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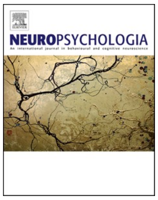

Modulation of midfrontal theta and posterior alpha during the construction and elaboration of autobiographical memories in individuals with highly superior autobiographical memory

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ABSTRACT

Individuals with highly superior autobiographical memory (HSAM) represent a rare population with the exceptional ability to recall autobiographical information with remarkable precision and detail. While research has begun to explore the neural mechanisms underlying this extraordinary memory performance, the role of brain oscillations has not yet been investigated in HSAM individuals. Here, we studied three individuals with HSAM and compared their results with 16 controls. We asked all participants to retrieve newer and older autobiographical memories (AMs) while their electroencephalogram (EEG) was being recorded. Participants were asked to press a button to indicate access and construction of their AM and to continue elaborating it. We focused on midfrontal theta oscillations during the construction phase of AM retrieval and posterior alpha oscillations during the elaboration phase. Compared to the controls, the HSAM participants exhibited greater theta during the retrieval of older as compared to newer AMs, and no increase of the initial posterior alpha during the elaboration phase power. These findings may reflect more efficient neural processes in HSAM individuals. Specifically, the selective midfrontal theta enhancement during retrieval of remote memories suggests a flexible engagement of control and inhibitory mechanisms, supporting complex memory construction. The lack of initial posterior alpha increase could indicate reduced cortical suppression and, speculatively, more vivid visual imagery during elaboration. These findings shed light on the unique neural dynamics underlying HSAM individuals and offer new insights into how their autobiographical memory is supported by highly efficient neuro-cognitive processes.

1. Introduction

Autobiographical memory (AM), which refers to the recall of personal past experiences, is fundamental to the formation of self-identity and the guidance of future behavior (Conway and Pleydell-Pearce, 2000; Schacter et al., 2012). This form of memory is complex, involving the retrieval of temporally and contextually rich episodes that are deeply embedded in an individual's life narrative (Fivush, 2011;

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Nyberg et al., 2010). The neural mechanisms supporting AM retrieval have been a major focus of cognitive neuroscience research (Cabeza and St Jacques, 2007; Daviddi et al., 2023, 2024).

Neuroimaging studies investigating the temporal dynamics of autobiographical recollection typically make a distinction between two phases: “construction” (sometimes referred to as “access”; e.g., Daselaar et al., 2008) and “elaboration”. The construction phase involves an initial, strategically guided search for specific memory content, driven by the current retrieval cue, and regulated by executive processes. Once a particular event is identified, the elaboration phase follows, characterized by the re-experiencing (or reliving) of perceptual details linked to the past event (Cabeza and St Jacques, 2007). The construction of AMs involves not only a search process but also monitoring and self-referential processes, all supervised by executive functions, which are thought to be associated with activity in medial prefrontal regions (Cabeza et al., 2004; Gilboa, 2004; Graham et al., 2003). In contrast, the elaboration phase, during which perceptual details associated with the past event are vividly re-experienced, appears to be associated with posterior visual regions (Cabeza and St Jacques, 2007; Gardini et al., 2006; McCormick et al., 2015; Rubin, 2006). An EEG study of Conway et al. (2001) mirrored these regional differences through ERP components associated with these two phases. Specifically, they revealed an initial slow frontal negativity, presumably reflecting cortical activation associated with construction processes, followed by a subsequent occipital negativity that possibly reflects the extraction of more detailed memories during the elaboration phase (see also Conway et al., 2003). However, while ERPs are well-suited for studying the timing and amplitude of brain responses to stimuli, they only reflect the evoked and phase-locked components of the relevant electrophysiological brain activity, implying that they may miss other relevant information. Furthermore, ERPs cannot easily be related to oscillatory rhythms that are present in the raw EEG, which have been related to different physiological functions (e.g., see Buzsáki, 2006, 2019; Klimesch, 2018). Thus, examining oscillatory activity offers a complementary perspective by revealing how the different frequency bands may contribute to AM retrieval.

Theta oscillations (4–8 Hz) registered over midfrontal regions are commonly linked to cognitive control, attention, working memory, and long-term memory functions (Hsieh et al., 2011; Klimesch et al., 2010; Van der Lubbe et al., 2021; White et al., 2012), with particular emphasis on their role in episodic and AM (Herweg et al., 2020; Hsieh and Ranganath, 2014; Klimesch, 1999; Nyhus and Curran, 2010). During episodic memory retrieval, theta oscillatory magnitude (i.e., power) is often found to increase, which has been interpreted as reflecting the engagement of neural networks necessary for the successful retrieval of detailed, context-rich memories (Addante et al., 2011; Gruber et al., 2008; Osipova et al., 2006). This relationship between theta activity and memory performance is thought to arise from the role of theta oscillations in synchronizing neural activity in key brain regions, such as the hippocampus, prefrontal cortex, and posterior parietal cortex, which are essential for integrating the various components of episodic-autobiographical memories (Guderian and Düzel, 2005; Sederberg et al., 2003). In particular, theta oscillations are thought to facilitate the binding of disparate elements of a memory trace, such as the spatial, temporal, and emotional aspects of an autobiographical event, into a coherent whole. This binding process is thought to be crucial for accurate construction or past experience and is considered one of the hallmarks of successful episodic-autobiographical memory retrieval (Hanslmayr and Staudigl, 2014; Hanslmayr et al., 2016). Moreover, disruptions in midfrontal theta activity have been associated with impairments in memory processes, highlighting its potential role in memory-related disorders such as Alzheimer's disease and depression (Mitchell et al., 2008; Olbrich and Arns, 2013). On the basis of this evidence, midfrontal theta oscillations could be particularly relevant during the strategic search and monitoring processes occurring during the construction phase of AMs (Hsieh and Ranganath, 2014).

After the construction phase, the memory elements - perceptual and other details - are elaborated, a process involving visual imagery and self-referential processing (Addis et al., 2007; Bauer et al., 2017; Daselaar et al., 2008; Manns et al., 2018; McCormick et al., 2015). Such a phase is associated with activity in the visual cortex and precuneus, potentially reflecting activation of sensory contents (Addis et al., 2007; Cabeza and St Jacques, 2007; Daselaar et al., 2008; Gardini et al., 2006; Holland et al., 2011; McCormick et al., 2015; Rubin, 2006). During visual elaboration, alpha-band modulation (8-12 Hz) appears to play a crucial role (Knyazev et al., 2015; Manns et al., 2018; Xie et al., 2020). On the one hand, increased alpha waves were found to be more prominent over posterior brain regions when the eyes are closed, but also when reduced/inhibited cortical activity is required (Berger, 1929; Pfurtscheller et al., 1996). The latter pattern has been linked to mechanisms of active suppression of irrelevant sensory inputs (Foxe and Snyder, 2011; Klimesch et al., 2007; Ray and Cole, 1985), which are considered crucial during self-directed attention (Cooper et al., 2003, 2006; Knyazev, 2013). On the other hand, during the elaboration of AMs, which has been associated with increased activity in the visual cortex (Cabeza and St Jacques, 2007; Daselaar et al., 2008) a reduction in alpha oscillations in visual regions has been also observed (Manns et al., 2018). This finding is consistent with studies on attentional processes suggesting that retrieval of visual memories is associated with a decrease in alpha power in previously engaged sensory regions, further supporting the idea that visual imagery reduces posterior alpha (Van der Lubbe et al., 2014, 2023). In line with that suggestion, there is substantial evidence indicating an inverse relationship between alpha power and metabolic activity, as shown in PET (Buchsbaum et al., 1984), fMRI (de Munck et al., 2007; Goldman et al., 2002; Laufs et al., 2003), and combined EEG-fMRI studies (e.g., Scheeringa et al., 2016). Therefore, the visual reliving that takes place during the elaboration phase of AMs (Cabeza and St Jacques, 2007) could be further explored by examining changes in alpha power over these posterior regions.

While the oscillatory correlates of episodic-autobiographical memory retrieval have begun to be explored in the normal population, brain oscillations under conditions of enhanced AM performance have never been investigated. While most people remember certain life events with some clarity, a rare subset of the population, known as individuals with highly superior autobiographical memory (HSAM), possess the ability to recall an extraordinary amount of autobiographical information with remarkable precision and accuracy (Parker et al., 2006), while exhibiting average performance on laboratory memory tasks (LePort et al., 2012; Parker et al., 2006; Santangelo et al., 2025) and other cognitive tests (Daviddi et al., 2022a; Patihis et al., 2013). Research has begun to elucidate the neural mechanisms underlying this unique memory performance. Santangelo and colleagues (2018) used functional neuroimaging to compare the neural activity of individuals with HSAM and matched controls during the construction and elaboration phase of older (e.g., “The first time you went to a concert”) and newer (e.g., “The last time you cooked something”) AMs. They found that HSAM individuals displayed increased neural activity in a distributed network of brain regions, including the anterior (medial prefrontal) and posterior (medial and lateral parietal) brain regions, the hippocampus, and sensory cortices. Activity in this network increased selectively during the initial period of memory access/construction. Moreover, the right temporal parietal junction, a brain region involved with bottom-up attention, showed higher functional connectivity with visuospatial sensory regions (Santangelo et al., 2018). Furthermore, within this network, anterior and posterior midline cortical regions were found to be particularly important for supporting HSAM, as subsequently demonstrated by both task-related (Mazzoni et al., 2019; Santangelo et al., 2020, 2021) and resting-state (Daviddi et al., 2022b; Orwig et al., 2024) studies.

Here, we aim to extend these findings, by investigating midfrontal theta and posterior alpha oscillations during the construction and elaboration phases in three rare individuals with HSAM. Altered patterns of brain oscillations in the theta and alpha bands may potentially contribute to their extraordinary memory abilities when recalling AMs. To explore this issue, we asked three HSAM participants and 16 controls to retrieve older and newer AMs while recording their EEG, focusing on theta oscillations over frontal midline regions (indexing for the construction phase; see, e.g., Hsieh and Ranganath, 2014; Klimesch, 1999; Nyhus and Curran, 2010), and alpha power over visuospatial occipito-parietal regions (indexing for the elaboration phase see, e.g., Manns et al., 2018; Knyazev et al., 2015; Xie et al., 2020). Obviously, investigating theta and alpha dynamics in HSAM could provide critical insights into whether superior memory is promoted by specific patterns of neural synchronization, and could make valuable contributions to our broader understanding of memory processes.

2. Materials and methods

2.1. Participants

The study focused on three rare individuals with HSAM (three males, aged 30, 33, and 45 years), and 16 control participants (sex: 6 males; 10 females; mean age: 29.5 years, range: 19-47 years). The screening process for HSAM followed established protocols outlined in previous literature (LePort et al., 2012, 2016). Specifically, these individuals underwent two tests: The Public Events Quiz and the Random Dates Quiz, which were adapted to the Italian language, as described in detail by Santangelo and colleagues (2018).

The Public Events Quiz comprised thirty questions divided into five categories: sporting events, political events, significant negative events, events related to famous individuals, and holidays. For fifteen of these questions, participants were asked to recall the exact date of a well-known public event, either national or international (e.g., “Please provide the day of the week and the exact date, including day, month, and year, when Federica Pellegrini, the renowned Italian swimmer, won the gold medal at the Beijing Olympics”). The remaining fifteen questions required participants to identify a significant public event that occurred on a given date (e.g., “What happened on June 25, 2009?”). All events mentioned took place when the participants were at least eight years old. The order of the questions was randomized and counterbalanced. For each question, the individual needed to identify the correct day of the week on which the date fell. One point was awarded for each correct response (including the event, day of the week, month, date, and year), with a maximum possible score of 88 points.

The Random Dates Quiz involved ten computer-generated random dates, ranging from the individuals age of fifteen to the day before the test. For each date, participants were required to provide three pieces of information: (1) the day of the week, (2) the description of a verifiable event that occurred within one month before or after the given date (this could be confirmed via a search engine), and (3) the description of a personal autobiographical event. One point was awarded for correctly identifying the day of the week, one point for correct recalling a public event, and one point for recounting an unverified personal AM, with a maximum score of 30 points. The three HSAM individuals scored 67.3 ± 9.9% (SE) on the Public Events Quiz, and 71.1 ± 20.6% on the Random Dates Quiz, confirming their exceptional memory capabilities.

None of the control participants reported HSAM or other superior memory abilities (for a similar approach, see LePort et al., 2012, 2016). Although they were not administered the full screening quizzes (i.e., the Public Events Quiz and the Random Dates Quiz), the absence of HSAM in the control participants was confirmed during the post-EEG interview (see the Stimuli and Procedure section), as they reported a significantly lower number of verifiable events compared to the HSAM participants (see the Results section).

2.2. Stimuli and Procedure

During the EEG recordings, participants were presented with auditory cues prompting them to retrieve 18 “older” events (e.g., “The first time you went to a concert” or “The first time you drove a car”) or 18 “newer” events (e.g., “The last time you cooked something” or “The last time you took a train”) within a 30-sec time window (for the full list of memory cues, see Santangelo et al., 2018, supplementary information). Participants confirmed their ability to retrieve the specific AM corresponding to the memory cue by pressing a response button and then continued to relive the memory in as much detail as possible. The button press allowed us to distinguish the initial “construction” phase from the subsequent “elaboration” phase of the AM retrieval. With this approach, the “construction” phase starts with the presentation of the auditory cue, whereas the “elaboration” phase begins after the button press, when the memory has been selected and can be further detailed (cf. Addis et al., 2007; Daselaar et al., 2008; for a review, see Daviddi et al., 2023). Throughout the entire task, participants were instructed to keep their eyes open. Immediately after the EEG recording, participants were again presented with the same order of memory cues and asked to orally recount the memories retrieved during the EEG recording phase. They were also asked to report the date of the event as accurately as possible (cf. St Jacques et al., 2011; Young et al., 2013), possibly reporting a verifiable event occurred within a range of ±30 days. Using this procedure, we have already found that “first time” and “last time” events recalled by participants (both HSAM and controls) effectively corresponded to older and newer events (cf. Santangelo et al., 2020).

2.3. EEG data recording and preprocessing

The EEG signal was continuously recorded (band-pass filter: 0.05–100 Hz; sampling rate: 500 Hz) using a BrainVision actiCHamp System (BrainProducts GmbH, Germany) with a set of 64 Ag/AgCl electrodes placed according to the 10/10 system (Oostenveld and Praamstra, 2001) and referenced to an electrode placed at FCz with a cephalic (forehead) location as the ground. An additional electrode was placed below the right eye to record electrooculographic (EOG) activity to detect eye movement artifacts such as blinking. Electrode impedances were maintained below 5 kΩ. A bandpass filter (0.1-30 Hz) was applied offline using a second order Butterworth zero-phase infinite impulse response (IIR) filter. The EEG signal was checked for large artifacts (maximal gradient: 100 μV/ms, low activity: 0.1 μ V for 100 ms) by means of an automatic artifact rejection method. The horizontal and vertical electrooculogram (hEOG and vEOG) were calculated as the difference obtained with the following subtractions: vEOG = EOG – Fp2; hEOG = AF7 – AF8. Subsequently, Independent Component Analysis (ICA) was performed to remove artifacts related to vertical and horizontal eye movements, such as blinks and saccades. Components representing these ocular artifacts were manually identified and removed. On average 2.7 components (SD = 0.9) out of 61 components were excluded. In the following, the EEG was checked for residual artifacts (maximal gradient: 50 μV/ms, min/max: ±150 μ V), and any trial exceeding these thresholds was rejected. Overall, the mean percentage of rejected segments after the preprocessing steps was 10.7 % ± 1.7 % (SE) for the control group and 2.8 % ± 1.6 % for the HSAM group. Next, activity for all electrodes was re-referenced to the average reference. All these preprocessing steps were performed offline using the Brain Vision Analyzer software (Version 2.3; Brain Products GmbH, Munich, Germany).

2.4. EEG data analysis

After preprocessing the EEG data, portions of the data from an early baseline period were selected to assess global differences between HSAM individuals and controls. Using this analysis, we confirmed that there were no differences between HSAM individuals and controls in the theta (θ; 3.9–7.8 Hz) and alpha (α; 7.8–11.7 Hz) frequency bands during the early baseline period (i.e., 5–35 s after the recording started), before the onset of the experimental manipulation (see Supplementary Material S1).

Subsequently, to assess the experimental effects, we first selected very long time intervals relative to the onsets of the cues, from −1000 to 30000 ms. To enable a proper baseline for these analyses, we applied Wavelet analyses on these long time intervals. A complex Morlet wavelet (c = 5) was chosen with Gabor normalization. Power was extracted from the following seven frequency bands: θ1 (lower-theta, 3.2–4.8 Hz), θ2 (middle-theta, 4.2–6.3 Hz), θ3 (upper-theta, 5.5–8.2 Hz), α1 (lower-alpha, 7.2–10.7 Hz), α2 (upper-alpha, 9.4–14.0 Hz), β1 (lower-beta, 12.2–18.4 Hz), and β2 (upper-beta, 16.0–24.0 Hz). These bands were established using a logarithmic separation method, as previously implemented in earlier studies (see Van der Lubbe and Utzerath, 2013; Van der Lubbe et al., 2014, 2019, 2021). We did not focus on the beta band as we had no specific predictions for this frequency band. A reference interval from −800 to −200 ms was chosen relative to cue onset, and data were normalized by assessing the percentage of change in power relative to this reference interval. Next, the data in which a memory content was reported were separated in four segments. Two segments (i.e., for older and newer AMs) were related to the onset of the auditory cues (from −1000 to 2500 ms, excluding segments containing an early button press; no event was excluded for the HSAM individuals and one event was excluded for the controls); these segments refer to the construction phase. The other two segments were related to the button presses (from −1000 to 10000 ms, excluding the early start of new events; one event was excluded for the HSAM individuals; seven events were excluded for the controls); these segments refer to the elaboration phase. Average time-frequency (TF) results were computed for each individual for each of the four relevant time periods. Moreover, to evaluate the time course of the construction and elaboration phases, the average percentage of change was extracted for ten time bins (bins of 250 and 1000 ms, respectively for the two phases).

For the statistical analyses of the construction phase, we focused on the midfrontal electrode Fz, since this region is most often associated with AM construction (Daviddi et al., 2023, 2024), and midfrontal theta activity appears to be most prominent at these sites (see, e.g., Hsieh and Ranganath, 2014, for a review on midfrontal theta). For the statistical analyses of the elaboration phase, we focused on eight posterior electrodes (O1, O2, Oz, PO3, PO4, PO7, PO8, POz), as elaboration is primarily supported by posterior visual-attentional regions (Cabeza and St Jacques, 2007; Gardini et al., 2006; McCormick et al., 2015; Rubin, 2006). For these electrodes, we analyzed changes in theta and alpha power for the construction and elaboration phases, respectively.

As a sanity check, before conducting the main analyses, we first verified that the construction and elaboration phases were primarily associated with changes in frontal theta and posterior alpha, respectively. To allow a direct comparison between the two phases of different durations (2.5 s for construction; 10 s for elaboration), we focused on the initial 2 s of each phase, i.e., the first 8 bins of the construction phase and the first 2 bins of the elaboration phase. We then conducted a linear mixed-effects model (LMM) to test whether the percentage of change relative to the reference interval was affected by the following within-subject factors (Baayen et al., 2008): (1) Frequency Band (theta, alpha) and (2) Memory Phase (construction, elaboration). Participants were included as random intercepts, with random slopes for Time Bin (8 bins for construction, 2 bins for elaboration), Frequency Sub-bands (θ1, θ2, θ3, α1, α2), and Memory Remoteness (older vs. newer events). The model was specified as: Percentage of Change ~ Frequency Band * Memory Phase + (1 + Bin + Sub-band + Stimulus | Subject). Finally, model diagnostics were performed using the DHARMa package in R (Hartig, 2022). The analysis revealed a small percentage of outliers (78 out of 4560 observations, ~1.7%) and no evidence of over- or under-dispersion (dispersion = 0.965, p = .904), indicating stable variance across conditions. However, residuals showed deviations from normality (Kolmogorov–Smirnov: D = 0.232, p < .001). This latter issue can be effectively addressed by LMMs, which are considered able to provide reliable estimates of fixed effects even under moderate violations of normality (Schielzeth et al., 2020; Knief and Forstmeier, 2021).

After this sanity check, we planned to examine whether theta and alpha activity differed as a function of Group (HSAM, controls). To this end, we performed separate LMMs for the construction and elaboration phases, respectively (Baayen et al., 2008). For both models, we tested whether the percentage of change in midfrontal theta power (construction) and posterior alpha power (elaboration) could be predicted by Group. In addition, we included the following repeated measures factors: (1) the 10 Time Bins of each phase (250 ms per bin for construction, 1000 ms per bin for elaboration), and (2) the Memory Remoteness (older vs. newer events). Only for the elaboration phase, we added also the factor Electrode (the eight posterior-occipital electrodes: O1, O2, Oz, PO3, PO4, PO7, PO8, POz), since the analysis of the construction phase focused only on Fz. Participants were included as random intercepts, with random slopes for frequency sub-bands (θ1, θ2, θ3 for the construction phase; and α1, α2 for the elaboration phase). The models were specified as: 1 – Percentage of Change of Theta power during the construction phase ~ Group * Time Bin * Memory Remoteness + (1 + Sub-band | Subject); 2 – Percentage of Change of Alpha power during the elaboration phase ~ Group * Electrode * Time Bin * Memory Remoteness + (1 + Sub-band | Subject). All possible interactions were included, since our goal was to investigate whether differences as a function of Electrode, Memory Remoteness, and Time Bin varied across groups.

Finally, we tried to further corroborate the role of Fz in the construction phase, as well as the posterior electrode identified by the LMM as being most strongly involved in AM elaboration (i.e., PO8; see the results section). Focusing exclusively on the control group, we conducted two LMMs to examine whether the Percentage of Change at these electrodes varied according to AM performance. This was defined as the percentage of AM reported for the "first time" and "last time" events, as confirmed through the post-scanning interview. We tested whether the Percentage of Change in power varied depending on memory remoteness and AM performance. For these models, all time bins of the theta and alpha signals were included, and the models were specified as: 1 – Percentage of change in theta power at Fz during the construction phase ~ percentage of AM * Memory Remoteness + (1 + Sub-band | Subject); 1 – Percentage of change in alpha power at PO8 during the elaboration phase ~ percentage of AM * Memory Remoteness + (1 + Sub-band | Subject). All LMMs were calculated using the lmer function from the lme4 package (Bates et al., 2015) in R using the RStudio environment, with Satterthwaite's approximation for degrees of freedom provided by the lmerTest package (Kuznetsova et al., 2017). Post-hoc comparisons were performed using the emmeans package (Lenth, 2022), with Tukey correction applied to control for multiple comparisons. All means reported throughout the manuscript for LMMs are estimated marginal means computed using the emmeans package (Lenth, 2022).

3. Results

3.1. Behavioral results

Behavioral analyses were performed to evaluate the overall performance of the HSAM and control participants on the AM task. This assessment included calculating the percentage of trials in which no memory event was retrieved (i.e., trials in which no response button was pressed) and the median reaction time (RT) of the button press. The HSAM participants retrieved memories for all trials with a median RT of 5.10 ± 0.57 (SE) sec: 4.97 ± 0.69 s for older and 5.58 ± 0.53 s for newer memories. The control participants failed to retrieve a memory event in 10.6 ± 1.7% of the trials (12.5 ± 2.7% concerned older and 8.7 ± 1.7% concerned newer memory events), with a median RT of 5.64 ± 0.4 s (5.54 ± 0.43 s for older and 5.95 ± 0.42 s for newer memory events). A Group (HSAM, controls) × Memory Remoteness (older, newer) mixed ANOVA on the percentage of reported memories revealed a significant main effect of Group [$F(1,17) = 6.90$, $p = .018$, generalized eta square (ges) = 0.19], indicating that HSAM participants recalled more events than controls. Neither the main effect of Stimulus [$F(1,17) = 0.30$, $p =$

.59] nor the Group × Memory Remoteness interaction [$F(1,17) = 0.30$, $p = .59$] were significant. Similarly, the same ANOVA on RT revealed no significant effect of Group, Memory Remoteness, or Group × Memory Remoteness interaction (all $Fs < 3.09$, all $ps > 0.097$).

Additionally, we conducted an analysis to assess the influence of Memory Remoteness, and the related accuracy in reporting a verifiable event within ±30 days of the retrieved memory, as confirmed with Google's search engine. We confirmed that the "first time" and "last time" events corresponded to older and newer memories. On average, older memories occurred 24.30 ± 2.17 years ago for the HSAM participants, and 15.58 ± 0.23 years ago for the control participants. In contrast, newer memories were 2.17 ± 0.11 years old for the HSAM participants, and 1.33 ± 0.52 years old for the control participants. The ANOVA confirmed the significant main effect of Memory Remoteness [$F(1,17) = 37.76$, $p < .001$, ges = 0.54]. The main effect of Group was not significant [$F(1,17) = 2.89$, $p = .11$], nor was the Group × Memory Remoteness interaction [$F(1,17) = 1.76$, $p = .20$], confirming the efficacy of our manipulation in eliciting memories of different remoteness in a similar way in both groups.

Regarding the percentage of verifiable events, the HSAM participants were able to provide a verifiable event for 69.4 ± 1.37% of the older, and 88.4 ± 0.51% of the newer memories. In contrast, controls provided verifiable events for 9.42 ± 0.20% of the older, and 39.5 ± 0.51% of the newer memories. The ANOVA confirmed a significant main effect of Group [$F(1,17) = 56.52$, $p < .001$, ges = 0.64], with HSAM participants reporting a higher percentage of verifiable events compared to the control participants. The ANOVA also showed a main effect of Memory Remoteness [$F(1,17) = 13.21$, $p = .002$, ges = 0.27], with more verifiable events provided for the newer than for the older memories. The Group × Memory Remoteness interaction was not significant [$F(1,17) = 0.67$, $p = .43$], indicating that both groups provided more verifiable events for newer than for older memories. Our behavioral results confirm the highly superior memory abilities of the HSAM participants in providing verifiable events as compared to the control participants.

3.2. *The contribution of theta and alpha signal change during the construction and elaboration phase*

Before conducting the main analyses, we first verified that the construction and elaboration phases were primarily associated with changes in frontal theta and posterior alpha, respectively. To do so, we conducted an LMM to test whether the percentage of change relative to the reference interval was affected by Frequency Band (theta, alpha) and Memory Phase (construction, elaboration). The analysis revealed significant main effects of Frequency Band [$F(1, 25.6) = 13.89$, $p = .001$]. Specifically, a larger increase in power was observed for alpha (Mean ± SE: 128.0 ± 61.7%) as compared to theta (103.0 ± 25.8%). The role of these frequency bands was further qualified by the significant interaction between Frequency Band and Memory Phase [$F(1, 4426.5) = 137.52$, $p < .001$]. The interaction revealed that during the construction phase there was a higher change in midfrontal theta power (107.0 ± 31.4%) as compared to posterior alpha power (59.2 ± 19.4%), whereas during the elaboration phase the highest change was in posterior alpha (163.0 ± 73.0%) rather than in midfrontal theta (101.0 ± 22.4%). Overall, these results confirm the crucial role of midfrontal theta during the construction of memory events and of posterior alpha during the subsequent memory elaboration.

3.3. *Theta power during the construction phase*

Our first aim was to determine whether the percentage of change in theta power at Fz differed between HSAM participants and controls during the construction phase of AMs. To this end, we performed a LMM with percentage of change in theta power as the dependent variable and the following predictors: Group (2 levels: HSAM vs. controls), Time Bin (10 levels), and Memory Remoteness (2 levels: older vs. newer events). Participants were included as random intercepts, with random slopes for the theta sub-bands (θ1, θ2, θ3).

The model revealed a significant main effect of Memory Remoteness [$F(1, 1083) = 12.59$, $p < .001$], and Time Bin [$F(9, 1083) = 13.80$, $p < .001$] (see Fig. 1A). Specifically, the percentage of change of frontal theta was larger during the construction of older memories (97.6%) as compared to newer memories (69.1%), especially at the beginning as compared to the end of the construction phase (e.g., Bin 1 and Bin 2: 150.2%, and 187.2% vs Bin 10: 51.0%, both $ps < 0.001$).

Regarding the factor Group, no main effect of Group [$F(1, 19) = 0.93$, $p = .35$], but a significant interaction between Group and Memory Remoteness [$F(1, 1083) = 20.95$, $p < .001$] was observed (see Fig. 1B). This interaction showed that, although HSAM and controls revealed a comparable increase in the percentage of change in theta power on average, the HSAM individuals revealed a larger difference in midfrontal theta according to the Memory Remoteness ($p < .001$) with a larger theta increase for older (129%), as compared to newer memories (63.9%), while the control participants showed no difference in the level of theta power ($p = .581$) for older (66.1%) as compared to newer memories (74.3%). All other higher-order interactions were not significant (all $ps > .347$). Fig. 2A/B displays the topographies of the percentage of change of theta power during the construction of older and newer memories across the 10 time bins in the HSAM compared to the control participants. Fig. 2C shows the time course of the percentage of change of theta power at Fz during the construction phase in the control compared to the HSAM participants for the older and newer memories.

3.4. *Alpha power during the elaboration phase*

Our second aim was to determine whether the percentage of change in alpha power at posterior sites differed between HSAM participants and controls during the elaboration phase of AMs. Again, we performed an LMM with percentage of change in alpha power as the dependent variable and the following predictors: Group (2 levels: HSAM vs. CTRL), Electrode (8 levels: O1, O2, Oz, PO3, PO4, PO7, PO8, POz), Time Bin (10 levels), and Memory Remoteness (2 levels: older vs. newer events). Participants were included as random intercepts, with random slopes for the frequency sub-bands (α1, α2).

The model revealed a significant main effect of Memory Remoteness [$F(1, 5724) = 45.81$, $p < .001$] (see Fig. 3A/B), with a larger increase in posterior alpha power during the elaboration of newer (128.7%) than older memories (86.3%). The model revealed also significant differences across electrodes [$F(7, 5724) = 3.00$, $p = .0038$] (see Fig. 3A) with the largest increase registered at PO8 (137%), which was significantly different from Oz (92.3%, $p = .009$), PO3 (97.9%, $p = .039$), and PO7 (97.9%, $p = .038$). Finally, the percentage of change in alpha power was reduced at the end of the construction phase: i.e., the main effect of Time bin [$F(9, 5724) = 3.32$, $p < .001$] (see Fig. 3B), with a gradual increase in the signal from Bin 1 to Bin 3, and a gradual decrease from Bin 4 to Bin 9 (significant differences: Bin 3 vs. Bin 8, $p = .011$; Bin 3 vs. Bin 9, $p = .015$; Bin 4 vs. Bin 8, $p = .029$; Bin 4 vs. Bin 9, $p = .040$).

Regarding the factor Group, the model revealed no main effect of Group [$F(1, 17) = 0.93$, $p = .35$], but showed a significant Group × Time bin interaction [$F(9, 5724) = 2.06$, $p = .029$]. The percentage of change in alpha power of the HSAM group did not significantly change across bins, whereas in the control group the percentage of change in alpha power varied as a function of Time bin. Specifically, alpha power increased steeply from Bin 1 to Bin 3 (Bin 1 vs. Bin 3, $p = .03$) and then gradually decreased from Bin 3 to Bin 8 (Bin 3 vs. Bins 5–10, all $ps < 0.001$; Bin 4 vs. Bins 5–10, all $ps < 0.001$), with Bins 6–8 showing less alpha power than at the beginning of the elaboration phase (Bin 1 vs. Bins 6–8, all $ps < 0.0298$) (see Fig. 3C). Fig. 4A/B displays the topographies of the percentage of change of alpha power during the elaboration of older and newer memories across the 10 time bins in the HSAM compared to the control participants. Fig. 4C shows the time course of percentage of change of theta power at PO8 during the elaboration

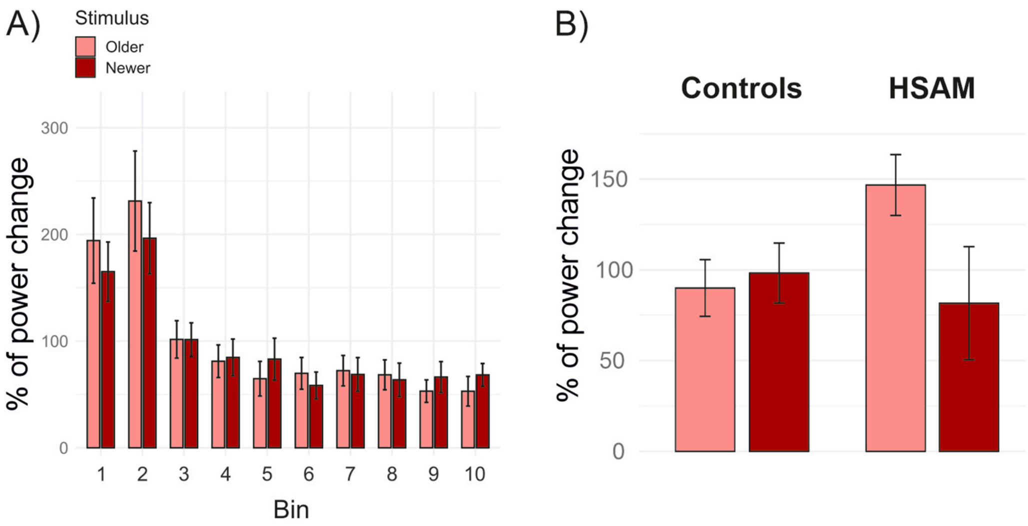

Fig. 1. **A)** Time course across ten time bins (bin duration = 250 ms) showing the observed average percentage change in theta power at electrode Fz during the construction phase for newer and older memories. **B)** Observed average percentage change in theta power collapsed across all bins for the two memory conditions, shown separately for the two groups (control vs. HSAM). The error bars in all bar plots represent the standard error of the mean.

phase in the control compared to the HSAM participants for the older and newer memories.

3.5. *Correlations of theta and alpha power with AM performance in the control group*

Finally, for the control participants we aimed to further explore the role of percentage of change in theta power at Fz during the construction phase, and the role of the percentage of change in alpha power at PO8 during the elaboration phase. Thus, we tested whether the percentage of change in power at these electrodes varied as a function of AM performance, which we defined as the percentage of AM reported for the “first time” and “last time” events, confirmed through the post scanning interview. In both cases, we tested whether theta power at Fz, and alpha power at PO8 power varied depending on memory remoteness and AM performance. Participants were included as random intercepts, with random slopes for the frequency sub-bands.

For the construction phase, the LMM on the percentage of change in theta power at Fz revealed a main effect of AM performance [$F(1, 731.94) = 19.23$, $p < .001$], a main effect of Memory Remoteness [$F(1, 874.97) = 4.18$, $p = .041$], as well as a significant interaction between AM performance and Memory Remoteness [$F(1, 875.67) = 4.42$, $p = .036$] (see Fig. 5A). This result indicates that the percentage of change in theta power was higher for older as compared to newer memories, with theta power modulated by AM performance especially for these older memories (i.e., the model revealed higher theta power during the construction of older memories in participants who were better at recalling AMs, whereas reduced modulation was observed for newer memories).

Similarly, for the elaboration phase, the LMM on percentage of change in alpha power at PO8 revealed a main effect of AM performance [$F(1, 618.14) = 21.85$, $p < .001$], Memory Remoteness [$F(1, 623.90) = 60.92$, $p < .001$], as well as a significant interaction between AM performance and Memory Remoteness [$F(1, 623.88) = 55.30$, $p < .001$] (see Fig. 5B). This confirmed that the percentage of change in alpha power was higher for newer as compared to older memories, with alpha power modulated by AM performance selectively for these recent memories (i.e., lower alpha power in participants who were better at recalling recent AMs, whereas no such modulation was observed for older memories).

4. Discussion

This study was especially designed to investigate the role of midfrontal theta and posterior alpha oscillations during, respectively, the construction and elaboration phases of AMs in three rare individuals with HSAM vs. 16 healthy controls. Notably, our findings revealed that, across the entire sample, the construction of AMs was characterized by a selective increase in midfrontal theta power, whereas the elaboration of AMs was primarily characterized by an increase in posterior alpha power (see the Result, section 3.2). The HSAM participants did not show a difference in the global mean percentage change in theta and alpha oscillatory power as compared to the control participants during these two phases, but rather a qualitatively different pattern of modulation, particularly with respect to memory remoteness for the midfrontal theta during the construction phase, and with respect to the temporal dynamics of the posterior alpha during the elaboration phase.

During the construction phase, we found that individuals with HSAM showed a strong modulation of theta power by remoteness, with greater theta during the retrieval of older as compared to newer events at the Fz electrode, i.e., overlaying a key region associated with theta activity (for reviews of frontal midline theta, see Cavanagh and Frank, 2014; Hsieh and Ranganath, 2014; Sauseng et al., 2010). This effect was absent in controls, who exhibited no difference across the two remoteness levels. This increase of theta power for older AM is in line with the well-known contribution of theta to a variety of processes that require sustained cognitive control, such as working memory (Gevins et al., 1997; Jensen and Tesche, 2002; Meltzer et al., 2007) or episodic memory (Addante et al., 2011; Gruber et al., 2008; Guderian and Düzel, 2005; Piñeyro Salvidegoitia et al., 2019; Osipova et al., 2006; for a review see, Herweg et al., 2020). There is growing evidence suggesting a crucial role of midfrontal theta in mechanisms related to cognitive control and inhibition (Eisma et al., 2021). The contribution of theta appears to reflect a more global mechanism, related to both the detection of the need for inhibitory control and its implementation across disparate brain regions (for reviews, see Cavanagh and Frank, 2014; Senoussi et al., 2022). According to this view, it is suggested that theta activity might play an important role in “orchestrating” the organization of the brain activity required for a cognitive task (see Sauseng et al., 2010, for a review). In line with this role of midfrontal theta, in the context of AM, theta oscillations could be crucial for the inhibitory control processes involved in memory retrieval, that is, the suppression of competing memories in order to selectively construct the desired one (see Messel et al., 2021; Norman et al., 2007). Moreover, with respect to memory functions, theta could have a role in organizing the interactions between the medial temporal lobe and the distributed neocortical memory traces

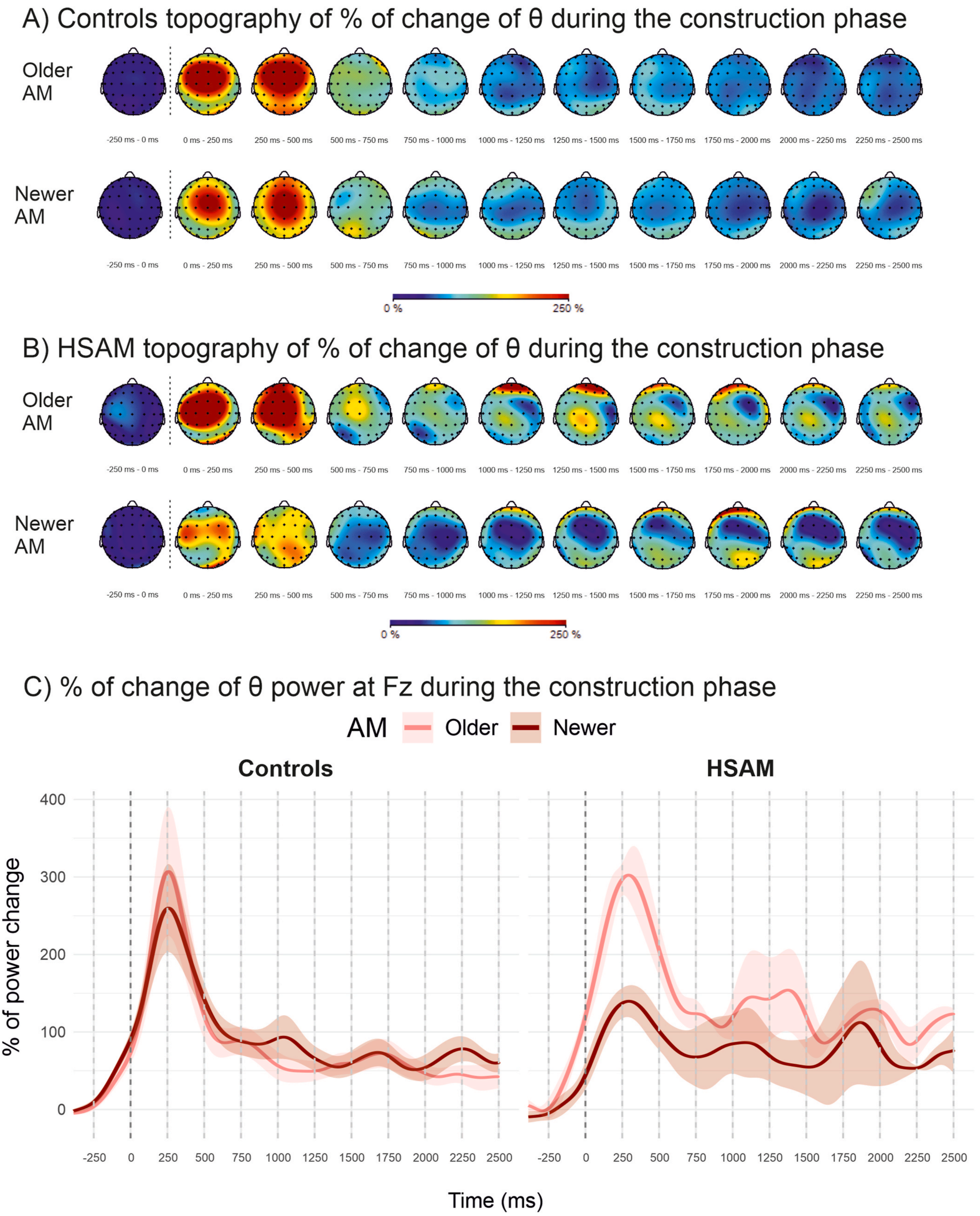

Fig. 2. Topographies of the percentage of change of theta power for the older and newer autobiographical memories (AM) across the 10 time bins in **A)** the control group, and **B)** the HSAM participants during the construction phase (0-2500 ms). **C)** Time course of the percentage of change of theta power in Fz for the controls vs. the HSAM participants during the construction of older and newer AM. Time 0 in the construction phase indicates the onset of the auditory cue. The bands represent the standard error of the mean.

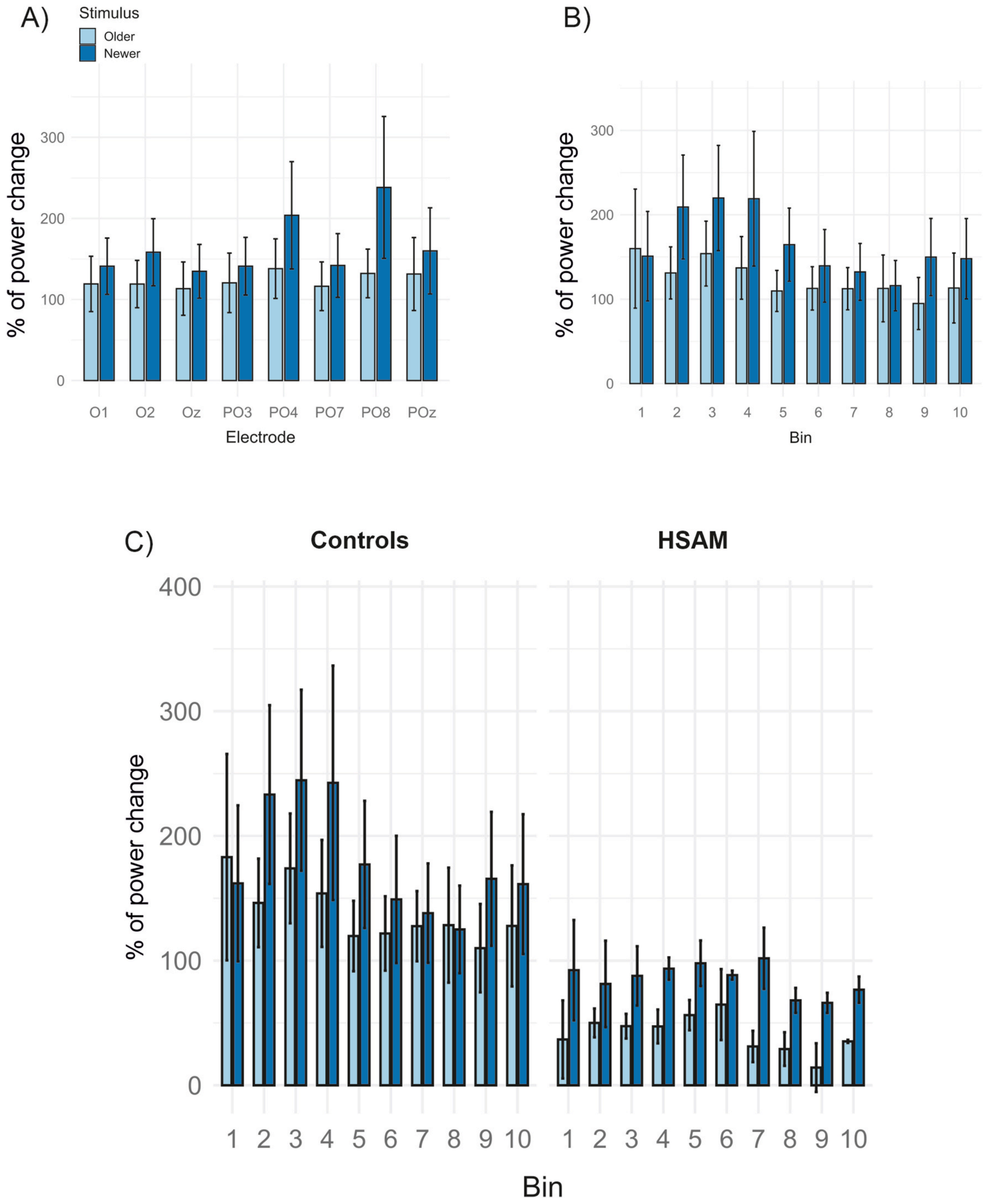

Fig. 3. Observed (raw) average percentage change in posterior alpha power during the elaboration phase for the newer and older memories, displayed **A)** across the eight electrodes and **B)** across the ten time bins (bin duration = 1 s). **C)** Time course across the ten time bins (bin duration = 1 s) showing the observed (raw) average percentage change in alpha power changes across the eight posterior electrodes for the two memory conditions, displayed separately for the two groups (control vs. HSAM). The error bars in all bar plots represent the standard error of the mean.

during AM retrieval (Fuentemilla et al., 2014), facilitating communication across key memory networks, and coordinating the integration of distributed information necessary for reconstructing complex autobiographical events (Guderian and Düzel, 2005; Sederberg et al., 2003). Moreover, theta appears to be generated in key brain structures involved with memory function, such as the hippocampus (Bastiaansen and Hagoort, 2003; Mitchell et al., 2008), the anterior cingulate cortex, and the medial prefrontal cortex (Asada et al., 1999; Onton et al., 2005; Tsujimoto et al., 2006, 2010), thus providing further support for a link between theta oscillations and memory functions. Here, the selective early increase of theta for older events in HSAM may reflect a more efficient and strategically focused engagement of retrieval mechanisms when accessing temporally distant experiences, while recent events may benefit from a more direct route requiring less frontal involvement (e.g., Addis et al., 2012; Daviddi et al., 2024). The modulation of theta as a function of memory remoteness is also consistent with a previous study in which a critical role of theta activity was observed with intracranial EEG for remote memories as compared to recent memories in a group of healthy participants (Steinvorth et al., 2010). The functional relevance of theta oscillations for AM performance in the current experiment has

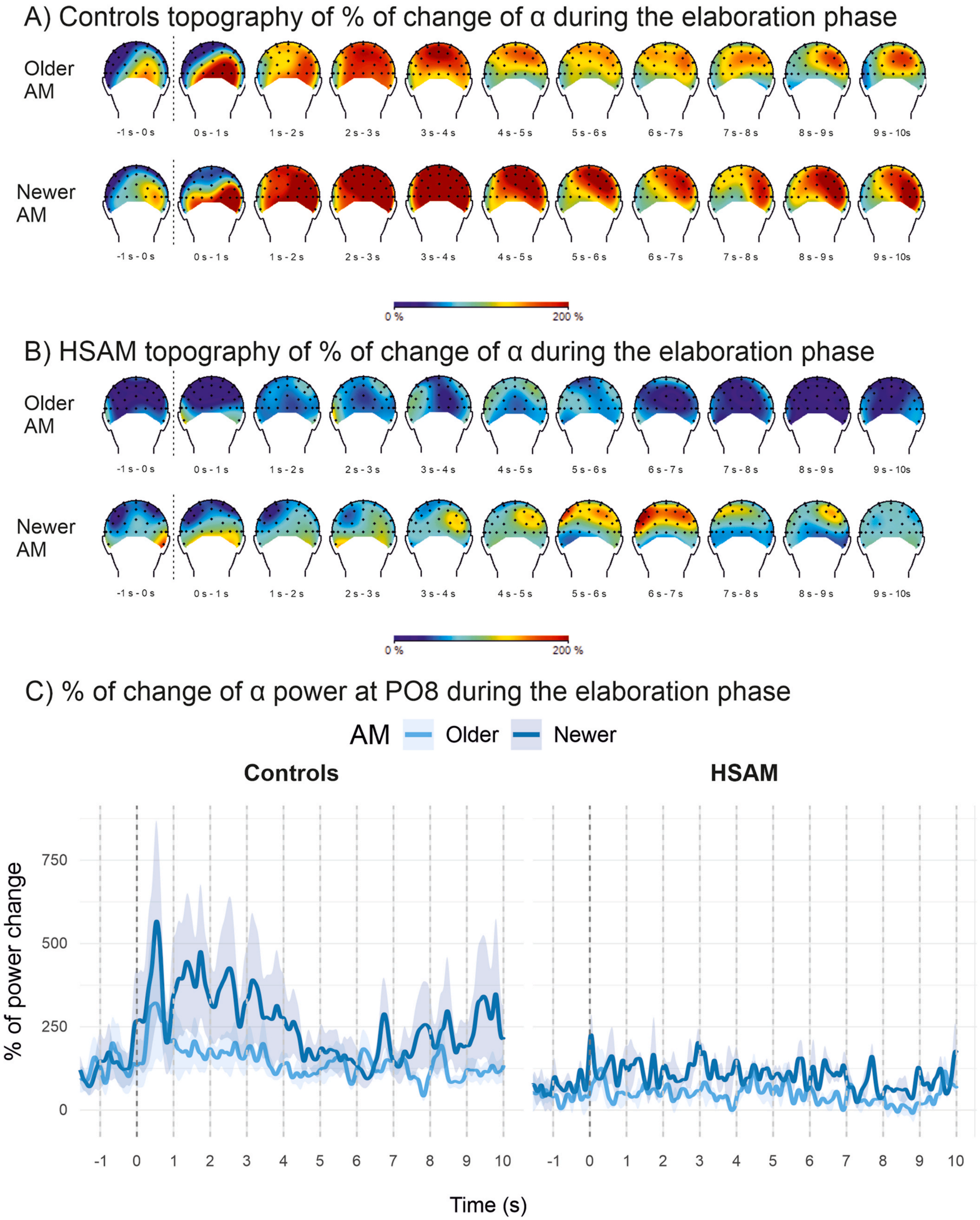

Fig. 4. Topographies of the percentage of change of alpha power for the older and newer autobiographical memories (AM) across the ten time bins in **A)** the control group, and **B)** the HSAM participants during the elaboration phase (0-10 s). **C)** Time course of the percentage of change of alpha power in PO8 for the controls vs the HSAM participants during the elaboration of older and newer AM. Time 0 in the elaboration phase indicates the response button press. The bands represent the standard error of the mean.

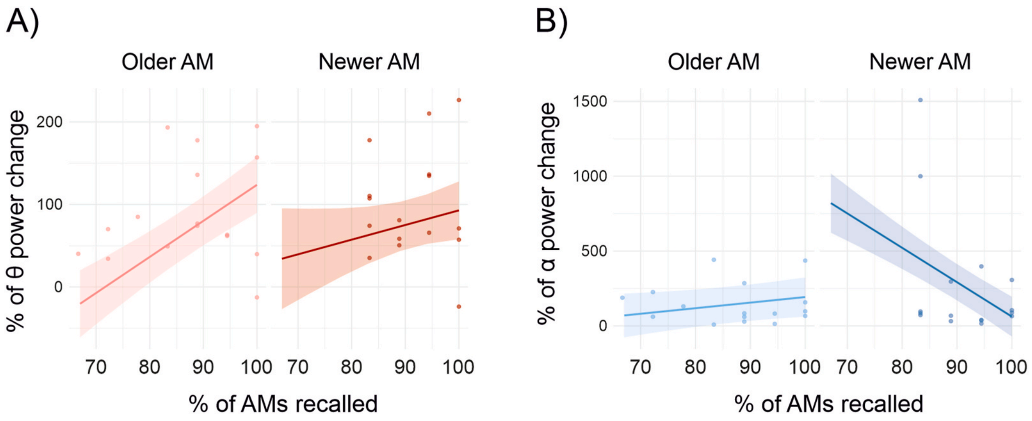

Fig. 5. Scatter plots displaying: **A)** the percentage of theta power change during the construction phase in the control group as a function of autobiographical memory (AM) performance (% of AMs recalled) and memory remoteness (older vs. newer), and **B)** the percentage of alpha power change during the elaboration phase in the control group as a function of the percentage of AMs performance and memory remoteness (older vs. newer). The bands around the regression lines represent the 95% confidence intervals of the model predictions.

been further corroborated by the correlational analyses restricted to the control group (see Fig. 5A), where midfrontal theta during the construction phase was higher in those participants with higher scores at the AM task, especially for remote memories, thus confirming the positive association between theta activity and more efficient memory performance in typical memory subjects. The current findings revealed a more efficient increase of theta oscillations in the HSAM participants as a function of the memory remoteness, since higher theta-mediated control was selectively engaged for temporally distant memories that require more complex reconstruction. These findings align with prior fMRI research using the same older/newer design with HSAM participants (Santangelo et al., 2018) where increased activity in HSAM was found during AM construction in a distributed network encompassing the anterior (medial prefrontal) and posterior (medial and lateral parietal) brain regions, the hippocampus, and sensory cortices (Santangelo et al., 2018). In particular, the ventromedial prefrontal cortex was found to discriminate between older vs. newer memories over an extended time period of around 20 years, using multivoxel pattern analysis (Santangelo et al., 2020). This region was also found to be associated with increased difficulty in retrieving memories in an individual with HSAM (Santangelo et al., 2021). The current findings further support this notion, suggesting that the increased midfrontal theta observed in HSAM participants during the construction of remote autobiographical memories may reflect more than a simple enhancement of frontal activation. Theta-band oscillations could play a role in coordinating the subsequent neuronal activity across midfrontal and distal cortical regions of the anterior and posterior midline, facilitating the integration of hippocampal and cortical inputs, and enabling the reconstruction of remote events that require the binding of distributed memory traces. This enhanced theta modulation in HSAM may index a more efficient engagement of control processes, that would enhance the efficacy of the brain circuits critical for complex memory construction, especially in the presence of more demanding (i.e., remote) memories.

Moving to the elaboration phase, a significant difference in the temporal dynamics of the posterior alpha power between the HSAM and the control participants was found in the occipital-parietal regions. Again, we did not find a difference between the two groups in terms of global changes in alpha percentage during the elaboration phase. However, HSAM individuals showed less modulation of alpha activity during the entire duration of the elaboration phase, while the control group required an initial alpha burst at the beginning of the elaboration phase, followed by a subsequent decrease of alpha power. Increased alpha power in occipital-posterior regions has been associated with cortical idling (for a review, see Pfurtscheller et al., 1996), but also with active suppression/inhibition of irrelevant sensory processes (Foxe and Snyder, 2011; Klimesch et al., 2007; Ray and Cole, 1985), especially during self-directed attention (Cooper et al., 2003, 2006; Knyazev, 2013). Higher alpha activity may indicate that a brain region is inhibited by other active brain regions, mimicking the alpha rhythm generally observed when the brain regions are inactive during resting state or closed eyes (Klimesch et al., 1999). On the other hand, Cooper and colleagues (2003) discussed the so-called “alpha-paradox”, proposing that a highly demanding internally-oriented task would require active inhibition of irrelevant sensory input and that an increase in alpha would sustain active cortical suppression to facilitate external filtering, thus connecting an increase of alpha to a more internally guided inhibitory control. According to both accounts, increased alpha in occipital-parietal areas (such as in PO8 as observed in our sample) at the beginning of the elaboration phase could indicate the need for cortical inhibition/deactivation to avoid distraction coming from irrelevant sensory stimuli. Accordingly, the alpha signal is thought to be inversely related to attentional and memory retrieval processes (Thut et al., 2006; Van der Lubbe et al., 2014, 2019, 2023), also involving AM retrieval (Manns et al., 2018). The initial alpha burst in the control group may indicate a difficulty in recalling the visual detail of the selected event and the requirement of a stronger initial inhibition to focus on the internally directed details. On the contrary, we can speculate that the HSAM individuals, who can easily relive and elaborate AMs, may require less sensory suppression of irrelevant stimuli at the beginning of the elaboration phase in order to focus on internally directed information. The functional relevance of the initial alpha oscillations for AM elaboration in the current experiment has been further corroborated by the correlational analyses conducted on the control group (see Fig. 5B). This showed that the posterior alpha negatively correlated with the ability of the control participants in recalling their AMs, confirming the negative relation between alpha activity and memory performance in this group. The negative correlation was particularly stronger for the newer memories. Such different impact of alpha activity during the elaboration of remote vs. recent AMs could be explained by the intrinsic characteristics of older/newer AMs. Older memories are more likely to be well-rehearsed or repeated and therefore can be more schematic, semantic-like, requiring less external sensory suppressions to be evoked; while recent events probably are less schematic, having had fewer occasions to be repeatedly reactivated and could be more “vividly” recollected, thus requiring higher sensory suppression to be relived (Robin and Moscovitch, 2017). As a side note, the current task was specifically designed to elicit autobiographical retrieval also in control participants by prompting the retrieval of highly salient and significant life events, which are typically memorable and accessible regardless of memory ability. Consistent with this, the behavioral results revealed no significant difference between recent and remote memories in the percentage of successfully retrieved events, indicating comparable recall performance across levels of memory remoteness. Thus, we hypothesize that the different contribution of alpha modulation reflects qualitative differences in remote versus recent memory representations (i.e., more vivid vs. more schematic), rather than a greater ease of retrieval for remote memories.

Moreover, the negative modulation of alpha power as a function of memory performance in the parietal-occipital regions in the control group is consistent with previous findings suggesting an inverse correlation of alpha activity and cognitive activity (Romei et al., 2008), as demonstrated by studies using PET (Buchsbaum et al., 1984), fMRI (de Munck et al., 2007; Goldman et al., 2002; Laufs et al., 2003), and combined EEG-fMRI techniques (e.g., Scheeringa et al., 2016; Michels et al., 2010; Moosmann et al., 2003). Accordingly, the use of psychedelic substances (e.g., ayahuasca or psilocybin), which are known to produce profound visual effects, has been shown to reduce alpha power, particularly in posterior regions (Kometer et al., 2013; Valle et al., 2016). Our findings revealed that, unlike typical memory participants, HSAM individuals did not require initial sensory suppression to elaborate their AMs. This reduced requirement for initial cortical idling is consistent with previous findings showing increased fMRI activity in posterior regions in HSAM individuals, such as in the temporo-parietal junction (TPJ), which has been found to be functionally connected with sensory cortices (Santangelo et al., 2018). Importantly, as we did not administer a formal assessment of mental imagery abilities to our participants, and given that previous evidence shows that HSAM individuals do not differ from controls in general imagery or cognitive abilities outside the autobiographical domain (LePort et al., 2017), we speculate that the observed differences in alpha modulation between the two groups pertain specifically to autobiographical memory imagery, rather than to sensory imagery abilities in general.

Taken together, the better modulation of theta as a function of memory remoteness, and the reduced require of alpha burst at the beginning of the elaboration phase may be due to a more efficient and flexible retrieval construction and elaboration in HSAM. These findings extend prior research on this rare phenomenon, suggesting that HSAM individuals may possess specific neurophysiological characteristics that support their superior memory abilities. For instance, LePort and colleagues (2012) found that HSAM individuals have structural differences in brain regions associated with memory, including increased gray matter density in the parahippocampal gyrus, a region closely connected to the hippocampus and involved in memory retrieval. Similarly, previous fMRI studies showed increased activity in a distributed network during AM retrieval in HSAM individuals along the anterior (medial prefrontal) and posterior (medial and lateral parietal) brain regions, the hippocampus, and sensory cortices (Mazzoni et al., 2019; Santangelo et al., 2018, 2020, 2021). Furthermore, resting-state fMRI studies of HSAM have suggested a unique pattern of functional connectivity in this cohort of participants, as compared to controls (Daviddi et al., 2022b; Orwig et al., 2024). Our findings extend this line of research by highlighting a better modulation of midfrontal theta and posterior alpha oscillations during access and elaboration of AMs.

While this study offers insights into the role of theta and alpha oscillations in HSAM, the limitation of the small sample size, i.e., the inclusion of only three HSAM individuals, should be considered, which limits the generalizability of the findings. Future studies should aim to replicate these findings in a larger sample of HSAM individuals to confirm the observed patterns of theta and alpha activity during the construction and elaboration of AM. Moreover, future magnetoencephalography (MEG) research could explore gamma oscillations, which, together with theta, may support episodic memory retrieval (Nyhus and Curran, 2010), as MEG is less affected by the noise and muscle artifacts that limit gamma detection with scalp EEG (Muthukumaraswamy, 2013). Finally, future research could use frequency-based functional connectivity analyses to investigate source-level inter-site phase coherence (ISPC; Asanowicz et al., 2023; Lachaux et al., 1999; Panek et al., 2025; Van der Lubbe et al., 2023) in HSAM individuals to better understand the underlying mechanisms of their superior memory.

5. Conclusions

In the current study, we found different modulations of midfrontal theta and posterior alpha power in the HSAM participant compared to controls, during the construction and elaboration phases of AM retrieval, respectively. During the construction phase, individuals with HSAM showed an optimized engagement of theta oscillations as a function of the remoteness of the memory being constructed. During the elaboration phase, we found no increase of the initial parietal-occipital alpha activity observed in typical memory participants, suggesting greater ease in generating vivid mental imagery with less inhibitory control. These findings shed light on the role of theta and alpha oscillations in extreme memory phenomena and contribute to the development of models that account for individual differences in the neural basis of AM.

CRediT authorship contribution statement

Tiziana Pedale: Writing – original draft, Visualization, Software, Formal analysis. **Rob Van der Lubbe:** Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Sarah Daviddi:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis. **Fabrizio Parente:** Writing – review & editing, Formal analysis. **Ilaria Cipriani:** Writing – review & editing, Investigation. **Patrizia Campolongo:** Writing – review & editing, Funding acquisition, Data curation. **Sabrina Fagioli:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Valerio Santangelo:** Writing – original draft, Supervision, Software, Resources, Methodology, Funding acquisition, Data curation, Conceptualization.

Ethics approval

The study was conducted in accordance with the Declaration of Helsinki and approved by the independent Ethics Committee of the IRCCS Santa Lucia Foundation (Prot. CE/PROG.748; 23 April 2020).

Consent to participate

Informed consent was obtained from all participants involved in the study.

Conflicts of interest

The authors have no financial or proprietary interests in any material discussed in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2026.109444.

Data availability

The conditions of our ethics approval do not permit public archiving of data when -also in an anonymized form-it is not possible to rule out any link to the individuals' identity. Here we reported data belonging to a rare individual that released several interviews to national and international press. For this reason, data anonymization cannot be fully guaranteed. Access will only be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data, upon completion of a data sharing agreement.

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