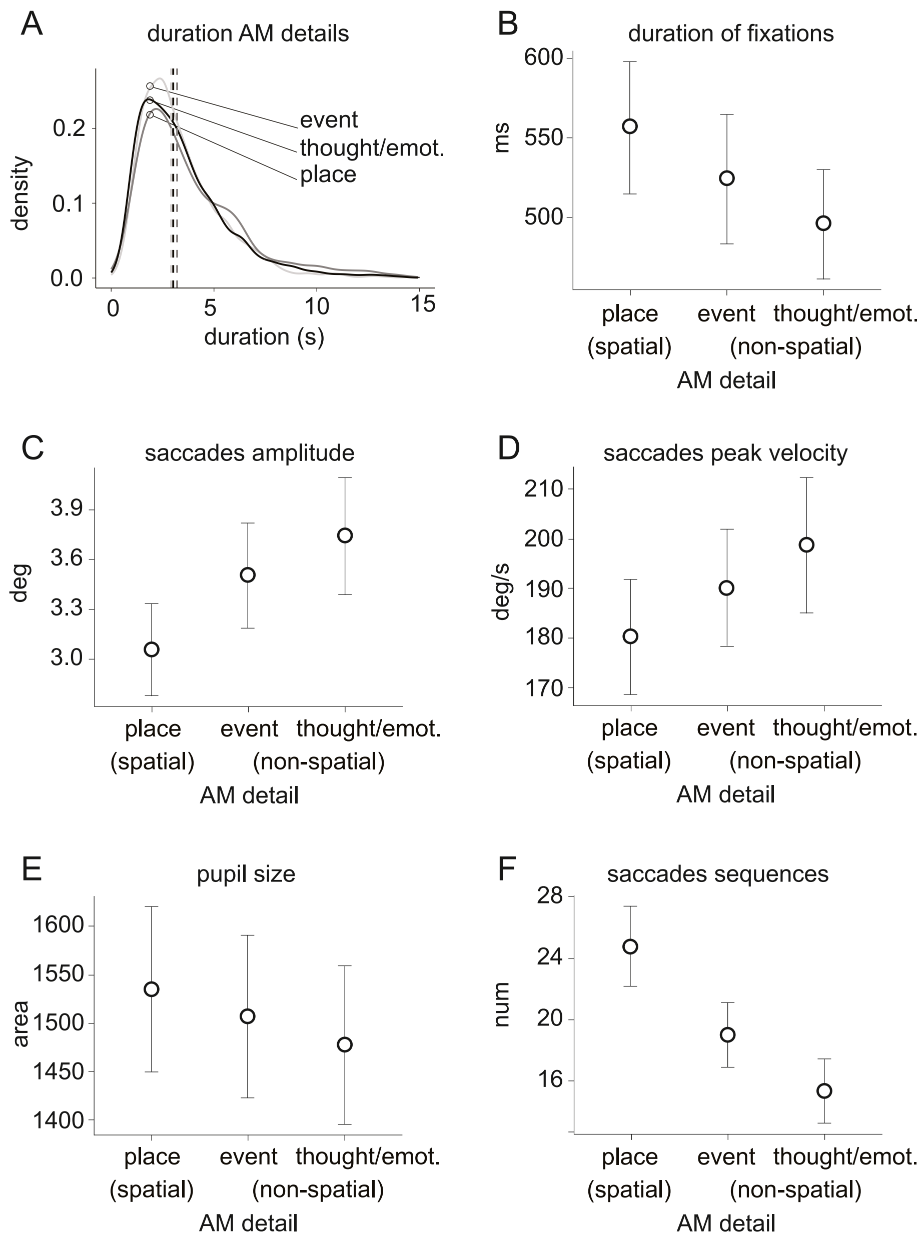

Fig. 2. A. Distribution of temporal length for the place, event and thought/emotion details. B-F. Average values (not log-transformed) of duration of fixations, amplitude and peak velocity of saccades, pupil size, and the number of saccades sequences in the same direction for the place, event and thought/emotion details. Dashed vertical lines are median for the distribution; error bars are 1 standard error.

Thought/Emotion conditions ($t = -1.20$; df = 41; p = .238; $d = .18$; BF10 = .32; see Fig. 2). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

2.4. Saccade sequences in the same direction

As for the number of consecutive saccades in the same direction, we found a significant main effect of the detail factor ($F(1.63, 66.80) = 11.03$, $\eta^2 = .21$, $p < .001$; BF10 > 1000; see Table 4). The post-hoc analysis revealed significantly higher number of consecutive unidirectional saccades for spatial Place details (M = 2.737 log(num); SD = .742) with respect to non-spatial Event (M = 2.417 log(num); SD = .920; $t = 2.73$; df = 41; p = .018; $d = .42$; BF10 = 4.31) and Thought/Emotion details (M = 2.090 log(num); SD = 1.006; $t = 5.23$; df = 41; $p < .001$; $d = .81$; BF10 > 1000). The difference between Event and Thought/Emotion conditions fell short of significance ($t = 1.96$; df = 41; p = .057; $d = .30$; BF10 = .94; see Fig. 2). The time distance factor showed no statistically significant effects. Although the interaction between detail and time distance was statistically significant, the Bayesian analysis did not confirm it (BF10 = 0.27, see Table 4). Therefore, the main effects of detail factor were not further qualified.

2.5. Recurrence quantification analysis

2.5.1. Percentage of recurrent fixations

The ANOVA on the percentage of recurrent fixations showed a statistically significant interaction effect between the detail and time distance factors ($F(2, 82) = 4.39$, $\eta^2 = .10$, p = .015; BF10 = 0.05; see Table 5), although the Bayesian analysis did not confirm this. Furthermore, the time distance factor and the detail factor did not show statistically significant effects. Examination of Holm-corrected post hoc tests showed no statistically significant differences.

Table 3
Means and Standard deviations of raw (not log-transformed) eye-movements parameters and fixations Recurrence Quantification Analysis parameters. Note. Far = distant autobiographical events (from 2 to 3 years ago). Short = recent autobiographical events (within the last 2 weeks). Details = Episodic informational bits of freely recalled memories. [a] Pupil area is recorded by the EyeLink 1000 tracker as an integer number with arbitrary units ("pupil" pixels in the image of the eye) and proportional to millimeters depending on the eye-to-camera distance (Hayes and Petrov, 2016).

Temporal distance	Far		
Detail	Place	Event	Thought/ Emotion
Duration of fixation (ms)	558.87 (283.34)	517.09 (274.39)	491.87 (242.61)
Fixation pupil size (pixel area) [a]	1558.83 (580.58)	1530.21 (552.87)	1498.99 (548.42)
Saccade amplitude (deg)	2.95 (1.80)	3.55 (2.13)	3.65 (2.27)
Saccade peak velocity (deg/s)	184.21 (102.71)	198.52 (96.01)	204.32 (111.59)
Saccade sequences (num)	21.81 (15.87)	14.31 (10.64)	14.17 (13.39)
Recurrence (%)	38.95 (20.52)	35.28 (20.72)	37.66 (21.77)
Determinism (%)	72.39 (19.81)	67.68 (21.00)	66.54 (20.31)
Laminarity (%)	74.70 (18.22)	67.55 (20.13)	65.10 (19.25)
CORM	29.31 (4.15)	29.43 (5.44)	30.88 (5.54)
Entropy	2.27 (0.91)	1.97 (0.82)	1.82 (0.66)
Temporal distance	**Short**		
Detail	**Place**	**Event**	**Thought/ Emotion**
Duration of fixation (ms)	553.73 (273.12)	531.16 (281.82)	499.42 (221.05)
Fixation pupil size (pixel area) [a]	1510.50 (546.34)	1482.32 (544.49)	1454.73 (536.08)
Saccade amplitude (deg)	3.17 (1.96)	3.46 (2.22)	3.82 (2.59)
Saccade peak velocity (deg/s)	176.17 (68.68)	181.70 (70.35)	193.08 (84.17)
Saccade sequences (num)	20.12 (15.91)	18.79 (14.13)	13.00 (12.84)
Recurrence (%)	33.83 (21.03)	37.54 (22.69)	41.09 (24.65)
Determinism (%)	68.11 (21.31)	67.88 (21.92)	66.04 (23.34)
Laminarity (%)	69.62 (20.69)	68.80 (21.25)	63.85 (21.31)
CORM	28.47 (4.60)	29.95 (4.41)	32.52 (6.12)
Entropy	2.16 (0.86)	1.98 (0.84)	1.85 (0.84)

2.5.2. *Determinism*

The ANOVA for the determinism parameter showed a statistically significant main effect of the detail factor ($F(2, 80) = 4.89$, $\eta^2 = .11$, p = .010; BF10 = .46; see Table 5). Post-hoc analysis revealed a significantly higher percentage of recurrence points forming diagonal lines for spatial Place details (M = 4.194 log(%); SD = .366) compared to non-spatial Thought/Emotion details (M = 4.117 log(%); SD = .402; t = 2.86; df = 40; p = .020; d = .45; BF10 = 5.68). No difference in determinism was found between the Place and Event conditions (M = 4.150 log(%); SD = .370; t = 1.91; df = 40; p = .126; d = .30; BF10 = .88), nor between the Event and Thought/Emotion conditions (t = 1.38; df = 40; p = .176; d = .21; BF10 = .40; see Fig. 3). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

2.5.3. *Laminarity*

As for the laminarity parameter, the ANOVA results showed a statistically significant main effect of the detail factor ($F(2, 80) = 10.34$, $\eta^2 = .21$, p < .001; BF10 = 52.16; see Table 5). The post-hoc analyses confirmed significantly higher percentage of recurrence points forming vertical lines for the spatial Place condition (M = 4.222 log(%); SD = .379) with respect to the non-spatial Thought/Emotion conditions (M = 4.096 log(%); SD = .392; t = 4.67; df = 40; p < .001; d = 0.73; BF10 = 659.12) and Event condition (M = 4.153 log(%); SD = .409; t = 2.86; df = 40; p = .013; d = 0.45; BF10 = 5.76). No difference was found between the Event and Thought/Emotion conditions (t = 1.80; df = 40; p = .08; d = .28; BF10 = .73; see Fig. 3). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

2.5.4. *CORM*

The ANOVA for the CORM parameter showed a statistically significant main effect of the detail factor (F(2, 80) = 8.45, $\eta^2 = .17$, p < .001; BF10 = 42.23; see Table 5). Post-hoc analysis revealed a significantly lower values for spatial Place details (M = 3.351 log(CORM); SD = .138) compared to non-spatial Thought/Emotion details (M = 3.440 log (CORM); SD = .147; t = −3.83; df = 40; p = .001; d = .60; BF10 = 63.81). No difference in CORM values was found between the Place and Event conditions (M = 3.377 log(CORM); SD = .136; t = −1.21; df = 40; p = .234; d = .19; BF10 = .33). Differences were also found between the Event and Thought/Emotion conditions, with significantly lower scores for the Event details (t = −2.83; df = 40; p = .015; d = .44; BF10 = 5.29; see Fig. 3). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

2.5.5. *Entropy*

The ANOVA results showed a statistically significant main effect of the detail factor for the entropy parameter (F(2, 74) = 13.31, $\eta^2 = .26$, p < .001; BF10 > 1000; see Table 5). Post-hoc analyses showed that the spatial Place condition (M = .711 log(entropy); SD = .399) had more complexity of dynamical fixation trajectories than the non-spatial Thought/Emotion (M = .515 log(entropy); SD = .391; t = 5.27; df = 37; p < .001; d = .85; BF10 > 1000) and Event conditions (M = .578 log

Table 4
Results of the statistical analyses on log-transformed eye-movements parameters. Temporal Distance = distance of autobiographical events condition (Categorical: Far/Short = from 2 to 3 years ago/within the last 2 weeks); Detail = Episodic informational bits of freely recalled memories; df = degrees of freedom; p-values were reported in bold when lower then 0.05; BF_{10} = Inclusion Bayes Factor, computed by means of Bayesian Model Averaging across models; Bayes Factor were reported in bold when supporting the alternative hypothesis. [a] Greenhouse-Geisser corrected degrees of freedom.

Variable	Effect	Factors	df	Statistics	p-value	η^2	BF_{10}	Support
Duration of fixation (ms)	main	temporal distance	(1,41)	*F = .17*	*.679*	.00	.12	H0
	main	detail	(2,82)	*F = 8.47*	***.000***	.17	**19.03**	**H1**
	interaction	temp. dist. ✻ detail	(1.74,71.48)[a]	*F = .50*	*.585*	.01	.05	H0
Fixation pupil size (Pixel area)	main	temporal distance	(1,41)	*F = 3.92*	*.055*	.09	**67.96**	**H1**
	main	detail	(2,82)	*F = 18.78*	***.000***	.31	**17.51**	**H1**
	interaction	temp. dist. ✻ detail	(2,82)	*F = .11*	*.893*	.00	.32	–
Saccade amplitude (deg)	main	temporal distance	(1,41)	*F = .06*	*.802*	.00	.11	H0
	main	detail	(1.64,67.19) [a]	*F = 9.86*	***.000***	.19	**7.60**	**H1**
	interaction	temp. dist. ✻ detail	(2,82)	*F = 1.44*	*.244*	.03	.08	H0
Saccade peak velocity (deg/s)	main	temporal distance	(1,41)	*F = .52*	*.472*	.01	.20	H0
	main	detail	(1.60,65.41) [a]	*F = 6.79*	***.004***	.14	.79	–
	interaction	temp. dist. ✻ detail	(2,82)	*F = .91*	*.410*	.02	.05	H0
Saccade sequences (num)	main	temporal distance	(1,41)	*F = .06*	*.813*	.00	.14	–
	main	detail	(1.63, 66.80) [a]	*F = 11.03*	***.000***	.21	**>1000**	**H1**
	interaction	temp. dist. ✻ detail	(2,82)	*F = 3.79*	***.027***	.08	.27	H0

Table 5
Results of the statistical analyses on log-transformed fixations Recurrence Quantification Analysis parameters. Temporal Distance = distance of autobiographical events condition (Categorical: Far/Short = from 2 to 3 years ago/within the last 2 weeks); Detail = Episodic informational bits of freely recalled memories; df = degrees of freedom; p-values were reported in bold when lower then 0.05; BF_{10} = Inclusion Bayes Factor, computed by means of Bayesian Model Averaging across models; Bayes Factor were reported in bold when supporting the alternative hypothesis. [a] Greenhouse-Geisser corrected degrees of freedom.

Variable	Effect	Factors	df	Statistics	p-value	η^2	BF_{10}	Support
Recurrence (%)	main	temporal distance	(1,41)	*F* = .06	.809	.00	.11	H0
	main	detail	(2,82)	*F* = 1.85	.164	.04	.09	H0
	interaction	temp. dist. ✻ detail	(2,82)	***F* = 4.39**	**.015**	**.10**	**.05**	**H0**
Determinism (%)	main	temporal distance	(1,40)	*F* = 1.01	.320	.02	.16	H0
	main	detail	(2,80)	***F* = 4.89**	**.010**	**.11**	**.46**	**-**
	interaction	temp. dist. ✻ detail	(2,80)	*F* = 1.01	.368	.02	.03	H0
Laminarity (%)	main	temporal distance	(1,40)	*F* = 1.39	.245	.03	.27	H0
	main	detail	(2,80)	***F* = 10.34**	**.000**	**.21**	**52.16**	**H1**
	interaction	temp. dist. ✻ detail	(2,80)	*F* = 2.37	.100	.06	.15	H0
CORM	main	temporal distance	(1,40)	*F* = .49	.489	.01	.20	H0
	main	detail	(2,80)	***F* = 8.45**	**.000**	**.17**	**42.23**	**H1**
	interaction	temp. dist. ✻ detail	(2,80)	*F* = 2.50	.088	.06	.31	H0
Entropy	main	temporal distance	(1,37)	*F* = .25	.620	.01	.10	H0
	main	detail	(2,74)	***F* = 13.31**	**.000**	**.26**	**>1000**	**H1**
	interaction	temp. dist. ✻ detail	(2,74)	*F* = .18	.832	.00	.04	H0

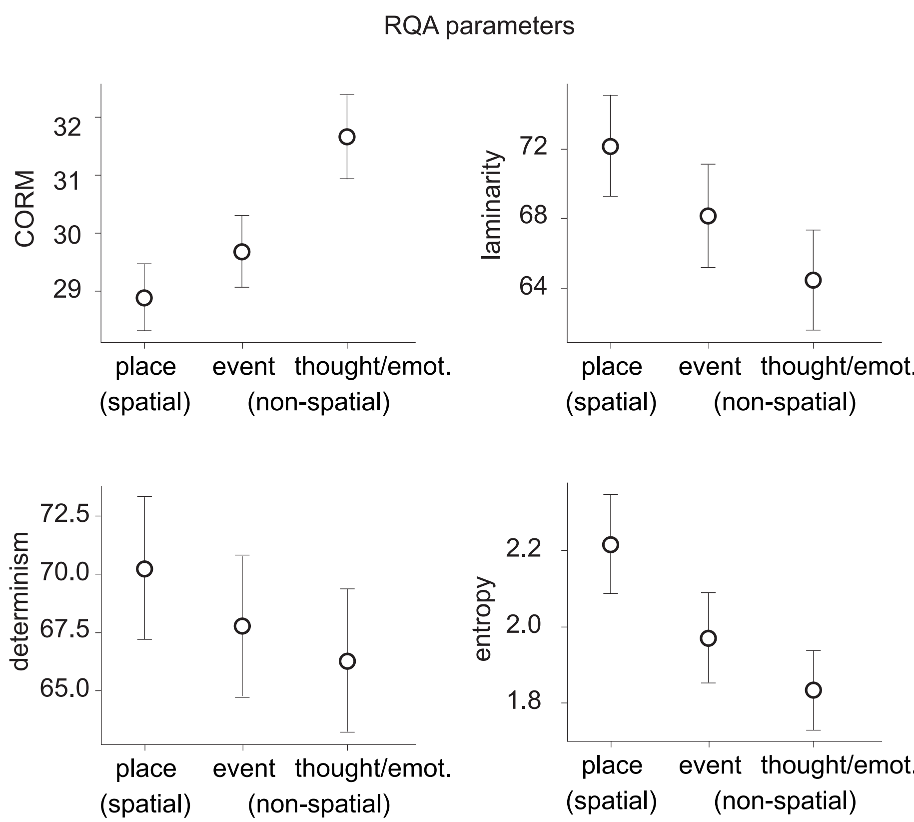

Fig. 3. Average values (not log-transformed) of three RQA parameters (CORM: center of recurrent mass; laminarity; determinism; entropy) for the place, event and thought/emotion details. Error bars are 1 standard error.

(entropy); SD = .434; t = 3.72; df = 37; p = .001; d = .60; BF10 = 45.19). There was no difference in entropy values between the Event and Thought/Emotion conditions (t = 1.47; df = 37; p = .151; d = .24; BF10 = .47; see Fig. 3). The time distance factor and its interaction with the detail factor showed no statistically significant effects.

3. Discussion

The current study compared spontaneous eye movements during the spatial recall of the *Place* associated with an autobiographical memory against the eye movements observed during the non-spatial recall of *Event* details and *Thought/Emotions* associated with the same memory. Eye movements during the spatial recall of Place were found to significantly differ from the recall of non-spatial details such as Event and Thought/Emotion across all the metrics assessed in the study. The spatial recall of Place had significantly higher fixation duration, and smaller saccade amplitude and peak velocity, as well as a significantly higher number of consecutive unidirectional saccades. Place details were also associated with significantly greater pupil area in comparison to non-spatial Event and Thought/Emotion details. Regarding the RQA indices of the spatial descriptions of the scenes, we generally found a higher complexity of the eye movement structure (entropy). This is also indicated by more patterns of fixations on specific spatial regions that were repeated in the same order (determinism) and longer sequences of refixations in the same spatial region (laminarity) that occurred close in time (CORM). Overall, the findings are consistent with the spontaneous production of more ordered and structured scan path patterns (Brandt and Stark, 1997; Johansson et al., 2010; Laeng and Teodorescu, 2002) and greater cognitive load (El Haj, Janssen, Gallouj and Lenoble, 2019; El Haj et al., 2022; Janssen et al., 2021) during the spatial recall of place details when compared to non-spatial event and thought/emotion details associated with the same autobiographical memory. The presence of higher fixation durations, smaller saccade amplitude and peak velocity, higher consecutive unidimensional saccades, and distinctive patterns of recurrent fixations is consistent with eye movements mirroring the mental construction and exploration of visuo-spatial mental images (Bourlon et al., 2011; Mast and Kosslyn, 2002).

These results are supportive of a functional role for the oculomotor system specifically during *mental scene construction* in autobiographical recall. Scene construction involves the generation and maintenance of mental images depicting a coherent and complex spatial layout (Hassabis and Maguire, 2007, 2009; Ladyka-Wojcik et al., 2022; Rubin, 2020). In the current study we show that when participants are describing spatial details of a physical environment where a recalled event took place (for example, the layout and the objects present), their spontaneous eye movements significantly differ from when describing non-spatial details such as the event itself or their recalled thoughts and emotions associated with the event. The increase in consecutive unidirectional saccades when participants recall place details is similar to findings reported when participants can freely scan complex external scenes (Hooge et al., 2005; Tatler and Vincent, 2008), and is consistent with systematic shifts of attention across a structured internal mental scene (Brandt and Stark, 1997; Johansson et al., 2010; Laeng and Teodorescu, 2002). This supports the hypothesis that eye movements are associated with the activation of relevant stored memory representations and the correct positioning of elements of a scene relative to other parts during mental imagery of complex scenes (Kosslyn, 1994; Mast and Kosslyn, 2002; Rubin and Umanath, 2015).

The increase in pupil size during recall of place details is also consistent with participants experiencing higher cognitive load during scene construction (El Haj et al., 2022; Goldinger and Papesh, 2012; Kahneman and Beatty, 1966) in comparison to recall of non-spatial episodic details. Previous studies have already reported that pupil size increases during autobiographical memory and have interpreted this in terms of mental imagery supporting the phenomenological experience of recall (e.g. Janssen et al., 2021; El Haj et al., 2019). Studies that have examined mental imagery independently of autobiographical recall have also shown that pupil size increases when more complex mental images are generated (e.g. Laeng and Sulutvedt, 2014; Sulutvedt et al., 2018). In our study we found that pupil size is significantly greater when participants recall autobiographical spatial details about the place associated with the memory, in comparison to either autobiographical event or thought/emotion details. We interpret this as the recall of place requiring higher cognitive effort due to the greater involvement of maintaining and inspecting complex mental images during scene construction.

Considering the temporal dynamics of fixations, this is to our knowledge the first study to use RQA analysis to describe eye movements during spontaneous AM descriptions. Overall, we observed that the pattern of recurrent fixations (i.e., laminarity, determinism, CORM and entropy) is consistent with the use of fixations and refixations as a mechanism for exploring and refreshing mental images. Indeed, high values of the determinism, laminarity and entropy parameters observed during the description of spatial details indicate longer sequences of refixations, more repetitions of the same fixation pattern and, in general, a more structured pattern of eye movements. On the other hand, lower values of the CORM parameter indicate that refixations occurred soon after the first fixation in order to help consolidate the image. Gurtner and colleagues (Gurtner et al., 2019; Gurtner et al., 2021) showed that when we imagine a previously observed scene, we have to repeatedly reactivate the mental image because it fades quickly. This reactivation leads to structured, repeated fixations and refixations on different parts of the imagined scene, which helps to maintain the mental image. Our study is very different, and we cannot directly compare visual images of spatial descriptions with real locations, but we have found that only during spatial autobiographical descriptions are RQA parameter values compatible with a highly structured and ordered pattern of eye movements.

Recall of place detail significantly differed from recall of event detail across the majority of eye movement metrics, while event recall was only associated with significantly larger pupil area in comparison to the recall of thoughts and emotions. Event details also had lower values on the CORM parameter in comparison to thoughts and emotions, but did not significantly differ on measures of determinism, laminarity, or entropy. This suggests the recall of autobiographical non-spatial event details involves greater cognitive load, but not the same degree of structured internal attention shifts as when recalling specific visuo-spatial details of a physical environment where an event took place. If recall of autobiographical event detail sometimes involves the generation and inspection of complex mental images (Brewer, 1996; Conway and Pleydell-Pearce, 2000) it could be expected there may still be some involvement of mental scene construction, although not to the same extent as when recalling specific details of a physical environment where an event took place. Our findings are consistent with Kosslyn's argument that the oculomotor system can facilitate the correct positioning of elements relative to other parts during mental construction of imaged scenes (Kosslyn, 1994; Mast and Kosslyn, 2002). Importantly, we are not claiming from our findings that eye movements are essential for the recall of spatial autobiographical details. Our study was not designed to distinguish overt shifts of attention associated with eye movements from purely covert internal attention shifts. However, previous studies have found restricting eye movements can significantly impair both autobiographical recall (Lenoble et al., 2019) and mental imagery (Ladyka-Wojcik et al., 2022; Laeng et al., 2014). It will be valuable in future research to explore whether similar restrictions on eye movements impair recall of episodic spatial details to a greater extent than non-spatial details. Johansson et al. examined spontaneous eye movements during encoding and recall of real-life scenes or object arrangements and found that the replay of scanpaths made during initial encoding was predictive of accurate reconstruction of spatial relationships between elements during recall (Johansson et al., 2022). Our findings cannot be directly related to the assumptions of scanpath theory. Obviously, in naturalistic autobiographical recall the specific eye movements made during initial encoding are not known. Furthermore, as autobiographical recall is a reconstructive process based on experiencing an event across multiple instances of encoding in different egocentric positions, it is highly unlikely observed eye movements are replaying scanpaths related to a single encoding event, as has been proposed for laboratory based studies of visual pattern recognition (e.g. Norton and Stark, 1971). Instead, we propose that the differential eye movements we observe during autobiographical recall are consistent with the oculomotor system attempting to activate and integrate stored memory representations (e.g., El Haj and Lenoble, 2018; Ladyka-Wojcik et al., 2022). El Haj suggests that saccades and fixations during autobiographical recall mirror internal shifts of attention made during construction of visual imagery associated with a retrieved autobiographical event (El Haj, 2024).

A strength of our study is the greater granularity afforded by comparing eye movements during recall of spatial and non-spatial episodic details associated with the same cued autobiographical event, rather than comparing recall of episodic and non-episodic features (Armson et al., 2021; Davis et al., 2021) or eye movements across different categories of autobiographical event (El Haj et al., 2017; Gautier and El Haj, 2023). To our knowledge, ours is the first study to examine eye movements produced specifically when participants are recalling the spatial layout of scenes associated with naturalistically encoded autobiographical events. Overall, our findings support a specific contribution of spontaneous eye movements to mental scene construction during autobiographical recall. The results are consistent with the theory of event memory proposed by Rubin (Rubin, 2020; Rubin et al., 2019; Rubin and Umanath, 2015) that states the spatial layout of an autobiographical event implicates visual imagery during scene construction rather than related non-spatial episodic content. Scene construction can therefore be viewed as a mental simulation of perceiving the environment associated with an autobiographical event, during which the oculomotor system plays a faciliatory role during the activation and correct positioning of elements of a complex scene relative to other imagined elements during recall.

Previous research has reported that the phenomenological characteristics of autobiographical recall such as vantage perspective can be affected by the age of the memory (Butler et al., 2016; Rice and Rubin, 2009), but in the present study we found no significant differences in eye movements or pupil size during the recall of recent and distant events. It may be our procedural definition of a distant autobiographical event for participants (an event experienced two to three years prior to testing) was insufficiently long to demonstrate any variability related to memory age (Anderson et al., 2000). El Haj et al. (2021) found significant differences in eye movement only when early childhood memories were compared to recall of events experienced in the last month, but not between recall of events experienced during late childhood/adolescence and the last month. Recall of remote childhood events was associated with fewer fixations and longer fixation duration, but no differences in number of saccades, saccade duration, or saccade amplitude.

If eye movements during scene construction are related to the generation of visuo-spatial mental imagery, it will be valuable in future research to examine the contribution of individual differences in imagery ability and experience. The case of *aphantasia*, in which individuals report an absence of consciously experienced imagery, may be particularly pertinent to investigate (Keogh and Pearson, 2017; Zeman et al., 2015). Aphantasics have been shown to recall significantly fewer internal episodic details using the Autobiographical Interview procedure (Milton et al., 2021), while an EEG study conducted by Furman et al. (2022) found reduced visual occipital activation when a congenital aphantasic performed mental imagery tasks in comparison to controls. Acquired aphantasia can also occur in cases of brain injury. Thorudottir et al. (2020) report a case study of an architect who experienced loss of mental imagery following a bilateral posterior cerebral artery stroke and associated this loss with lesions to the left fusiform gyrus. Patients with traumatic brain injury (including diffuse and frontal lobe lesions) have been shown to recall and imagine significantly fewer episodic event-specific details for past and future events compared to healthy controls (Rasmussen and Berntsen, 2014). It will be valuable to explore whether such TBI patients also display abnormal eye movement patterns when performing tasks that typically rely on mental scene construction. Mental scene construction has also been linked to over-general autobiographical memory (Rubin et al., 2019), in which individuals are impaired in recalling temporally-specific autobiographical events (Williams et al., 2007). Examining eye movements and pupil size during autobiographical recall in cases of over-general memory may help illuminate specific areas of functional impairment (Bulteau et al., 2023).

In conclusion, our study is the first to examine eye movements spontaneously produced during the recall of the spatial details of environments associated with naturalistically encoded autobiographical events. We have demonstrated that the recall of internal spatial episodic detail is associated with more ordered and structured spontaneous eye movement patterns and higher cognitive load than the recall of non-spatial event or thought/emotion details associated with the same autobiographical memory. These results are consistent with theories that have attributed a functional role for the oculomotor system during mental scene construction in autobiographical recall. Specifically, the oculomotor system facilitates the activation, correct positioning and maintenance (with refixations) of elements of a complex scene relative to other imagined elements during autobiographical recall.

CRediT authorship contribution statement

P. Bernardis: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Grassi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D.G. Pearson:** Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

All data files are available at https://osf.io/je59c/?view_only=cc07ed9577f24b9c840ce087da1bc736.

References

Anderson, N.C., Bischof, W.F., Laidlaw, K.E., Risko, E.F., Kingstone, A., 2013. Recurrence quantification analysis of eye movements. Behav. Res. Methods 45, 842–856. https://doi.org/10.3758/s13428-012-0299-5.

Anderson, S.J., Cohen, G., Taylor, S., 2000. Rewriting the past: some factors affecting the variability of personal memories. Appl. Cogn. Psychol.: The Official Journal of the Society for Applied Research in Memory and Cognition 14 (5), 435–454. https://doi.org/10.1002/1099-0720(200009)14:5%3C435::AID-ACP662%3E3.0.CO;2-B.

Armson, M.J., Diamond, N.B., Levesque, L., Ryan, J.D., Levine, B., 2021. Vividness of recollection is supported by eye movements in individuals with high, but not low trait autobiographical memory. Cognition 206, 104487. https://doi.org/10.1016/j.cognition.2020.104487.

Andrade, J., Kavanagh, D., Baddeley, A., 1997. Eye-movements and visual imagery: a working memory approach to the treatment of post-traumatic stress disorder. Br. J. Clin. Psychol. 36 (2), 209–223. https://doi.org/10.1111/j.2044-8260.1997.tb01408.x.

Armson, M.J., Ryan, J.D., Levine, B., 2019. Maintaining fixation does not increase demands on working memory relative to free viewing. PeerJ 7, e6839. https://doi.org/10.7717/peerj.6839.

Ball, K., Pearson, D.G., Smith, D.T., 2013. Oculomotor involvement in spatial working memory is task-specific. Cognition 129 (2), 439–446. https://doi.org/10.1016/j.cognition.2013.08.006.

Barrowcliff, A.L., Gray, N.S., Freeman, T.C., MacCulloch, M.J., 2004. Eye-movements reduce the vividness, emotional valence and electrodermal arousal associated with negative autobiographical memories. J. Forensic Psychiatr. Psychol. 15 (2), 325–345. https://doi.org/10.1080/14789940410001673042.

Bicanski, A., Burgess, N., 2019. A computational model of visual recognition memory via grid cells. Curr. Biol. 29 (6), 979–990. https://doi.org/10.1016/j.cub.2019.01.077.

Bochynska, A., Laeng, B., 2015. Tracking down the path of memory: eye scanpaths facilitate retrieval of visuospatial information. Cogn. Process. 16, 159–163. https://doi.org/10.1007/s10339-015-0690-0.

Bone, M.B., St-Laurent, M., Dang, C., McQuiggan, D.A., Ryan, J.D., Buchsbaum, B.R., 2019. Eye movement reinstatement and neural reactivation during mental imagery. Cerebr. Cortex 29 (3), 1075–1089. https://doi.org/10.1093/cercor/bhy014.

Bourlon, C., Oliviero, B., Wattiez, N., Pouget, P., Bartolomeo, P., 2011. Visual mental imagery: what the head's eye tells the mind's eye. Brain Res. 1367, 287–297. https://doi.org/10.1016/j.brainres.2010.10.039.

Brandt, S.A., Stark, L.W., 1997. Spontaneous eye movements during visual imagery reflect the content of the visual scene. J. Cognit. Neurosci. 9 (1), 27–38. https://doi.org/10.1162/jocn.1997.9.1.27.

Brewer, W.F., 1996. What is recollective memory. In: Rubin, David C. (Ed.), Remembering Our Past: Studies in Autobiographical Memory. Cambridge University Press, UK, pp. 19–66.

Bulteau, S., Malo, R., Holland, Z., Laurin, A., Sauvaget, A., 2023. The update of self-identity: importance of assessing autobiographical memory in major depressive disorder. Wiley Interdisciplinary Reviews: Cogn. Sci., e1644 https://doi.org/10.1002/wcs.1644.

Butler, A.C., Rice, H.J., Wooldridge, C.L., Rubin, D.C., 2016. Visual imagery in autobiographical memory: the role of repeated retrieval in shifting perspective. Conscious. Cognit. 42, 237–253. https://doi.org/10.1016/j.concog.2016.03.018.

Conway, M.A., 2009. Episodic memories. Neuropsychologia 47 (11), 2305–2313. https://doi.org/10.1016/j.neuropsychologia.2009.02.003.

Conway, M.A., Pleydell-Pearce, C.W., 2000. The construction of autobiographical memories in the self-memory system. Psychol. Rev. 107 (2), 261. https://doi.org/10.1037/0033-295X.107.2.261.

Davis, E.E., Chemnitz, E., Collins, T.K., Geerligs, L., Campbell, K.L., 2021. Looking the same, but remembering differently: preserved eye-movement synchrony with age during movie watching. Psychol. Aging 36 (5), 604–615. https://doi.org/10.1037/pag0000615.

El Haj, M., 2024. When you look at your past: eye movement during autobiographical retrieval. Conscious. Cognit. 118, 103652. https://doi.org/10.1016/j.concog.2024.103652.

El Haj, M., Delerue, C., Omigie, D., Antoine, P., Nandrino, J.L., Boucart, M., 2014. Autobiographical recall triggers visual exploration. Journal of Eye Movement Research 7 (5). https://doi.org/10.16910/jemr.7.5.1.

El Haj, M., Lenoble, Q., 2018. Eying the future: eye movement in past and future thinking. Cortex 105, 97–103. https://doi.org/10.1016/j.cortex.2017.05.024.

El Haj, M., Mj Janssen, S., Gallouj, K., Lenoble, Q., 2019. Autobiographical memory increases pupil dilation. Transl. Neurosci. 10 (1), 280–287. https://doi.org/10.1515/tnsci-2019-0044.

El Haj, M., Nandrino, J.L., Antoine, P., Boucart, M., Lenoble, Q., 2017. Eye movement during retrieval of emotional autobiographical memories. Acta Psychol. 174, 54–58. https://doi.org/10.1016/j.actpsy.2017.02.002.

El Haj, M., Boutoleau-Bretonnière, C., Janssen, S.M.J., 2021. Eye movements of recent and remote autobiographical memories: fewer and longer lasting fixations during the retrieval of childhood memories. Psychol. Res. 85 (6), 2466–2473. https://doi.org/10.1007/s00426-020-01403-3.

El Haj, M., Janssen, S.M., Lenoble, Q., Robin, F., Gallouj, K., 2022. The eyes of the past: larger pupil size for autobiographical memories retrieved from field perspective. Neurol. Sci. 43, 661–666. https://doi.org/10.1007/s10072-021-05297-w.

Faul, F., Erdfelder, E., Buchner, A., et al., 2009. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav. Res. Methods 41, 1149–1160. https://doi.org/10.3758/BRM.41.4.1149.

Furman, M., Fleitas-Rumak, P., Lopez-Segura, P., Furman, M., Tafet, G., de Erausquin, G. A., Ortiz, T., 2022. Cortical activity involved in perception and imagery of visual stimuli in a subject with aphantasia. An EEG case report. Neurocase 28 (4), 344–355. https://doi.org/10.1080/13554794.2022.2122848.

Gamer, M., Lemon, J., Singh, I.F.P., 2019. irr: various coefficients of interrater reliability and agreement. R package. https://CRAN.R-project.org/package=irr.

Gautier, J., El Haj, M., 2023. Eyes don't lie: eye movements differ during covert and overt autobiographical recall. Cognition 235, 105416. https://doi.org/10.1016/j.cognition.2023.105416.

Gilboa, A., Moscovitch, M., 2021. No consolidation without representation: correspondence between neural and psychological representations in recent and remote memory. Neuron 109 (14), 2239–2255. https://doi.org/10.1016/j.neuron.2021.04.025.

Goldinger, S.D., Papesh, M.H., 2012. Pupil dilation reflects the creation and retrieval of memories. Curr. Dir. Psychol. Sci. 21 (2), 90–95. https://doi.org/10.1177/0963721412436811.

Gurtner, L.M., Bischof, W.F., Mast, F.W., 2019. Recurrence quantification analysis of eye movements during mental imagery. J. Vis. 19 (1), 17. https://doi.org/10.1167/19.1.17, 17.

Gurtner, L.M., Hartmann, M., Mast, F.W., 2021. Eye movements during visual imagery and perception show spatial correspondence but have unique temporal signatures. Cognition 210, 104597. https://doi.org/10.1016/j.cognition.2021.104597.

Hassabis, D., Maguire, E.A., 2007. Deconstructing episodic memory with construction. Trends Cognit. Sci. 11 (7), 299–306. https://doi.org/10.1016/j.tics.2007.05.001.

Hassabis, D., Maguire, E.A., 2009. The construction system of the brain. Phil. Trans. Biol. Sci. 364 (1521), 1263–1271. https://doi.org/10.1098/rstb.2008.0296.

Hayes, T.R., Petrov, A.A., 2016. Mapping and correcting the influence of gaze position on pupil size measurements. Behav. Res. Methods 48, 510–527. https://doi.org/10.3758/s13428-015-0588-x.

Hebb, D.O., 1968. Concerning imagery. Psychol. Rev. 75 (6), 466.

Hooge, I.T.C., Over, E.A., van Wezel, R.J., Frens, M.A., 2005. Inhibition of return is not a foraging facilitator in saccadic search and free viewing. Vis. Res. 45 (14), 1901–1908. https://doi.org/10.1016/j.visres.2005.01.030.

Janssen, S.M., Foo, A., Johnson, S.N., Lim, A., Satel, J., 2021. Looking at remembering: eye movements, pupil size, and autobiographical memory. Conscious. Cognit. 89, 103089. https://doi.org/10.1016/j.concog.2021.103089.

Jarosz, A.F., Wiley, J., 2014. What are the odds? A practical guide to computing and reporting Bayes factors. The Journal of Problem Solving 7 (1), 2. https://doi.org/10.7771/1932-6246.1167.

Johansson, R., Holsanova, J., Holmqvist, K., 2010. Eye movements during mental imagery are not reenactments of perception. Proceedings of the Annual Meeting of the Cognitive Science Society 32 (32).

Johansson, R., Nyström, M., Dewhurst, R., Johansson, M., 2022. Eye-movement replay supports episodic remembering. Proceedings. Biological sciences 289 (1976), 20220964. https://doi.org/10.1098/rspb.2022.0964.

Kahneman, D., Beatty, J., 1966. Pupil diameter and load on memory. Science 154 (3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583.

Keogh, R., Pearson, J., 2017. The perceptual and phenomenal capacity of mental imagery. Cognition 162, 124–132. https://doi.org/10.1016/j.cognition.2017.02.004.

Kosslyn, S.M., 1994. Image and Brain: the Resolution of the Imagery Debate. The MIT Press.

Ladyka-Wojcik, N., Liu, Z.X., Ryan, J.D., 2022. Unrestricted eye movements strengthen effective connectivity from hippocampal to oculomotor regions during scene construction. Neuroimage 260, 119497. https://doi.org/10.1016/j.neuroimage.2022.119497.

Laeng, B., Bloem, I.M., D'Ascenzo, S., Tommasi, L., 2014. Scrutinizing visual images: the role of gaze in mental imagery and memory. Cognition 131 (2), 263–283. https://doi.org/10.1016/j.cognition.2014.01.003.

Laeng, B., Sulutvedt, U., 2014. The eye pupil adjusts to imaginary light. Psychol. Sci. 25 (1), 188–197. https://doi.org/10.1177/0956797613503556.

Laeng, B., Teodorescu, D.S., 2002. Eye scanpaths during visual imagery reenact those of perception of the same visual scene. Cogn. Sci. 26 (2), 207–231. https://doi.org/10.1016/S0364-0213(01)00065-9.

Landis, J.R., Koch, G.G., 1977. The measurement of observer agreement for categorical data. Biometrics 33 (1), 159–174.

Lenoble, Q., Janssen, S.M., El Haj, M., 2019. Don't stare, unless you don't want to remember: maintaining fixation compromises autobiographical memory retrieval. Memory 27 (2), 231–238. https://doi.org/10.1080/09658211.2018.1501068.

Levine, B., Svoboda, E., Hay, J.F., Winocur, G., Moscovitch, M., 2002. Aging and autobiographical memory: dissociating episodic from semantic retrieval. Psychol. Aging 17 (4), 677. https://doi.org/10.1037/0882-7974.17.4.677.

Maguire, E.A., Mullally, S.L., 2013. The hippocampus: a manifesto for change. J. Exp. Psychol. Gen. 142 (4), 1180. https://doi.org/10.1037/a0033650.

Mast, F.W., Kosslyn, S.M., 2002. Eye movements during visual mental imagery. Trends Cognit. Sci. 6 (7), 271–272. https://doi.org/10.1016/s1364-6613(02)01931-9.

McAteer, S.M., McGregor, A., Smith, D.T., 2023. Oculomotor rehearsal in visuospatial working memory. Atten. Percept. Psychophys. 85 (1), 261–275. https://doi.org/10.3758/s13414-022-02601-4.

Mertens, G., Krypotos, A.M., van Logtestijn, A., Landkroon, E., van Veen, S.C., Engelhard, I.M., 2019. Changing negative autobiographical memories in the lab: a comparison of three eye-movement tasks. Memory 27 (3), 295–305. https://doi.org/10.1080/09658211.2018.1507041.

Miller, T.D., Chong, T.T., Aimola Davies, A.M., Johnson, M.R., Irani, S.R., Husain, M., et al., 2020. Human hippocampal CA3 damage disrupts both recent and remote episodic memories. Elife 9, e41836. https://doi.org/10.7554/eLife.41836.

Milton, F., Fulford, J., Dance, C., Gaddum, J., Heuerman-Williamson, B., Jones, K., et al., 2021. Behavioral and neural signatures of visual imagery vividness extremes: aphantasia versus hyperphantasia. Cerebral cortex communications 2 (2), tgab035. https://doi.org/10.1093/texcom/tgab035.

Morey, R.D., Rouder, J.N., 2018. BayesFactor: computation of bayes factors for common designs. R package version 0.9.12–4.2. https://CRAN.R-project.org/package=BayesFactor.

Mullally, S.L., Intraub, H., Maguire, E.A., 2012. Attenuated boundary extension produces a paradoxical memory advantage in amnesic patients. Curr. Biol. 22 (4), 261–268. https://doi.org/10.1016/j.cub.2012.01.001.

Norton, D., Stark, L., 1971. Scanpaths in eye movements during pattern perception. Science 171 (3968), 308–311. https://doi.org/10.1126/science.171.3968.308.

Palombo, D.J., Hayes, S.M., Peterson, K.M., Keane, M.M., Verfaellie, M., 2018. Medial temporal lobe contributions to episodic future thinking: scene construction or future projection? Cerebr. Cortex 28 (2), 447–458. https://doi.org/10.1093/cercor/bhw381.

Pearson, D., Sahraie, A., 2003. Oculomotor control and the maintenance of spatially and temporally distributed events in visuo-spatial working memory. The Quarterly Journal of Experimental Psychology Section A 56 (7), 1089–1111. https://doi.org/10.1080/02724980343000044.

Pearson, D.G., Ball, K., Smith, D.T., 2014. Oculomotor preparation as a rehearsal mechanism in spatial working memory. Cognition 132 (3), 416–428. https://doi.org/10.1016/j.cognition.2014.05.006.

Race, E., Keane, M.M., Verfaellie, M., 2011. Medial temporal lobe damage causes deficits in episodic memory and episodic future thinking not attributable to deficits in narrative construction. J. Neurosci. 31 (28), 10262–10269. https://doi.org/10.1523/JNEUROSCI.1145-11.2011.

Rasmussen, K.W., Berntsen, D., 2014. Autobiographical memory and episodic future thinking after moderate to severe traumatic brain injury. J. Neuropsychol. 8 (1), 34–52. https://doi.org/10.1111/jnp.12003.

Rice, H.J., Rubin, D.C., 2009. I can see it both ways: first-and third-person visual perspectives at retrieval. Conscious. Cognit. 18 (4), 877–890. https://doi.org/10.1016/j.concog.2009.07.004.

Rubin, D.C., 2020. The ability to recall scenes is a stable individual difference: evidence from autobiographical remembering. Cognition 197, 104164. https://doi.org/10.1016/j.cognition.2019.104164.

Rubin, D.C., Umanath, S., 2015. Event memory: a theory of memory for laboratory, autobiographical, and fictional events. Psychol. Rev. 122 (1), 1–23. https://doi.org/10.1037/a0037907.

Rubin, D.C., Deffler, S.A., Umanath, S., 2019. Scenes enable a sense of reliving: implications for autobiographical memory. Cognition 183, 44–56. https://doi.org/10.1016/j.cognition.2018.10.024.

Schacter, D.L., Addis, D.R., Hassabis, D., Martin, V.C., Spreng, R.N., Szpunar, K.K., 2012. The future of memory: remembering, imagining, and the brain. Neuron 76 (4), 677–694. https://doi.org/10.1016/j.neuron.2012.11.001.

Selker, R., Love, J., Dropmann, D., 2020. Jmv: the "jamovi" analyses. https://CRAN.R-project.org/package=jmv.

Shannon, C.E., 1948. A mathematical theory of communication. The Bell system technical journal 27 (3), 379–423.

Sheldon, S., Cool, K., El-Asmar, N., 2019. The processes involved in mentally constructing event-and scene-based autobiographical representations. J. Cognit. Psychol. 31 (3), 261–275. https://doi.org/10.1080/20445911.2019.1614004.

Sulutvedt, U., Mannix, T.K., Laeng, B., 2018. Gaze and the eye pupil adjust to imagined size and distance. Cogn. Sci. 42 (8), 3159–3176. https://doi.org/10.1111/cogs.12684.

Summerfield, J.J., Hassabis, D., Maguire, E.A., 2010. Differential engagement of brain regions within a 'core'network during scene construction. Neuropsychologia 48 (5), 1501–1509. https://doi.org/10.1016/j.neuropsychologia.2010.01.022.

Tatler, B.W., Vincent, B.T., 2008. Systematic tendencies in scene viewing. Journal of Eye Movement Research 2 (2). https://doi.org/10.16910/jemr.2.2.5.

Thorudottir, S., Sigurdardottir, H.M., Rice, G.E., Kerry, S.J., Robotham, R.J., Leff, A.P., Starrfelt, R., 2020. The architect who lost the ability to imagine: the cerebral basis of visual imagery. Brain Sci. 10 (2), 59. https://doi.org/10.3390/brainsci10020059.
van den Hout, M., Muris, P., Salemink, E., Kindt, M., 2001. Autobiographical memories become less vivid and emotional after eye movements. Br. J. Clin. Psychol. 40 (2), 121–130. https://doi.org/10.1348/014466501163571.
Williams, J.M.G., Barnhofer, T., Crane, C., Herman, D., Raes, F., Watkins, E., Dalgleish, T., 2007. Autobiographical memory specificity and emotional disorder. Psychol. Bull. 133 (1), 122. https://doi.org/10.1037/0033-2909.133.1.122.
Wynn, J.S., Shen, K., Ryan, J.D., 2019. Eye movements actively reinstate spatiotemporal mnemonic content. Vision 3 (2), 21. https://doi.org/10.3390/vision3020021.
Zeman, A., Dewar, M., Della Sala, S., 2015. Lives without imagery–Congenital aphantasia. Cortex 73, 378–380. https://doi.org/10.1016/j.cortex.2015.05.019.