Original Research:

Hippocampal-occipital connectivity reflects autobiographical memory deficits in aphantasia

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Abstract

Aphantasia prohibits people from experiencing visual imagery. While most of us can readily recall decade-old personal experiences (autobiographical memories, AM) with vivid mental images, there is a dearth of information about whether the loss of visual imagery in aphantasics affects their AM retrieval. The hippocampus is thought to be a crucial hub in a brain-wide network underlying AM. One important question is whether this network, especially the connectivity of the hippocampus, is altered in aphantasia. In the current study, we tested 14 congenital aphantasics and 16 demographically matched controls in an AM fMRI task to investigate how key brain regions (i.e., vmPFC, hippocampus and visual-perceptual cortices) interact with each other during AM re-experiencing. All participants were interviewed with an Autobiographical Memory Interview to examine their episodic and semantic recall of specific events. Aphantasics reported more difficulties in recalling AM, were less confident about their memories, and described less internal and emotional details than controls. Neurally, aphantasics displayed decreased hippocampal and increased visual-perceptual cortex activation during AM retrieval compared to controls. In addition, aphantasics exhibited stronger connectivity between the hippocampus and the visual cortex during AM and at rest. Connectivity at rest showed opposite relations to visualization self-reports in the two participant groups. Our results indicate that visual mental imagery is essential for detailed-rich, vivid AM and that the functional connection between the hippocampus and visual-perceptual cortex is crucial for this type of retrieval.

Keywords: autobiographical retrieval, episodic memory, visual cortex, neural networks, functional connectivity

Significance Statement

The current study unravels the role of visual mental imagery in episodic autobiographical memory (AM) retrieval. We show that a lack of mental imagery (= aphantasia) leads to less detailed memories. Neurally, this deficit is associated with hypoactivity in the hippocampus and hyperactivity in the visual-perceptual cortices, as well as hyperconnectivity between both structures. Future studies will show whether mental imagery training leads to changes in these structures and improves recall of AM, which in turn could be used in various disorders involving AM deficits such as dementia.

Introduction

Our unique and personal memories are stored in autobiographical memories (AM) providing stability and continuity of our self (Svoboda et al., 2006). For most of us, travelling mentally back in time and re-visiting such unique personal events is associated with vivid, detail-rich mental imagery (D'Argembeau & Van der Linden, 2006; Greenberg & Knowlton, 2014). This vivid mental imagery during the re-experiencing of AMs has become a hallmark of autonoetic, episodic AM retrieval. However, up to date, it remains unclear to what extent episodic AM retrieval depends on visual mental imagery and what neural consequences a lack of mental imagery has on episodic AM retrieval. This knowledge gap exists because separating AM retrieval from mental imagery is a complex and challenging task.

One way to address this conundrum is to study people with aphantasia (Zeman et al., 2015). Recent research defines aphantasia as a neuropsychological condition in which people experience a marked reduction or complete lack of voluntary sensory imagery (Monzel et al., 2022). This condition is associated with psychophysiological alterations, such as reduced imagery-induced pupil contraction (Kay et al., 2022) and reduced imagery-induced priming effects (Keogh & Pearson, 2018; Monzel, Keidel, et al., 2021). Thus, aphantasics offer the unique opportunity to examine the consequences for episodic AM retrieval in the absence of voluntary imagery. Indeed, a handful of previous studies report convergent evidence that aphantasics report less sensory AM details than controls (Dawes et al., 2020, 2022; Milton et al., 2020; Zeman et al., 2020).

Neurally, the hippocampus has been established as a central brain structure to support the detail-rich episodic AM retrieval in the healthy brain (Bauer et al., 2017; Brown et al., 2018;

Burianova et al., 2010; McCormick et al., 2020; Moscovitch et al., 2005). In fact, hippocampal activity correlates with the vividness of AM recollection (Addis et al., 2004; Sheldon & Levine, 2013) and patients with hippocampal damage show marked deficits in retrieving episodic AM (Miller et al., 2020; Rosenbaum et al., 2008). In addition, neuroimaging studies illuminate that the hippocampus is almost always co-activated with a wider set of brain regions, including the ventromedial prefrontal cortex (vmPFC), lateral and medial parietal cortices, as well as visual-perceptual cortices (Svoboda et al., 2006). Interestingly, especially during the elaboration phase of AM retrieval, the hippocampus exhibits a strong functional connection to the visual-perceptual cortices, suggesting a crucial role of this connection for the embedding of visual-perceptual details into AMs (McCormick et al., 2015).

Yet, not many studies have examined the neural correlates of aphantasia, and none during AM retrieval. Of the little evidence there is, reports converge on a potential hyperactivity of the visual-perceptual cortices in aphantasia (Fulford et al., 2018; Keogh et al., 2020). A prominent theory posits that because of this hyperactivity, small signals elicited during the construction of mental imagery may not be detected. If true, episodic AM retrieval deficits seen in aphantasia may be due to a disrupted connectivity between hippocampus and visual-perceptual cortices (Pearson, 2019). In the same vein, Blomkvist (2022) proposes the extended constructive episodic simulation hypotheses (CESH+) that suggests that imagination and memory rely on similar neural structures, since both represent simulated recombinations of previous impressions. This hypothesis has been supported by shared representations for memory and mental imagery in early visual cortex (Albers et al., 2013; see also Zeidman & Maguire, 2016). Within this framework, the hippocampus is supposed to initiate downstream

sensory retrieval processes (e.g., in the visual-perceptual cortices; Danker & Anderson, 2010), comparable to its role in the hippocampal memory indexing theory (Langille & Gallistel, 2020; . Blomkvist (2022) speculates that in aphantasics, either the hippocampal memory index or the downstream retrieval processes may be impaired.

The main goal of our study was to examine the neural correlates of AM deficits associated with aphantasia. We hypothesized that the deficits in AM seen in aphantasia rely on altered involvement of the hippocampus, visual-perceptual cortices and their functional connectivity.

Materials and methods

Participants

In total, 31 healthy individuals with no previous psychiatric or neurological condition participated in this study. 15 congenital aphantasics and 16 matched controls were recruited from the database of the *Aphantasia Research Project Bonn* (Monzel, Keidel, et al., 2021; Monzel, Vetterlein, et al., 2021). Due to technical issues during MRI scanning, one aphantasic had to be excluded from the analyses. Groups were matched for basic demographic data, that is, sex, age, and education, as well as intelligence assessed with a short intelligence screening (Baudson & Preckel, 2015) (see Table 1). Oral and written informed consent was obtained from all participants prior to the commencement of experimental procedure in accordance with the Declaration of Helsinki (World Medical Association, 2013) and the ethics board of the University Hospital Bonn.

Table 1.

Demographic data for aphantasics, controls and the total sample.

	Total (n = 30)	Aphantasics (n = 14)	Controls (n = 16)	Test statistic	*p*	BF_{01}
Age				0.80[a]	.431	2.30
M	29.77	31.47	28.19			
SD	11.36	10.45	12.27			
IQ						
M	93.77	91.73	95.69	0.81[a]	.425	2.29
SD	13.53	16.61	10.02			
Sex				2.76[b]	.097	0.69
Male (%)	32.3	53.3	81.3			
Female (%)	67.7	46.7	18.8			
Education				1.59[b]	.662	7.90
Secondary school (%)	6.5	6.7	6.3			
A-levels (%)	35.5	40.0	31.3			
University degree (%)	54.8	46.7	62.5			
Doctoral degree (%)	3.2	6.7	0.0			

Note. BF_{01} = Bayes Factor, indicates how much more likely H0 is compared to H1. [a] *t*-test, [b] χ^2-test.

Material

Vividness of visual imagery questionnaire

Aphantasia is typically assessed with the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973, 1995), a subjective self-report questionnaire that measures how vivid mental scenes can be constructed by an individual. For example, individuals are asked to visualize a sunset with as much detail as possible and rate their mental scene based on a 5-point Likert scale (ranging from 'no image at all, you only "know" that you are thinking of the object' to 'perfectly clear and as vivid as normal vision'). Since there are 16 items, the highest score of the VVIQ is 80 indicating the ability to visualize mental images with such vividness as if the event were happening right there and then. The minimum number of points is 16 indicating that an individual reported no mental image for any of the items at all. Aphantasia is at the lower end of the spectrum of imagery-abilities and usually diagnosed with a VVIQ-score between 16 and 32 (e.g., Dawes et al., 2020, 2022).

Binocular rivalry task

Since self-report questionnaires such as the VVIQ are associated with several drawbacks, such as their reliance on introspection (Schwitzgebel, 2002), we administered a mental imagery priming-based binocular rivalry task to assess mental imagery more objectively (for more details, see Keogh & Pearson, 2018; Pearson et al., 2008). In short, after imagining either red-horizontal or blue-vertical Gabor patterns, participants were presented with a red-horizontal Gabor pattern to one eye and a blue-vertical Gabor pattern to the other eye. Subsequently, participants were asked to indicate which type of Gabor pattern they predominantly observed.

Usually, successful mental imagery leads subjects to select the Gabor pattern which they had just visualized. This selection bias can be transferred into a priming score representing visual imagery strength. Mock stimuli consisting of only red-horizontal or blue-vertical Gabor patterns were displayed in 12.5 % of the trials to be able to detect decisional biases.

Autobiographical memory interview

Detailed behavioral AM measures were obtained in blinded semi-structured interviews either in-person or online via Zoom (Zoom Video Communications Inc., 2016) using the Autobiographical Memory Interview (AMI; Levine et al., 2002). During the AMI, the interviewer asks the participant to recall five episodic AMs from different life periods: early childhood (up to age 11), adolescent years (ages 11–17), early adulthood (ages 18–35), middle age (35–55), and the previous year. For participants who were younger than 34 years, the middle age memory was replaced by another early adulthood memory. Memories from the first four periods were considered remote, whereas the memory from the previous year was considered recent. The interview is structured so that each memory recollection consists of three parts: free recall, general probe, and specific probe. During free recall, the participants were asked to recall as many details as possible for a memory of their choice that is specific in time and place within the given time period. When the participant came to a natural ending, the free recall was followed by the general and specific probes. During the general probe, the interviewer asked the participant encouragingly to promote any additional details. During the specific probe, specific questions were asked for details about the time, place, perception, and emotion/thoughts of each memory. Then, participants were instructed to rate their recall in terms of their ability to visualize the event on a 6-point Likert scale (ranging from 'not at all' to

'very much'). The interview was audiotaped, and afterwards transcribed and then scored by two independent raters according to the standard protocol (Levine et al., 2002). The interviews were scored after all data had been collected, in random order, and scorers were blind to the group membership of the participant.

For scoring, the memory details were assigned to two broad categories, that is, internal and external details. There were the following subcategories of internal details: internal events (happenings, weather conditions, people present, actions), place (country, city, building, part of room), time (year, month, day, time of the day), perceptual details (visual, auditory, gustatory, tactile, smell, body position), and emotion/thought (emotional state, thoughts). The subcategories for external details were semantic details (factual or general knowledge), external events (other specific events in time and place but different to the main event), repetition (repeated identical information without request), and other details (metacognitive statements, editorializing). In addition, following the standard procedure, an “episodic richness” score was given for each memory by the rater on a 7-point Likert scale (ranging from “not at all” to “perfect”). Furthermore, we added a novel rating score of confidence to the protocol since many participants indicated very strong belief in the details they provided, while others were insecure about the correctness of their own memories. Confidence scores were again rated on a 7-point Likert scale (ranging from 'not at all' to 'perfect').

Experimental design

Experimental fMRI task

The experimental fMRI task was adapted from a previous protocol by McCormick et al. (2015). Two conditions, an AM retrieval task and a simple math task (MA), each consisting of 20 randomized trials, were included in this experiment. During AM trials, cue words, such as 'a party', were presented and participants were instructed to recall a personal event relevant to the word cue which was specific in time and place (e.g., their 30th birthday party). Participants were asked to press a response button, once an AM was retrieved to indicate the time point by which they would start to engage in the AM elaboration phase. For the rest of the trial duration, participants were asked to re-experience the chosen AM and elaborate as many details as possible in their mind's eye. After each AM trial, participants were instructed to rate via button presses whether their retrieval had been vivid or faint. During MA trials, simple addition or subtraction problems, for example, 47 + 19, were presented. Here, participants were instructed to press a response button once the problems were solved and asked to engage in adding 3s to the solutions, for example, (47 + 19) + 3 + ... + 3, until the trial ended. The MA trials were followed by a rating whether the MA problems had been easy or difficult to solve. Each trial lasted for a maximum of 17 s and was followed by a jittered inter-stimulus interval (ISI) between 1 to 4 s.

MRI data acquisition

Anatomical and functional data were acquired at the German Center for Neurodegenerative Diseases (DZNE), Bonn, Germany, using a 3 Tesla MAGNETOM Skyra MRI scanner (Siemens Healthineers, Erlangen, Germany). A mirror was mounted on the 32 channel receiver head coil and was placed in the scanner for the participants to view the stimuli shown on an MRI

conditional 30-inch TFT monitor (medres medical research, Cologne, Germany) placed at the scanner's rear end. The MRI protocol consisted of anatomical, resting-state, and AM task-based fMRI scanning sessions. Of note, the resting state scans were acquired before participants engaged in the AM task in order to prevent reminiscing about personal memories during the resting state. For the anatomical scans, an in-house developed 0.8 mm isotropic whole-brain T1-weighted sagittal oriented multi-echo magnetization prepared rapid acquisition gradient echo (MEMPRAGE; Brenner et al., 2014) was employed with the following parameters: TR = 2.56 s, TEs = 1.72/3.44/5.16/6.88 ms, TA = 6:48, matrix = 320 x 320 x 224, readout pixel bandwidth = 680 Hz/Pixel, CAIPIRINHA mode. Resting-state (190 volumes, TA = 7 min) and AM task-based fMRI scans (460 volumes, TA = 15 min) were acquired using an interleaved multi-slice 3.5 mm isotropic echo planar imaging (EPI) sequence with TR = 2 s, TE = 30 ms, matrix = 64 x 64 x 39, readout pixel bandwidth = 2112 Hz/Pixel (see Jessen et al., 2018). The images were obtained in an oblique-axial slice orientation along the anterior-posterior commissure line. During resting state, the participants were asked to close their eyes to provoke spontaneous imagery. The first 5 frames of each functional session were excluded for the scanner to reach equilibrium. Before each functional session an optimal B0 shim was determined and individually mapped by 2-echo gradient echo (GRE) with same voxel resolution and positioning for later post-processing. Additional experimental data were also collected, albeit not part of the current study.

MRI data processing

SPM12 (Statistical Parametric Mapping 12) software package (www.fil.ion.ucl.ac.uk/spm/) on MATLAB v19a (MathWorks) computing platform (https://matlab.mathworks.com/) was used to perform resting-state and AM task-based fMRI data preprocessing. The anatomical T1w RMS of all MEMPRAGE's echoes and functional 2D-EPI images were reoriented along the anterior-posterior commissure axis. The phase and magnitude images within the field maps were applied to calculate the voxel displacement maps (VDM) for geometrical correction of the distorted EPI images. The echo times were set to 4.92 ms (short) and 7.38 ms (long). The total EPI readout time was 34.56 ms. The calculated EPI and VDMs were applied to the functional scans for realignment and unwarping. The functional scans were then co-registered to the segmented bias corrected T1 scans.

Whole-brain differences between groups were evaluated. Thus, co-registered scans were normalized to the Montreal Neurological Institute (MNI) space and a Gaussian smoothing kernel of 8 mm FWHM was applied. In addition, for functional connectivity analyses, denoising was applied using a linear regression model of potential confounding effects (global white matter signal, CSF signal, and ART scrubbing parameters) in the BOLD signal using CONN software package (www.nitrc.org/projects/conn/). Temporal band pass filter was set from 0.01 to infinite to further minimize artifacts.

Statistical analyses

Behavioral analyses

Independent samples t-tests were calculated to assess differences in the priming scores of aphantasics and controls in the binocular rivalry task. One sample t-tests were used to

distinguish the performances of both groups from chance. To assess differences of AMI scores between aphantasics and controls, two 2-way mixed ANOVAs with Tukey's multiple comparison post-hoc tests were calculated, one for internal and one for external memories, with memory recency (remote vs. recent) as within-subject factor and group (aphantasics vs. controls) as between-subject factor. Afterwards, two 2-way mixed ANOVAs with Tukey's multiple comparison were conducted for specific internal (time, place, internal event, perception, emotion) and external (external event, semantic, repetition, other) memory subcategories. Differences in memory ratings (confidence, episodic richness) and self-reported visualization were assessed via t-tests.

Whole-brain fMRI activation analyses

We followed a standard GLM procedure in SPM12 to examine whole-brain activation differences during AM retrieval and MA between aphantasics and controls. We specified our main contrast of interest, i.e., AM versus MA on the first level, which was then brought to the second group level using a two-sided Student t-test. Finally, the activation maps of the two groups were compared using a two-sample t-test. For whole-brain analysis, we applied a significance threshold of $p < .001$, and voxel cluster size of 10 adjacent voxels, uncorrected.

ROI-to-ROI functional connectivity analyses

One of our main hypotheses stated that the hippocampus and visual-perceptual cortex show differential engagement during AM retrieval associated with aphantasia. Because of the striking activation differences during AM retrieval between aphantasics and controls in exactly those

regions, in a next step, we sought to examine the functional connectivity between those areas. Towards this end, we created regions of interest (ROIs, spheres with a diameter of 10 mm consisting of 536 voxels) around the three peaks of the activation differences using the MarsBaR HBM toolbox (Brett et al., 2002). The ROIs comprised (1) the right hippocampus, MNI: x = 39, y = -31, z = -13, (2) the right visual cortex, MNI: x = 12, y = -79, z = 5, and (3) the left visual cortex, MNI: x = -9, y = -76, z = 29. Using CONN, we examined functional connectivity (i.e., Generalized Psycho-Physiological Interactions, weighted general linear model with bivariate correlation) between the hippocampal ROI and the ROIs situated in the visual-perceptual cortex during AM task-based fMRI and during resting-state. Furthermore, in order to examine how well functional connectivity between hippocampus and the visual cortex reflected an individuals' ability to visualize mental events, we examined a regression model with the visualization scores of the AMI as criterion and connectivity values, group allocation and the interaction term of connectivity values and group allocation as predictors. For these ROI analyses, we applied a significance threshold of $\alpha = .05$, small volume corrected, and a voxel cluster threshold of 10 adjacent voxels.

Results

Group validation

Aphantasics (M = 16.57, SD = 1.02), scored significantly lower on the VVIQ than controls (M = 62.94, SD = 8.71), $t(15.47) = 21.12$, $p < .001$, $d = 7.23$. Furthermore, aphantasics and controls differed in the priming score of the binocular rivalry task, $t(18.04) = 2.41$, $p = .027$, $d = 0.87$). While controls were primed by their own mental imagery in 61.3 % (SD = 13.1 %) of the trials,

aphantasics were only primed 52.6 % (*SD* = 4.9 %) of the time. In fact, the performance of controls differed from chance, $t(14) = 3.34$, $p = .005$, $d = 0.86$, whereas performance of aphantasics did not, $t(13) = 1.96$, $p = .072$. Moreover, the VVIQ scores correlated positively with the performance on the binocular rivalry task, $r(28) = .43$, $p = .022$. For the mock trials, no differences in priming scores were found between groups, $t(28) = 0.86$, $p = .396$, or related to chance (aphantasics: $t(13) = 0.74$, $p = .475$; controls: $t(15) = 0.42$, $p = .682$). These findings validate our groups by indicating that visual imagery strength was objectively diminished in aphantasics.

Autobiographical Memory Interview

We found stark differences between the AM reports of the aphantasics and controls. Figure 1A and 1B display the comparison of the mean internal and external details between aphantasics and controls for their descriptions of remote and recent memories on the AMI. On average, 2-way ANOVA suggested that aphantasics described less internal details than controls, $F(3, 81) = 22.4$, $p < .001$, regardless of whether the memories were remote, $p < .001$, $d = 1.25$, or recent, $p = .001$, $d = 1.63$. On the other hand, external details did not differ significantly between aphantasics and controls, $F(3, 81) = 0.16$, $p = .922$, neither for remote, $p = .938$, $d = 0.09$, nor recent memories, $p = .992$, $d = 0.16$.

We further compared different internal and external specific details acquired from aphantasics and controls, as shown in Figure 1D. Specific internal detail categories showed significant differences between aphantasics and controls ($F(9, 641) = 117.1$, $p < .001$), including internal events, $p < .001$, $d = 0.75$, time, $p = .435$, $d = 0.94$, place, $p = .058$, $d = 0.94$,

emotion/thought, $p < .001$, $d = 1.15$, and perception, $p < .001$, $d = 1.17$. However, for external details, no significant differences were found between the two groups, $F(7, 498) = 42.89$, $p < .001$, including external events, $p = .970$ $d = 0.16$, semantic details, $p > .999$, $d = 0.01$, repetition, $p = .997$, $d = 0.13$, and other details, $p = .998$, $d = 0.13$.

Last, significant differences between aphantasics and controls were revealed for the ratings of episodic richness, $t(142.09) = 12.61$, $p < .001$, $d = 2.09$, and for confidence, $t(140.93) = 8.51$, $p < .001$, $d = 1.41$ (see Figure 1C). When comparing self-reported visualization scores, aphantasics rated their own memories as less visual, $t(140.39) = 16.77$, $p < .001$, $d = 2.80$.

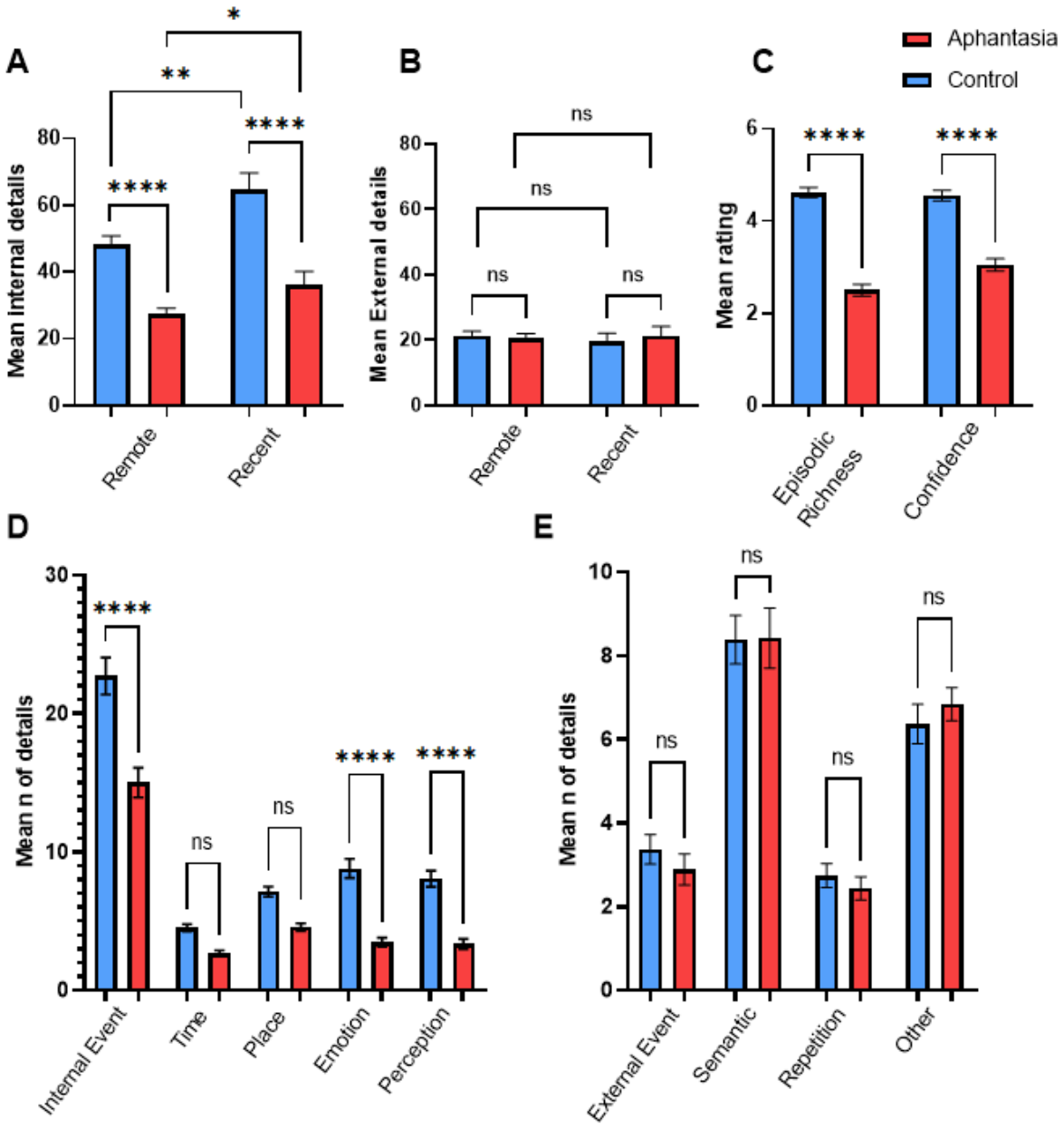

Figure 1. Behavioral AM deficits associated with aphantasia. (A) Mean amount (± SEM) of internal details (B) and external details for recent and remote memories. (C) Episodic richness and confidence scores for controls and aphantasics. (D) Specific internal and (E) external memory detail categories for aphantasics and controls. * $p < .05$, ** $p < .01$, *** $p < .001$, **** $p < .0001$, n.s. = non-significant.

Behavioral results of the fMRI AM task

We found stark differences for the vividness response between groups, $t(28) = 5.29$, $p < .001$. While controls reported in 86 % (*SD* = 26 %) of trials that their AM retrieval had been vivid, aphantasics indicated only in 20 % (*SD* = 20 %) of trials that their AM retrieval had been vivid. Moreover, aphantasics responded slower (*M* = 1.34 s, *SD* = 0.38 s) than controls (*M* = 1.00 s, *SD* = 0.29 s) when they were asked if their retrieved memories were vivid or faint, $t(28) = 2.78$, $p = .009$. In contrast, there were no differences between groups during the MA trials, neither on the easy/hard response, $t(28) = 1.16$, $p = .255$, nor on the reaction times, $t(28) = 0.58$, $p = .567$. Overall, participants engaged with a good response rate to the AM task in the scanner. There were only 9 % missing values in AM trials and 7 % missing values in MA trials with no differences of missing values between groups, neither for AM trials, $t(19.98) = 1.11$, $p = .281$, nor for MA trials, $t(18.13) = 0.52$, $p = .609$.

Activation patterns associated with AM retrieval

Whole-brain activation during AM retrieval of both groups is displayed in Figure 2A and B. Overall, both groups showed greater activation in all areas typically associated with AM, including bilateral hippocampus, vmPFC, and medial/lateral parietal regions, during AM retrieval in comparison to MA solving. When examining the difference in activation, aphantasics displayed greater activation in the bilateral visual-perceptual regions (maximum in lingual gyrus) in the occipital cortex than controls, $t(28) = 4.41$, $p < .001$ (MNI: right visual cortex: x = 12, y = -79, z = 5; left visual cortex: x = -9, y = -76, z = 29, see Figure 2C and D). In contrast, controls showed greater activation in the right posterior hippocampus than aphantasics, $t(28) =$

3.77, $p < .001$ (MNI: x = 39, y = -31, z = -13). An additional correlation analysis revealed that those participants with higher visual-perceptual cortex activation had less hippocampal activation, $r(28) = -.39$, $p = .041$.

Of note, in order to examine hippocampal activation in greater detail, we manually segmented the hippocampus anatomically into left anterior, left posterior, right anterior and right posterior parts (see Supplementary Material for Methods and Results). For each subject, we then extracted fMRI signals during AM retrieval and MA. We found that aphantasics showed less AM-associated activation in all hippocampal parts (see Supplementary Material: Figure S1).

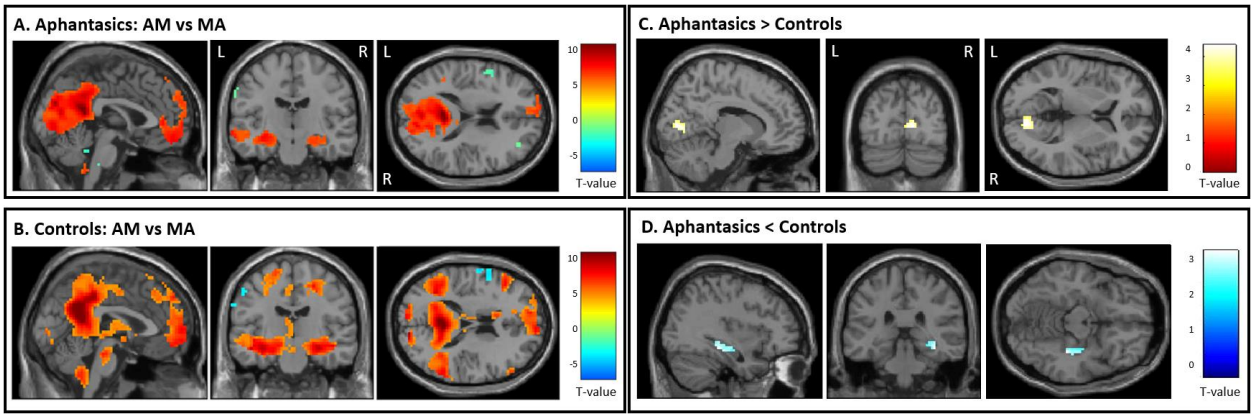

Figure 2. Activation during AM retrieval. (A) Stronger activated cortical regions during AM retrieval (in warm colors) in comparison to math problem solving (in cool colors) in aphantasics (B) and controls. (C) Aphantasics showed greater activation in visual-perceptual cortices than controls. (D) Controls showed stronger activation in the right posterior hippocampus than aphantasics (D). Images thresholded at $p < 0.001$, cluster size 10, uncorrected, except (D) which is thresholded at $p < 0.01$, clustersize 10, for display purposes.

Exploring functional connectivity of hippocampus and visual-perceptual cortices during AM and resting state

The whole-brain analyses strengthened our hypothesis that a core difference between aphantasics and controls lies in the interplay between the visual-perceptual cortex and the hippocampus. To test this interplay, we examined functional connectivity between the peak differences of the hippocampus and visual-perceptual cortex during AM retrieval and resting state (see Figure 3A and B). During AM retrieval, we found that aphantasics showed strikingly stronger functional connectivity between the right hippocampus and bilateral visual-perceptual cortices than controls (right visual cortex: $t(28) = 2.31$, $p = .01$; left visual cortex: $t(28) = 2.65$, $p = .006$). However, this effect was not specific to AM retrieval, since aphantasics also showed stronger resting-state connectivity between the right hippocampus and the left visual-perceptual cortex than controls, $t(29) = 2.83$, $p = .004$.

In a next step, we examined whether functional connectivity between the right hippocampus and visual-perceptual cortex carried information about one's ability to visualize AMs. While connectivity alone did not predict the visualization scores in the AMI, $\beta = -.06$, $p = .391$, group allocation, $\beta = .92$, $p < .001$, and the interaction between group allocation and connectivity, $\beta = .26$, $p < .001$, did (see Figure 3B). Interestingly, for controls, we found a positive correlation between the resting-state connectivity of the right hippocampus and the visual cortex and the visualization scores from the AMI, $r(13) = .65$, $p = .011$. On the other hand, for aphantasics, we found a negative correlation between the resting-state connectivity of the right hippocampi and the visual cortex and the visualization scores from the AMI, $r(14) = -.57$, $p = .027$.

Thus, our fMRI results indicate that aphantasics show an increased activation and functional connectivity of the visual-perceptual cortex, and that this over-response seems to be directly associated with the deficit in visualization of autobiographical events.

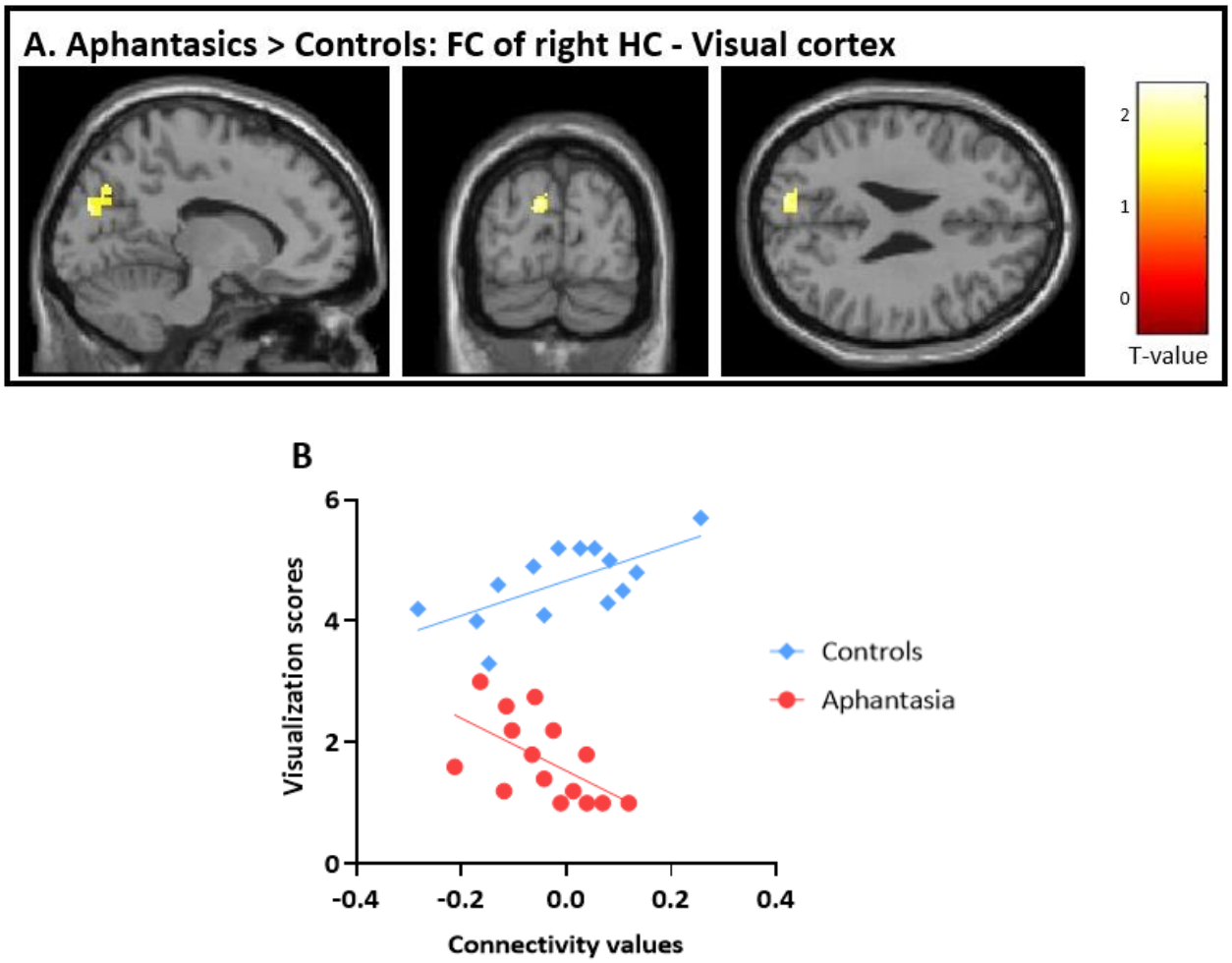

Figure 3. Functional connectivity between the visual-perceptual cortex and hippocampus during AM retrieval and resting state. (A) During AM retrieval, stronger ROI-to-ROI connectivity between the hippocampus and visual-perceptual cortex in aphantasics compared to controls. (B) Resting-state functional connectivity between the visual-perceptual cortex and hippocampus correlates with visualization abilities**.** Fitted straight lines indicate a negative

correlation for aphantasics (red) and a positive correlation for controls (blue) between visualization scores and functional connectivity.

Discussion

In this study, we set out to examine the neural correlates of episodic AM retrieval in aphantasia as a way to examine the influence of visual imagery on episodic AM. In line with previous reports, we found that aphantasics reported less sensory details during AM retrieval regardless of the recency of memory (cf. Dawes et al., 2020; 2022; Milton et al., 2020; Zeman et al., 2020). Strikingly, the deficit in constructing visual imagery associated with aphantasia not only led to a reduced retrieval of visual-perceptual details but to a broader impairment in retrieving episodic AMs, including reduced emotions and confidence attached to the memories. Thus, in agreement with a recent account of aphantasia (Blomkvist, 2022), our results support the idea that a diminished construction of visual details during AM retrieval leads to a more general episodic memory deficit. We expand the current knowledge by adding that this AM deficit is reflected neurally by an increased activation and connectivity of the visual-perceptual cortex and decreased activation of the hippocampus associated with aphantasia. Our findings provide novel insights into three current debates: 1) the mechanisms of aphantasia-related AM deficits, 2) the similarities and differences between aphantasics and individuals with hippocampal damage, and 3) the neural models of AM.

Potential mechanisms of aphantasia-related AM deficits

We report that aphantasics show increased activation of the visual-perceptual cortices as well as decreased hippocampal activation during AM retrieval in comparison to controls. In addition, aphantasics showed increased functional connectivity between the hippocampus and visual-perceptual cortices during AM retrieval and resting-state, and the strength of this functional

connectivity predicted worse visualization capacity. These findings fit well to previous neuroimaging studies pointing towards a central role of the dynamic interplay between the hippocampus and visual-perceptual cortex during AM retrieval (McCormick, et al. 2015). This interplay seems to be especially important during the elaboration stage of AM retrieval, a period when specific visual-perceptual details are being actively broad back into the mind's eye. At this point, it remains unclear whether the disruption of AM elaboration at the encoding, storage or retrieval process.

Furthermore, increased fMRI activity in the visual-perceptual cortices in aphantasia has been reported previously (Fulford et al., 2018; Keogh et al., 2020). A prominent hypothesis states that this heightened activity of the visual-perceptual cortices hinders aphantasics to detect small imagery-related signals (Pearson, 2019). Our findings support this hypothesis since fMRI-dependent changes in visual-perceptual cortices were not exclusively seen during the AM paradigm but were also present in the resting-state functional connectivity, indicating a more generally heightened state of arousal rather than a memory-specific reaction. In our study, increased visual-perceptual cortex connectivity during resting state directly correlated with worse visualization scores in aphantasics. Thus, the increased activity and connectivity of the visual-perceptual cortex may disrupt the much-needed dynamical exchange with the hippocampus during the active attempt to retrieve visual-perceptual details for AMs.

The extended constructive episodic simulation hypothesis proposes a top-down hierarchy during mental imagery (Blomkvist, 2020). In this model the hippocampus initiates retrieval processes in primary sensory brain regions, such as the visual-perceptual cortex in order to retrieve visual-perceptual details associated with a specific AM. Evidence for such top-down

hierarchies during mental imagery have been observed in fronto-parietal and occipital networks via effective connectivity analyses, such as Granger Causality and Dynamic Causal Modelling (Dentico et al., 2014; Dijkstra et al., 2017; Mechelli et al., 2004). In aphantasia, it is hypothesized that this top-down hierarchy is disrupted and therefore, the hippocampus can no longer retrieve and incorporate visual-perceptual details in one coherent mental event. Because of the slow temporal resolution of the fMRI sequence, our data cannot directly answer the question of temporal directionality between the hippocampus and visual-perceptual cortex. Nonetheless, our findings suggest that the bidirectional connectivity between both brain structures is crucial for the re-experience of episodic AMs. As such, hippocampal memory indices may be needed to retrieve specific details and if these details are not provided by the visual-perceptual cortices, the entire episodic AM retrieval seems to fail.

Similarities and differences between aphantasics and individuals with hippocampal lesions

At face value, the selective episodic AM deficits reported previously (Dawes et al., 2020; 2022; Milton et al., 2020; Zeman et al., 2020) and observed in our sample suggest that aphantasia is an episodic memory condition, similar to the AM amnesia known from individuals with hippocampal damage. In fact, aphantasics and individuals with hippocampal damage report less internal details across memory detail subcategories (Rosenbaum et al., 2008; St-Laurent et al., 2009; Steinvorth et al., 2005) and this deficit can be observed regardless of the recency of the memory (Miller et al., 2020). These similarities suggest that aphantasics are not merely missing the visual-perceptual details to specific AMs but they have a profound deficit associated with the retrieval of AMs. However, there are also stark differences between aphantasics and

individuals with hippocampal damage. Foremost, aphantasics seem not to have difficulties to retrieve spatial information (Blomkvist, 2020), which is another inherent function of the hippocampus (Burgess et al., 2002; O'Keefe, 1991), potentially relying on different paths (Pearson, 2019). The scene construction theory states, that the hippocampus is crucially needed for the construction of spatially coherent mental models of scenes (Maguire & Mullally, 2013). For example, patients with hippocampal damage cannot imagine the spatial layout of fictitious scenes (Hassabis et al., 2007), they detect less errors in spatially-incoherent scenes than controls (McCormick et al., 2017), and they show less scene-dependent mind-wandering episodes (McCormick, Rosenthal, et al., 2018). In the current study, we did not set out to examine spatial cognition in aphantasics, however, parts of our data speak to this aspect. For example, aphantasics did not differ from controls in their reported amount of spatial details on the AMI. When asked in our debriefing questions, aphantasics explained that they know how the space around them felt, they just cannot see it in front of their mind's eye. In fact, one aphantasic put her finger on it, describing it as: "I can put my consciousness in my kitchen at home and feel all around but there is no visual image attached to this feeling." Thus, we would predict that aphantasics do not show any deficits in tasks that depend on hippocampal scene construction processes. What could be impaired in aphantasics are all cognitive functions which rely on the population of the constructed scenes with visual-perceptual details, such as episodic AM retrieval, episodic future thinking, complex decision-making, and complex empathy tasks.

Towards a novel neural model of autobiographical memory

While more research is required exploring the cognitive landscape associated with aphantasia, such as spatial cognition and scene construction, our data contribute to an old debate of how AM retrieval and visual imagery are intertwined. We propose that the hippocampus is embedded in a brain-wide network, comprising the vmPFC and visual-perceptual cortices, in which each of these nodes contributes specific processes to the re-construction of extended detail-rich mental events (see also Ciaramelli et al., 2019; McCormick, Ciaramelli, et al., 2018). Within this model, the vmPFC initiates and overseas the scene construction process which takes place in the hippocampus. Judging from our data, these processes are not disturbed in aphantasia. Further, the visual-perceptual cortex provides the visual details which are essential to populate the hippocampal-constructed scenes. This model is backed up by a previous dependent MEG study revealing that the vmPFC directs hippocampal activity during the initiation of AM retrieval (McCormick et al., 2020). This finding has been replicated and extended by Chen et al. (2021), showing that the vmPFC leads hippocampal involvement during scene construction and other scene-based processes (Monk et al., 2021). On the other hand, there are a few case reports of damage to the occipital cortex causing AM amnesia (Greenberg et al., 2005), potentially by preventing the population of the hippocampally constructed scenes. Indeed, our current study suggests that a reliable connectivity between the hippocampus and the visual-perceptual cortices is essential to provide the visual details necessary for successful vivid, detail-rich AM retrieval.

Conclusion

Aphantasia provides a natural knock-out model for the influence of visual imagery on different cognitive functions. We here report a tight link between visual imagery and our ability to retrieve vivid and detail-rich personal past events, as aphantasics do not only report fewer visual-perceptual details for episodic AMs but also show decreased confidence and emotionality associated with the AMs. In this context, we highlight the central role of the functional connectivity between the hippocampus and occipital cortex to assemble visual-perceptual details into one coherent extended mental event. Exciting novel research avenues will be to examine hippocampal-dependent spatial cognition in aphantasics and to investigate whether neuroscientific interventions can be used to enhance AM retrieval by enhancing visual imagery.

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Supplementary material

Native space hippocampal fMRI activation

Since our main goal was to assess hippocampal involvement during AM retrieval in aphantasia, we sought to examine in depths whether there were any group differences in hippocampal activation in respect to the hemispheric laterality or along its long-axis. For this analysis, we used the anatomical hippocampal masks in native space and divided them into anterior and posterior portions, using the location of the uncus as boundary, for both hemispheres. We then extracted signal intensity values from these ROIs for each participant and each condition using the MATLAB-based Response Exploration toolbox (REX; www.nitrc.org/projects/rex/). Potential laterality effects and effects between the anterior and posterior hippocampus were assessed using a 2-way ANOVA with a posthoc Tukey's multiple comparison test, applying a significance threshold of $\alpha = .05$.

Differences in hippocampal activation during AM retrieval

We found stark group differences in hippocampal activation during AM versus MA. Aphantasics showed reduced activation of bilateral hippocampi, $F(17, 252) = 3.03$, $p < .001$, including the left anterior, left posterior, right anterior, and right posterior hippocampus (see Figure S1). There was no laterality effect nor differences along the pattern of activation down the anterior-posterior axis between the groups (all *p*s > .05). Together, these findings indicate that the behavioral AM deficit associated with aphantasia is reflected neurally by a reduced bilateral hippocampal activation.

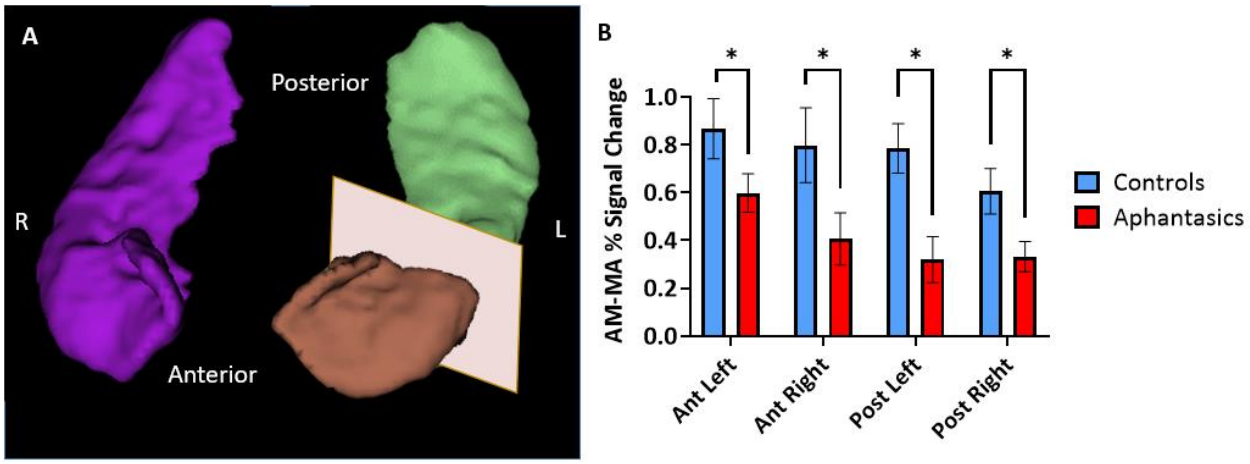

Figure S1. Reduced hippocampal activity during AM retrieval associated with aphantasia. The signal intensities during AM and MA were extracted from the hippocampal masks created from each individual participant. (A) An example of a 3D reconstruction of the hippocampus, separated into anterior and posterior portions. (B) The comparison between the percentage of signal change during the AM and MA tasks in the hippocampus of aphantasics and controls. Aphantasics show reduced differentiation between AM and MA than controls in all portions of the hippocampus. * $p < .05$.

Table S1. Peak coordinates of the AM and MA activation for Aphantasia.

Region	Hemisphere	MNI Coordinates			Voxels	T-value
		X	Y	Z		
Activation AM > MA						
Posterior Cingulate Gyrus	Right	18	-57	11	4657	11.00
Parahippocampual Gyrus*	Left	-21	-31	-13		9.06
Hippocampus	Left	-27	-17	-19	205	8.40
Superior Frontal Gyrus	Left	-12	47	50	926	8.38
Angular Gyrus	Left	-42	-55	23	165	7.88
Lateral Orbitofrontal Cortex	Left	-42	38	-16	208	7.58
Hippocampus	Right	18	-37	-1	199	6.89
Cerebellum	Right	15	-79	-37	109	6.33
Brainstem	Right	3	-46	-52	43	6.03
Parahippocampual Gyrus*	Right	24	-31	-13		6.02
Middle Temporal Gyrus	Right	60	2	--19	76	5.27
Supramarginal Gyrus	Right	54	-58	32	26	4.99
Middle Frontal Gyrus	Left	-39	20	50	12	4.52
Activation MA > AM						
Precuneus	Left	-18	-58	41	594	-3.85
Inferior Temporal Gyrus	Right	51	-46	-13	123	-3.85
Precuneus	Right	24	-49	53	718	-3.85
Insula	Left	-30	23	11	48	-3.85
Inferior Temporal Gyrus	Left	-51	-49	-13	67	-3.86
Cerebellum	Right	30	-67	-52	27	-3.87
Middle Frontal Gyrus	Right	33	41	17	34	-3.87
Superior Frontal Gyrus	Right	30	5	59	52	-3.87

Inferior Frontal Gyrus	Right	54	14	29	35	-3.88
Insula	Right	39	11	8	51	-3.88
Inferior Frontal Gyrus	Left	-57	11	26	182	-3.88
Lateral Globus Pallidus	Right	23	-7	14	14	-3.92
Cerebellum	Left	-24	-64	-46	16	-3.93

*Sub-cluster level, Cluster size = 10 voxels, p-value = 0.001

Table S2. Peak coordinates of the AM and MA activation for healthy controls.

Region	Hemisphere	MNI Coordinates			Voxels	T-value
		X	Y	Z		
Activation AM > MA						
Parahippocampal Gyrus	Right	27	-28	-19	11319	12.41
Parahippocampal Gyrus*	Left	-24	-25	-16		9.01
Cerebellum	Left	-18	-76	-37	108	7.67
Anterior Cingulate	Right	9	35	11	13	7.01
Medial Frontal Gyrus	Right	18	32	29	233	6.93
Inferior Frontal Gyrus	Right	60	32	11	53	5.94
Hippocampus	Left	-36	-22	-16	252	5.64
Hippocampus	Right	27	-22	-16	233	5.28
Hypothalamus	Right	3	-4	-10	16	4.93
Activation MA > AM						
Post Central Gyrus	Left	-33	-43	62	643	-3.73
Precuneus	Right	21	-52	53	483	-3.74
Inferior Frontal Gyrus	Right	51	8	26	16	-3.74
Middle Occipital Gyrus	Right	33	-82	2	26	-3.75
Middle Temporal Gyrus	Left	-51	-58	-1	18	-3.76

*Sub-cluster level, Cluster size = 10 voxels, p-value = 0.001