

Metacognitive Awareness and the Subjective Experience of Remembering in Aphantasia

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In press, *Journal of Cognitive Neuroscience*

Keywords

Aphantasia, consciousness, episodic memory, mental imagery

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Abstract

Individuals with aphantasia, a non-clinical condition typically characterised by mental imagery deficits, often report reduced episodic memory. However, findings have hitherto rested largely on subjective self-reports, with few studies experimentally investigating both objective and subjective aspects of episodic memory in aphantasia. In this study, we tested both aspects of remembering in aphantasic individuals using a custom 3D object and spatial memory task that manipulated visuospatial perspective, which is considered to be a key factor determining the subjective experience of remembering. Objective and subjective measures of memory performance were taken for both object and spatial memory features under different perspective conditions. Surprisingly, aphantasic participants were found to be unimpaired on all objective memory measures, including those for object memory features, despite reporting weaker overall mental imagery experience and lower subjective vividness ratings on the memory task. These results add to newly emerging evidence that aphantasia is a heterogeneous condition, where some aphantasic individuals may lack metacognitive awareness of mental imagery rather than mental imagery itself. Additionally, we found that both participant groups remembered object memory features with greater precision when encoded and retrieved in the first person versus third person, suggesting a first-person perspective might facilitate subjective memory reliving by enhancing the representational quality of scene contents.

Introduction

In most individuals, mental imagery—the ability to form sensory-like representations in the absence of perception (Pearson & Kosslyn, 2015)—pervades subjective conscious experience. For example, mental imagery allows us to direct our senses inward and ‘see’ with our mind’s eye the contents of a dream or ‘hear’ with our mind’s ear the voice of a loved one. More concretely, visual mental imagery is thought to support cognitive faculties such as visual working memory and episodic processing (Pearson, 2019), where visual mental imagery is typically evoked during the recollection of personal events (i.e., episodic memory) or while imagining future or counterfactual ones (Schacter et al., 2012; Schacter & Madore, 2016). Although mental imagery has long been reported to vary across individuals (Galton, 1888), the study of mental imagery extremes has only recently received renewed scientific interest. Of relevance to this study, a minority of individuals self-report a profound weakness in, or a complete inability to voluntarily form, mental imagery. This phenomenon has recently been termed ‘aphantasia’ (Zeman et al., 2015).

Aphantasia is estimated to occur in approximately 2-4% of the general population and is usually congenital (Dance et al., 2022; Faw, 2009; Zeman et al., 2015, 2020), although it can also be acquired through psychiatric disturbances or brain injury (Bartolomeo, 2008; Farah, 1984; Zago et al., 2011; Zeman et al., 2010; see also de Vito & Bartolomeo, 2016). While aphantasia is typically identified via subjective self-reports, often using scales such as the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973), the condition is considered by many to reflect an objective deficit in voluntary mental imagery ability. For instance, aphantasics show little imagery-based binocular rivalry priming relative to non-aphantasic controls (Keogh & Pearson, 2018; see also Pearson, 2014). Additionally, aphantasics do not typically show automatic physiological responses associated with mental imagery. For example, aphantasics do not show a significant imagery-based pupillary light response, which has been shown to index both perceptual luminance and the trial-by-trial vividness of visual mental imagery in typical imagers (Kay et al., 2022). Similarly, aphantasics show flat-line levels of skin conductance while imagining fear-inducing scenarios, unlike non-aphantasic control participants (Wicken et al., 2021). Some aphantasics report experiencing involuntary mental imagery during lower states of awareness such as dreaming, but also as intrusions during wakefulness (Dawes et al., 2020; Milton et al., 2021; Palermo et al., 2022; Zeman et al., 2015, 2020), although such intrusions may be less common in aphantasics than in typical imagers (Dawes et al., 2020).

Visual mental imagery is thought to be separable into object and spatial subcomponents (Farah et al., 1988; Levine et al., 1985). Object imagery concerns low-level perception-like representations of visual object attributes such as size, shape, colour, or brightness. By contrast, spatial imagery involves the representation of environments such as spatial configurations among or within objects, their locations, and movements. On measures distinguishing between these imagery subcomponents, aphantasics typically indicate difficulties with object, but not spatial, imagery (Bainbridge et al., 2021; Dawes et al., 2020, 2022; Koegh & Pearson, 2018). Accordingly, mental imagery has been suggested to dissociate along the classic ventral “what” and dorsal “where” processing streams associated with visual perception (Levine et al., 1985), with aphantasia reflecting selective dysfunction of the “what” stream (Pearson, 2019).

While aphantasia is typically defined primarily by a deficit in visual (i.e., object) imagery, other areas of cognition can also appear to be impaired. For example, many aphantasics report difficulty with recognising faces, termed prosopagnosia (Dawes et al., 2020). Many aphantasics also report reduced memory for personal events (i.e., episodic memory) (Dawes et al., 2020, 2022; Milton et al., 2021; Zeman et al., 2020). In the first large-scale questionnaire study to explore the cognitive profile of aphantasia, Dawes et al. (2020) found that aphantasics report less vivid and phenomenologically rich autobiographical memory (ABM) recall and imagined future scenarios than control participants. In a large sample online study, Bainbridge et al. (2021) found aphantasics had objective memory deficits consistent with their self-reported selective object memory difficulties when tasked with drawing photographs from memory. Although such objective task-based evidence for selective object memory deficits is currently scarce, mnemonic deficits are perhaps unsurprising given the importance of visual mental imagery in episodic processing (D’Argembeau & van der Linden, 2006; Greenberg & Knowlton, 2014; Palombo et al., 2018; Vannucci et al., 2016; Simons et al., 2022; Zaman & Russell, 2022). Indeed, a recent proposal extending the constructive episodic simulation hypothesis (Schacter et al., 2012, 2020) has argued that aphantasia may reflect a condition of the episodic system rather than mental imagery *per se* (Blomkvist, 2022). However, aphantasics do not always show deficits on memory tasks. For example, while Monzel et al. (2022) found evidence for a general memory impairment across both visual and verbal short-term and long-term memory tasks, others have not observed such deficits (Milton et al., 2021; Pounder et al., 2022). These mixed findings raise the question of whether objective memory deficits necessarily

accompany subjective memory complaints made by aphantasics, which may, in some cases, reflect deficient metacognitive awareness of mental imagery (Nanay, 2021; see also Pounder et al., 2022). Therefore, direct examination of both objective and subjective memory measures in the same task and participants is needed.

Aphantasics are as accurate as controls on mental rotation tasks thought to tap spatial imagery (Pounder et al., 2022; Zeman et al., 2010). However, aphantasics do not always exhibit the expected linear increase in response times as the angular disparity between different presented object orientations increases (Pounder et al., 2022; Zeman et al., 2010; but see Zhao et al., 2022), suggesting spatial processing may not be entirely unaffected. Indeed, the rotation-related negativity, an electrophysiological correlate of mental spatial transformations, has been shown to be absent in a patient with acquired aphantasia (Zhao et al., 2022). Moreover, recent evidence suggests a spatial subtype of aphantasia (Palermo et al., 2022), and visual imagery often involves the adoption of a particular visuospatial perspective (Libby & Eibach, 2011). A first-person self-referential (i.e., egocentric) visuospatial perspective is thought to play an important role in the subjective experience of remembering, enabling one to project oneself into recollected scenes (Simons et al., 2022; Zaman & Russell, 2022). Aphantasics have previously been shown to score higher on autism traits that indicate difficulties with theory of mind (Dance et al., 2021), which may depend on the ability to adopt alternative visuospatial perspectives (Conson et al., 2015; Gauthier et al., 2018; Kessler & Wang, 2012), as well as report a less distinctive perspective during dreaming (Dawes et al., 2020) and ABM recall (Dawes et al., 2022). However, visuospatial perspective and its impact on the subjective experience of episodic remembering has yet to be experimentally investigated in aphantasics, despite subjective reports indicating reduced subjective memory reliving (Dawes et al., 2020, 2022).

The present study tested whether visual and spatial aspects of first-person (egocentric) episodic recall is impaired in people with aphantasia. A mixed design was employed in which aphantasic and non-aphantasic control participants completed a novel 3D object and spatial memory task that manipulated visuospatial perspective. In this task, participants first studied the location and colour hue of objects placed within familiar virtual environments, which were viewed from either a first-person or third-person perspective. Following a brief delay period, participants used continuous measures to precisely reproduce each object's remembered study location and colour hue, and to report the subjective vividness of their memory. Furthermore, recall perspective was varied such that it either remained unchanged

or was switched to the alternate perspective to test whether aphantasics are impaired at manipulating spatial representations, given the abovementioned inconclusive findings from mental rotation tasks (Pounder et al., 2022; Zeman et al., 2010; Zhao et al., 2022).

Accordingly, these manipulations resulted in the following four spatial memory conditions: stay first person (i.e., studied and tested in a first-person perspective), switch first person (i.e., studied in third person but tested in first person), stay third person (i.e., studied and tested in a third-person perspective), and switch third person (i.e., studied in first person but tested in third person). To maximise the number of trials available for mixture modelling, there were only two object memory conditions by comparison: study first person and study third person.

First-person spatial recall was predicted to be generally less accurate than third-person spatial recall, given prior findings (Iriye & St Jacques, 2021). Moreover, an asymmetric perspective switch cost was predicted (Ly & Hu, 2020), with switch third person trials being recalled less accurately than switch first person trials relative to the respective perspective stay trials. Despite benefitting spatial memory accuracy (Iriye & St. Jacques, 2021), third-person recall was predicted to be rated as less vivid in general than first-person recall (Nigro & Neisser, 1983; Rice & Rubin, 2009; Robinson & Swanson, 1993). Turning specifically to the aphantasics, the limited previous literature means that our predictions were more speculative. However, the subjective vividness of recall was predicted to be rated lower overall when compared against controls, as is commonly reported (Dawes et al., 2020, 2022; Milton et al., 2021; Zeman et al., 2020).). Based on the importance of a first-person visuospatial perspective in subjective episodic memory experience (Simons et al., 2022; Zaman & Russell, 2022), first-person (egocentric) spatial memory performance was predicted to be lower in aphantasics relative to controls. In contrast, third-person spatial memory was predicted to be relatively unimpaired in aphantasics (Bainbridge et al., 2021). Finally, aphantasics were predicted to have generally worse object memory performance than controls based on the previously observed deficits in object imagery (Dawes et al., 2020) and object memory (Bainbridge et al., 2021), albeit with potentially greater deficits in the first-person condition.

Materials & Methods

Participants

Participants were assigned to the aphantasic or non-aphantasic control group based on their score on the VVIQ, which is a widely used non-clinical self-report measure that assesses how vividly participants can visualise different scenarios involving people and scenes. The

VVIQ shows high reliability and construct validity across different versions (Campos & Pérez-Fabello, 2009; McKelvie, 1995). As there is currently no consensus on the appropriate cut-off score to identify aphantasia, a VVIQ score ≤ 32 was used for the aphantasic sample in the present study (see Figure 1 for histogram of VVIQ scores in both imagery groups). While more conservative thresholds have been used in some previous studies (e.g., ≤ 25 in Bainbridge et al., 2021), a cut-off score of 32 nonetheless corresponds to very weak visual mental imagery across all questionnaire items and corresponds to the threshold used in an influential questionnaire-based cognitive characterisation of aphantasia (Dawes et al., 2020)

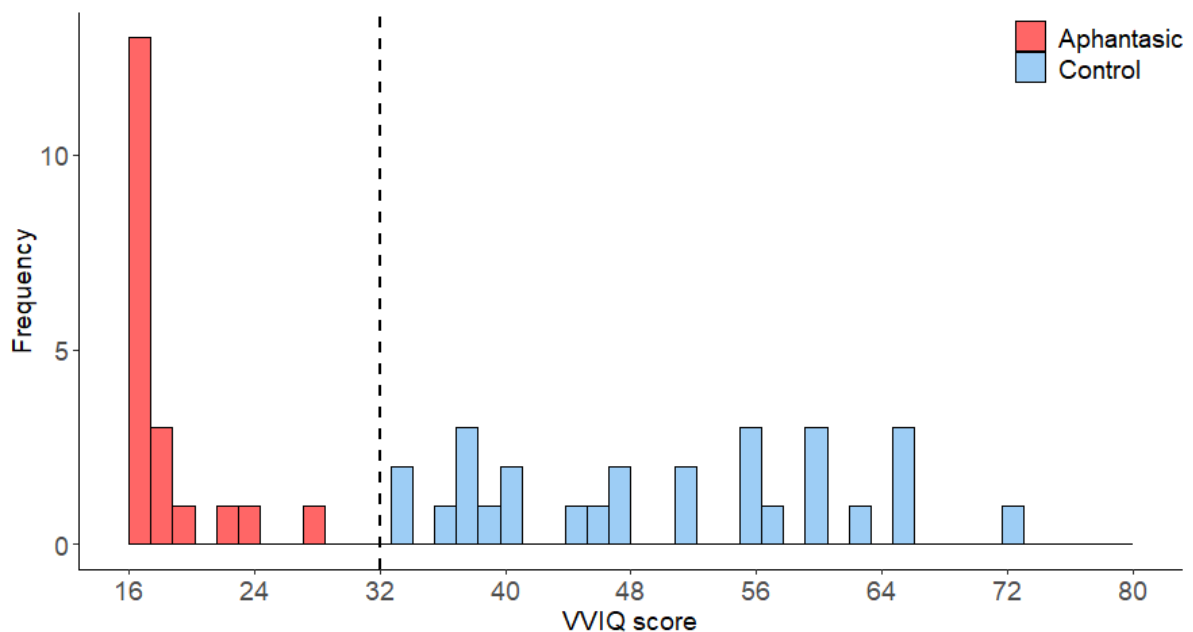


Figure 1. Histogram of VVIQ scores for aphantasic and control groups. The dotted vertical line indicates the *a priori* VVIQ cut-off score of 32 used to define aphantasia in this study.

Aphantasics. 20 congenitally aphantasic individuals (35% male) with a mean VVIQ score of 17.70 (SD = 3.18, range = 16 – 28), mean age of 26.70 (SD = 5.01, range = 18 – 35), and an undergraduate median education level were included in the analyses. The self-reported imagery experience of the current aphantasics closely aligned with that documented in large sample surveys of the condition (Dawes et al., 2020; Zeman et al., 2020). Furthermore, the majority of aphantasic participants ($n = 13$) reported a complete absence of visual mental imagery (VVIQ = 16). An additional eight aphantasic participants were tested but excluded due to study non-completion, excessive anticipatory responses, or below chance mean performance in the object or spatial components of the memory task, averaged across conditions. Aphantasic participants were recruited from various online aphantasic communities on Reddit and Facebook.

Controls. 27 non-aphantasic individuals (44% male) with a mean VVIQ score of 51.37 (SD = 11.20, range = 34 – 72), mean age of 27.73 (SD = 5.60, range = 20 – 35), and an undergraduate median education level were included in the analyses. No control participants had VVIQ scores indicating extreme imagery ability/experience, referred to as hyperphantasia (VVIQ \geq 75; Zeman et al., 2015, 2020). A further 17 control participants were tested but excluded from analysis due to early withdrawal from the study, excessive anticipatory responses, or below chance mean performance across conditions in either component of the memory task. All control participants were recruited from the online testing platform Prolific (<https://www.prolific.co/>).

All participants reported native-like English proficiency, had normal or corrected-to-normal colour vision, and confirmed they had no current or historical diagnoses of developmental, psychiatric, or neurological conditions. Participants gave informed consent prior to testing and were remunerated in a manner approved by the University of Cambridge Psychology Research Ethics Committee. Given the limited prior literature on episodic memory in aphantasia, it is difficult to estimate a priori the appropriate sample size to ensure adequate experimental power. Nevertheless, the samples collected in this study are comparable in size to those of many other task-based studies of aphantasia more generally (e.g., Keogh et al., 2021; Keogh & Pearson, 2018; Pounder et al., 2022). The proportion of participants excluded for below chance performance was similar in both groups ($n = 2/8$ excluded aphantasics and $n = 4/17$ excluded controls).

Stimuli

Stimuli were 80 targets comprising everyday objects and 40 external landmarks consisting of natural and artificial environmental features. All target object stimuli were 256 x 256 pixels whereas the landmark stimuli were 512 pixels high but had varying widths (M = 526, SD = 244.8, range = 167 – 1134). Both target object and landmark stimuli were presented as view plane-aligned 2D sprites to equate the amount of perceptual information available across both perspective conditions. The landmark stimuli were obtained from various internet sources whereas the target stimuli were a subset of object images used by Brady et al. (2013). While the landmark stimuli were naturalistically coloured, target stimuli were colour-rotated in 360° CIELAB perceptually uniform colour space (International Organization for Standardization, 2019) to randomly vary their hue during the study and test phases (see Figure 2 for an example of a colour-rotated target object stimulus). The CIELAB colour space is well suited for continuous manipulations of colour as a given distance

between two colours in this space approximates their perceptual colour distance. This property of the CIELAB colour space has previously been leveraged to investigate the fidelity of both working memory retrieval (Bays et al., 2009; Zhang & Luck, 2008; Panichello et al., 2019) and long-term memory retrieval (Brady et al., 2013; Korkki et al., 2020, 2023; Richter et al., 2016). To minimise potential biases in colour memory, only objects without specific colour associations were selected for use as target stimuli in this study.

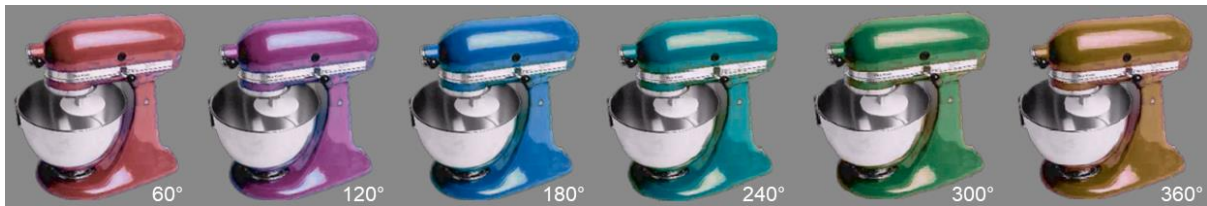


Figure 2. An example target object stimulus, colour-rotated in 60° increments. Note that colour hue was allowed to vary continuously during the actual experiment.

Virtual environment

Participants studied both object feature types and subsequently had their spatial memory tested within a 3D virtual circular environment 50 virtual meters (vm) in diameter with a solid light grey floor and bounded by a 4vm high solid dark grey wall. These dimensions are comparable to those employed in similar object location memory tasks (e.g., Bellmund et al., 2020). Four equally spaced distal landmarks were placed 5vm beyond the boundary wall at each cardinal direction. Landmark sets persisted for the duration of each testing block, serving as both locational memory aids and stable orientation cues. The sky, which was visible only in the first-person perspective, had a naturalistic blue gradient but was otherwise featureless. Participants viewed the environment in a standard 16:9 aspect ratio via first-person and third-person virtual cameras. The first-person camera had a fixed 60° field of view (FOV) and was oriented perpendicular to the ground at a fixed height of 1.5vm to approximate an average person's eye level. In contrast, the third-person camera had a variable FOV (10 – 75°) that functioned as a variable zoom and was angled 90° down toward the ground at a fixed height of 55vm to give a bird's eye view of the environment. The virtual environment was created using the Unity game engine (v2019.4.19f1; Epic Games, 2019).

Procedure

In a mixed design, aphantasic and control participants completed a novel computer-based 3D object and spatial memory task and two questionnaires relating to mental imagery

and memory experience. Both the memory task and questionnaires were completed in a single online testing session, and their order was counterbalanced across participants. The main task, which will first be briefly summarised, consisted of 10 testing blocks with each comprising an exploration, study, arithmetic, and test phase. In the exploration phase, participants familiarised themselves with the empty circular testing environment from both first-person and third-person perspectives. The testing environment changed with every block and was differentiated by four unique external landmarks placed in cardinal directions just beyond the boundary wall. Next, in the study phase, participants learned the colour and location (relative to the distal landmarks) of eight target objects. These target objects were presented in a sequence at random locations within the testing environment. Participants then solved self-paced simple arithmetic problems for a fixed 30s to prevent working memory rehearsal before finally beginning the test phase, during which they had to precisely reproduce the studied target object features (see Figure 3 for schematic illustration of the task).

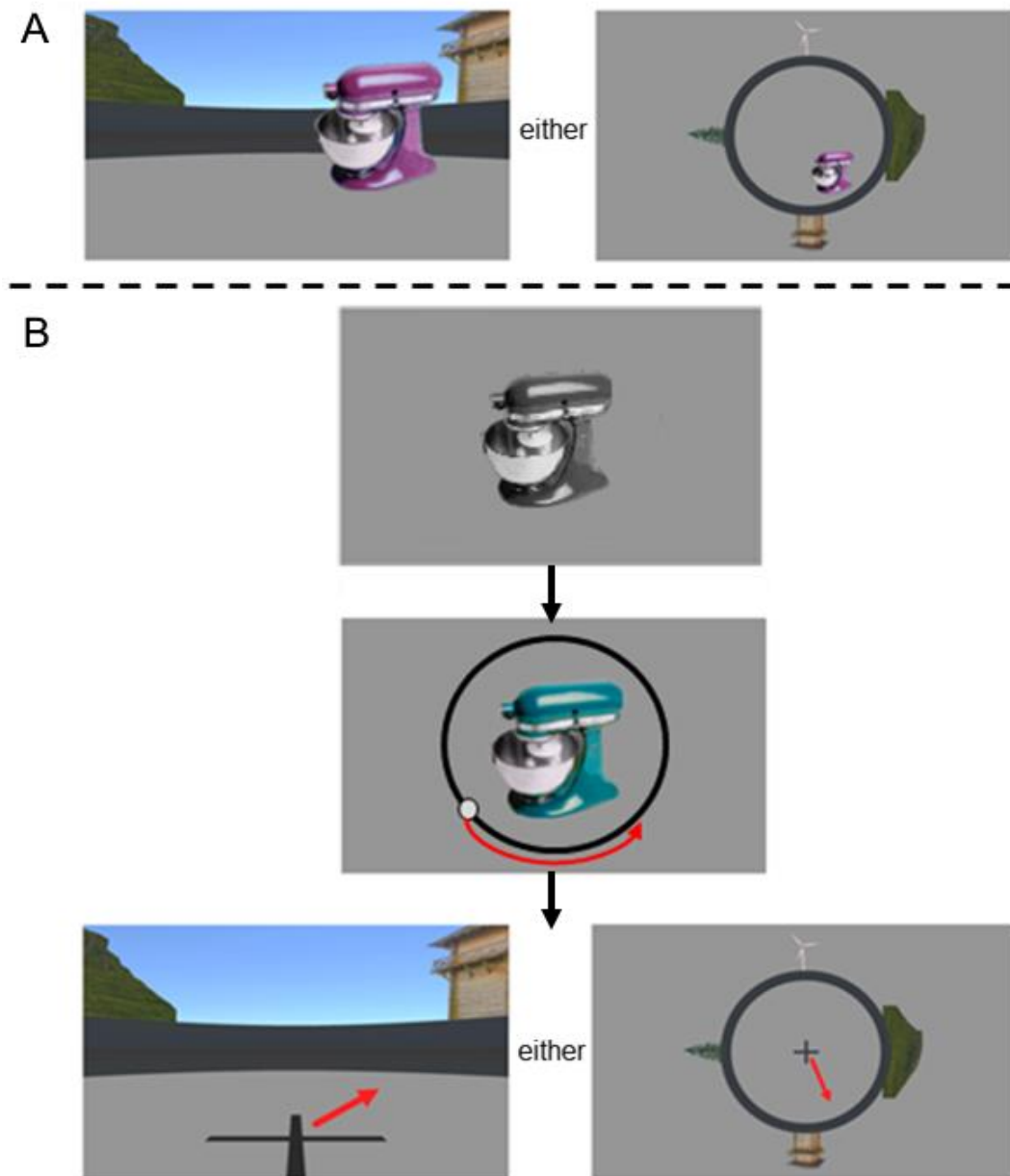


Figure 3. Schematic representation of a testing block in the object and spatial memory task.

Participants initially familiarised themselves with the testing environment during the exploration phase (not shown). A) Then, in the study phase, participants learned the colour and location of eight target objects. These target objects were presented in a series at random locations in the testing environment, which were viewed from either a first-person (left) or third-person (right) perspective. After the study phase, participants solved simple self-paced arithmetic problems for 30s (not shown). B) Finally, in the test phase, studied target objects were first cued in greyscale (top) before participants made subjective memory imagery vividness ratings on (not shown), then reproduced, their object (middle) and spatial memory features, the latter of which were tested in the same or alternative studied perspective (bottom left or right). Vividness ratings always preceded feature reproduction, but object and spatial memory assessment order randomly varied. Note that target object size has been increased for clarity in this figure.

Participants began each testing block by first exploring the virtual environment to increase immersion and gain familiarity with the distal landmarks, which were randomly varied each block. In this exploration phase, participants were initially placed at the centre of the testing environment with no target objects present, viewing it from either a first-person or third-person perspective (see Figure 1 for example). After 15s elapsed, participants were placed once again at the centre of the environment and viewed it for another 15s from the alternative perspective. Initially, the first-person camera faced a random direction whereas the third-person camera was placed at a height of 55vm with a 75° FOV so that all distal landmarks were fully visible. In both perspectives, participants pressed the ‘a’, ‘d’, ‘w’, and ‘s’ keyboard keys to move left, right, forward, and backward within the virtual environment with an acceleration of 0.3vm/second (s) and a maximum speed of 25vm/s. This permitted quick traversal of the environment while simultaneously allowing fine positional adjustments within the span of a trial. The virtual camera was coupled to the position of participants in both perspectives. When in first person, participants could move their computer mouse to laterally rotate the camera and their heading at 200 arbitrary units/s. In third person, moving the computer mouse adjusted camera FOV at 40 units/s to permit variable zoom of target and landmark objects. These values were multiplied by the interval (in s) between the previous and current frames to ensure consistent (i.e., framerate independent) timing across devices. These movement and camera controls were used in the exploration phase, study phase, and spatial memory feature reproduction component of the test phase.

Next, in the study phase, participants memorised the colour and location (relative to the distal landmarks) of eight target objects. Importantly, these distal landmarks aided locational memory and served as stable orientation cues when in first person. Target object colour hues randomly varied, and their locations were uniformly randomly distributed within the virtual environment but were constrained to within a 20vm radius to prevent visual occlusion by the boundary wall. The colour and location of each target object was memorised sequentially, yielding eight study trials per block. Study trials began with a central black fixation cross presented for 500ms against a grey background, followed by a fixed 10s period in which participants memorised both target object features. Participants began this period at the centre of the environment, which they viewed from either a first-person or third-person perspective. The studied perspective randomly varied across trials and in equal proportion. The first-person camera initially faced the target whereas the third-person camera was placed 55vm above the centre of the environment to equate the maximum amount of time available

to study a target location in both perspectives. Participants could then freely study the object features using the camera/movement controls for the given perspective condition.

After memorising the target locations, participants completed the arithmetic phase, which served as both a distractor task and attention check. The arithmetic phase lasted for 30s and involved solving simple addition and subtraction problems on positive double-digit integers. Arithmetic trials were self-paced until the fixed 30s timeout was reached, and each began with a 500ms central black fixation cross, followed by a randomly generated problem. Participants typed their answer, which was displayed on-screen, using the number keys on their keyboard. Mistakes could be deleted by pressing the 'backspace' key. Responses were submitted by pressing the 'space' key.

In the test phase, participants rated the vividness of, and reproduced, both the colour (i.e., object memory) and location (i.e., spatial memory) of the eight target objects studied earlier in the testing block. No unstudied objects were tested. This resulted in a total of 80 test trials in the main task. These trials were equally split across first person and third person perspective conditions in the object memory assessment (i.e., 40 target object colours were studied in first-person and 40 in third-person), which were further divided into perspective switch and stay conditions in the spatial memory assessment (i.e., 20 target object locations were studied and tested in first person, 20 were studied in third person but tested in first person, 20 were studied and tested in third person, and 20 were studied in first person but tested in third person). Furthermore, these conditions were pseudorandomly allocated to each test phase in equal proportions. All test trials began with the presentation of a black central fixation cross for 500ms. This was followed by the cueing of a studied object in greyscale for 1s., then the object and spatial memory feature assessments. Both types of feature assessment were separated by a 500ms-long black central fixation cross, and their order was randomised across trials. However, the subjective vividness of both memory features was assessed before objective feature reproduction. This was done to eliminate the influence of objective memory performance on subjective vividness ratings (Richter et al., 2016).

Object memory. The object memory assessment was adapted from the continuous report episodic memory task developed by Richter et al. (2016). First, participants rated the subjective vividness with which they could remember a cued target object's studied colour. To increase the likelihood that these task-based vividness ratings would tap the same construct of mental imagery as the VVIQ, the same language was used to define the ratings

scale. These ratings could span a continuum ranging from 0 (i.e., “no imagery at all” for colour) to 100 (i.e., colour imagery “as vivid as sight”) and were made using a horizontal response slider. Participants indicated the level of colour vividness by holding the ‘a’ or ‘d’ keyboard keys to move the slider left or right. Both the ratings slider and this scale remained on-screen until participants made a response by pressing the ‘space’ key or the 10s deadline was reached. Following the vividness rating, participants had up to 15 seconds to reproduce the studied colour hue of the cued target object as precisely as they could from memory. The target object remained on-screen during this period and was initially presented in a random hue that differed from its original. Participants adjusted the colour hue of the target object by holding the ‘a’ or ‘d’ keys to move a response slider that encircled the target clockwise or counterclockwise. As with the vividness rating, participants submitted their response by pressing the ‘space’ key.

Spatial memory. Participants first rated the subjective vividness with which they could remember a cued target object’s studied location within the greater scene. Like the object memory assessment, these ratings were made using the same continuous scale, response slider, and controls and within the same 10s response deadline. Likewise, participants then had up to 15s to precisely reproduce the target object’s studied location from memory. The testing environment in which these responses were made was viewed from either the same (i.e., perspective stay condition) or alternative (i.e., perspective switch condition) studied perspective of the target object. At the start of this period, participants were placed in the environment’s centre and faced a random direction when in first person whereas the camera was placed at fixed height facing down toward the ground when in third person. Viewpoint could be adjusted in both conditions by rotating the first-person camera left/right or zooming the third-person camera in/out using the computer mouse/trackpad. Using the movement/camera controls, participants moved a black crosshair, placed on the ground ahead of the first-person camera or centred under the third-person camera, to precisely indicate a given target object’s studied location. Responses were submitted by pressing the ‘space’ key.

Questionnaires

Measures of general mental imagery and memory experience were obtained for each participant using the VVIQ and the Survey of Autobiographical Memory (SAM; Palombo et al., 2013) self-report questionnaires, respectively. The VVIQ consists of 16 items to which participants rate their level of agreement with statements related to person and scene visual mental imagery. VVIQ items are rated using a 5-point Likert scale, with ratings of 1

corresponding to “no image at all, you only ‘know’ that you are thinking of the object” while ratings of 5 correspond to imagery “perfectly clear and as vivid as normal vision”. VVIQ scores range from 16 to 80. The SAM has 26 items and measures agreement level with statements related to various memory abilities. Like the VVIQ, SAM items are rated using a 5-point scale, with a score of 1 corresponding to “strongly disagree” while a score of 5 corresponds to “strongly agree”. The total SAM score, as well as separate scores for the episodic, semantic, spatial, and future subcomponents, were derived from item-specific weights for each response using materials provided by the questionnaire’s creators.

Task measures and analysis

The main analysis was performed on mean object and spatial memory performance and their corresponding imagery vividness ratings. Median response time (RT) was also examined for both task components. Raw object memory errors were quantified as the absolute angular deviation between a given target object’s studied colour hue and the hue reproduced by a participant during the test phase (range = 0-180°). Raw spatial memory errors reflected the Euclidean distance between a given target object’s studied location in the virtual environment and the location indicated by a participant during the test phase. Trials in which no responses were given or a response was given within 500ms were excluded from analysis (5% of all trials in control participants and 6% of all trials in aphantasic participants in the present study).

Raw errors on continuous report tasks like the one used here to probe object memory are thought to reflect both the overall success and varying precision of episodic memory retrieval, properties that have been separated behaviourally (Harlow & Yonelinas, 2016) and neurally (Richter et al., 2016) using probabilistic mixture modelling (Bays et al., 2009; Zhang & Luck, 2008). Given that a measure of the fidelity or precision of object memory retrieval rather than its overall success is more likely to be sensitive to visual imagery-based memory deficits than alternative verbal or symbolic strategies, probabilistic mixture models were fitted to the raw object memory errors for each task condition and in each participant. These mixture models had two components: a von Mises circular normal distribution centred at a mean raw error of 0°, with a concentration parameter Kappa (K), and a circular uniform distribution representing the probability of random guesses (pU). Retrieval success (pT) was calculated as the probability of responses emanating from the von Mises distribution versus the uniform distribution ($pT = 1 - pU$), whereas retrieval precision (K) was the concentration of the von Mises distribution. pT ranged from 0 (i.e., complete retrieval failure) to 1 (i.e.,

complete retrieval success), with 0.5 reflecting random guesses. By contrast, *K* had a minimum value of 0, reflecting a perfectly uniform response distribution, with increasing values indicating increasing levels of object memory retrieval precision.

As target object locations studied closer to the virtual environment's boundary have a larger maximum possible spatial memory error than those studied in its centre, a correction is needed to account for varying difficulty across different target locations. This was achieved by computing the accuracy percentile of a given response relative to all other possible responses as a memory score (MS) (Jacobs et al., 2016). Each MS was computed by first generating 10,000 possible response locations uniformly distributed throughout the environment. Next, the distance between each possible response location and a given target location was calculated, yielding trial-specific error distributions. Finally, the proportion of possible response errors less than the actual response error was calculated for each target, resulting in a MS ranging from 0 to 1. A MS of 1 corresponds to perfect performance, a score of 0.5 to chance level performance, and a score 0 to the worst possible performance (i.e., the furthest possible location from a true target location).

All analyses were conducted using R Statistical Software (v4.1.2; R Foundation for Statistical Computing, Vienna, Austria). Linear mixed models were run on mean object and spatial memory vividness ratings and performance measures using the 'lme4' package (Bates et al., 2015). All models were fitted via restricted maximum likelihood parameter estimation and all models included the between-subjects fixed factor of *imagery group* (controls, aphantasics). However, these models differed in their number of within-subjects fixed factors. The object memory model had a single within-subjects fixed factor of *study perspective* (first person, third person), representing the perspective in which a given object feature was studied and tested. As visuospatial perspective was additionally manipulated in the spatial memory component of the task during the test phase, the corresponding model had two within-subjects fixed factors of *switch status* (stay, switch) and *test perspective* (first person, third person). These fixed factors were represented using effects coding as their interactions were of chief concern (Singmann & Kellen, 2019). Under this scheme, fixed factor coefficients indicate the deviation of each factor level from the grand mean, represented by the intercept. Finally, all models accounted for repeated measures by including a by-subject random intercept (Barr, 2013; Barr et al., 2013). The general form of the object (1) and spatial (2) memory models are provided below in lme4 syntax:

object ~ imageryGroup * studyPerspective + (1 | subject) (1)

spatial ~ imageryGroup * switchStatus * testPerspective + (1 | subject) (2)

Model assumptions were evaluated by inspecting standard diagnostic residual plots. Outliers were detected using the interquartile range method (i.e., values greater than 1.5x the interquartile range). The influence of outliers, where present, was checked by re-running analyses without the subjects who contributed them. *P*-values for the fixed effects were calculated using Satterthwaite degrees of freedom approximation (Satterthwaite, 1941), implemented in the ‘lmerTest’ package (Kuznetsova et al., 2017). Significant interactions were followed up on with simple contrasts on the estimated marginal means using the “modelbased” package (Makowski et al., 2020). All tests were two-sided and used a canonical alpha level of 0.05. Exact *p*-values are reported to three decimal places (unless $p < 0.001$).

Results

Demographics and questionnaires

Demographics. Due to unequal sample sizes, a Welch’s two-sample *t*-test assuming unequal between-group variances was conducted on age and found no significant difference between aphantasic and non-aphantasic participants ($t(42.94) = 0.66, p = .51$). These groups did not significantly differ in the proportion of males and females as determined by a Fisher’s exact test of independence on the sex count data ($p = .55, Fisher’s exact test$). A Mann-Whitney U test was performed on formal education level and similarly found no significant between-group difference ($W = 304, p = .30$). Together, these results indicate aphantasic and control groups were matched on all demographic variables (see Table 1 for descriptive statistics).

Table 1. Mean (SD in brackets) participant demographic and questionnaire data.

Variable	Controls (<i>n</i> = 27)	Aphantasics (<i>n</i> = 20)	<i>p</i> -value
Age	27.73 (5.60)	26.70 (5.01)	0.514 ^a
Sex	12 male, 15 female	7 male, 13 female	0.551 ^b
Education	undergraduate	undergraduate	0.295 ^c
VVIQ	51.37 (11.20)	17.70 (3.18)	< 0.001 ^a
SAM	93.83 (12.28)	84.90 (12.71)	0.020 ^a
Episodic	99.62 (13.75)	86.69 (13.01)	0.002 ^a
Semantic	95.12 (13.70)	97.45 (17.90)	0.630 ^a
Spatial	90.70 (18.08)	87.49 (18.56)	0.557 ^a
Future	90.81 (10.75)	79.43 (2.33)	< 0.001 ^a

Note. VVIQ = Vividness of Visual Imagery Questionnaire, SAM = Survey of Autobiographical Memory. The median education level is reported.

a Tested using a two-sided Welch's two-sample *t*-test.

b Tested using a two-sided Fisher's exact test of independence.

c Tested using a two-sided Mann-Whitney U test.

Questionnaires. Welch's two-sample *t*-tests assuming unequal between-group variances were performed on the VVIQ, SAM composite, and SAM component scores (see Table 1). On the VVIQ, aphantasic participants reported significantly less vivid visual mental imagery than controls ($t(31.46) = 14.83, p < 0.001$). Aphantasic participants also reported significantly worse overall memory ability than controls, as measured by the SAM composite score ($t(40.29) = 2.42, p = 0.020$). Consistent with a selective deficit in episodic cognition, however, aphantasics reported significantly lower ability in episodic memory ($t(42.27) = 3.29, p = 0.002$) and future event prospection ($t(29.25) = 5.33, p < 0.001$), but not in semantic memory ($t(34.34) = -0.49, p = 0.630$) or spatial memory ($t(40.48) = 0.59, p = 0.557$).

Object memory

Vividness. As predicted for the model on object memory vividness (Figure 4A), there was a significant main effect of *imagery group* ($\beta = 14.07, SE = 3.58, t(45) = 3.93, p < .001$), where aphantasic participants rated their object memory vividness lower than controls (see Table 2 for descriptive statistics). There was no significant main effect of *study perspective* ($\beta = 0.39, SE = 0.36, t(45) = 1.08, p = .29$) or a significant *imagery group* x *study perspective* interaction ($\beta = -0.10, SE = 0.36, t(45) = -0.28, p = .78$). No outliers were detected in these data. For descriptive statistics of the vividness ratings and performance measures on the object memory component of task, see Table 2 below.

Table 2. Mean (SD in brackets) object memory vividness and performance measures.

Condition	Controls				Aphantasics			
	Vividness	pT	K	RT	Vividness	pT	K	RT
First person	62.89 (15.30)	0.81 (0.13)	11.09 (7.70)	4.72 (1.13)	34.95 (32.94)	0.83 (0.15)	11.25 (5.14)	5.00 (1.37)
Third person	62.31 (15.68)	0.82 (0.13)	8.11 (5.19)	5.01 (1.32)	33.98 (32.80)	0.80 (0.21)	8.73 (4.55)	5.38 (1.36)

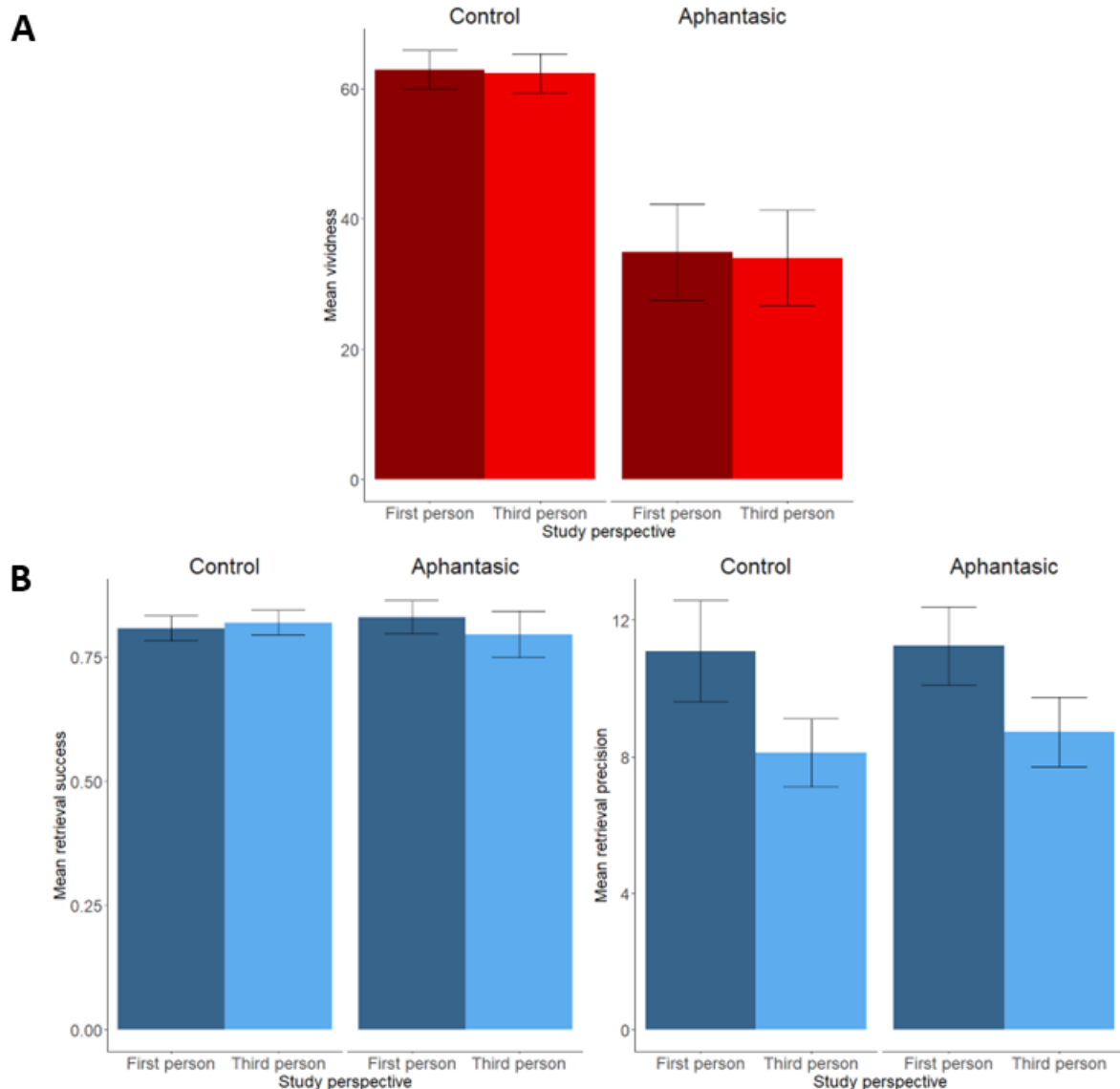


Figure 4. Mean object memory vividness ratings (A) and retrieval success (B, left) and precision (B, right) measures across imagery groups and task perspective conditions. Error bars denote SEM.

Retrieval success. In the model on object memory retrieval success (see Figure 5B, left), there were no significant main effects of *imagery group* ($\beta < 0.01$, $SE = 0.02$, $t(45) = 0.02$, $p = .98$) or *study perspective* ($\beta < 0.01$, $SE < 0.01$, $t(45) = 0.62$, $p = .54$). Likewise, there

was no significant *imagery group* x *study perspective* interaction ($\beta < -0.01$, $SE < 0.01$, $t(45) = -1.20$, $p = .23$). One outlier participant was detected, but their exclusion did not influence the results.

Retrieval precision. Contrary to our prediction, the model on object memory precision (see Figure 3B, right) revealed no significant main effect of *imagery group* ($\beta = -0.20$, $SE = 0.76$, $t(45) = -0.26$, $p = .80$). However, there was a significant main effect of *study perspective* ($\beta = 1.38$, $SE = 0.42$, $t(45) = 3.24$, $p = .002$), where object memory was generally recalled with higher fidelity when studied in a first-person versus a third-person perspective (see Table 2). There was no significant *imagery group* x *study perspective* interaction ($\beta = 0.12$, $SE = 0.42$, $t(45) = 0.27$, $p = .79$). Excluding outlier participants ($n = 5$) did not affect the results.

Raw error. For completeness, raw object memory errors, which were not derived from mixture modelling, were also analysed. Mirroring the analyses of *pT* and *K*, there was a significant main effect of *study perspective* ($\beta = -1.72$, $SE = 0.63$, $t(45) = -2.71$, $p = .010$), but no significant main effect of *imagery group* ($\beta = 1.12$, $SE = 1.71$, $t(45) = 0.66$, $p = .52$) or a significant *imagery group* x *study perspective* interaction ($\beta = 0.645$, $SE = 0.63$, $t(45) = 1.02$, $p = 0.31$), suggesting the lack of group differences in object memory retrieval success and precision were unlikely to be attributable to the modelling approach used to derive those measures. One outlier participant was excluded, but the results did not change.

Response time. Finally, the model on object memory RTs (see Table 2) showed no significant main effect of *imagery group* ($\beta = -0.16$, $SE = 0.19$, $t(45) = -0.88$, $p = .39$), but there was a significant main effect of *study perspective* ($\beta = -0.16$, $SE = 0.04$, $t(45) = -4.19$, $p < .001$). The *imagery group* x *study perspective* interaction was not significant ($\beta = 0.02$, $SE = 0.04$, $t(45) = 0.59$, $p = .56$). Two outlier participants were detected, but their removal did not change the results.

Spatial memory

Vividness. As in the object memory analysis, the model on spatial memory vividness (see Figure 4A) revealed a significant main effect of *imagery group* ($\beta = 12.93$, $SE = 3.24$, $t(45) = 3.99$, $p < .001$), where aphantasic participants rated their spatial memory vividness lower than controls. There were no significant main effects of *switch status* ($\beta = -0.37$, $SE = 0.49$, $t(135) = -0.76$, $p = .45$) or *test perspective* ($\beta = 0.06$, $SE = 0.49$, $t(135) = 0.13$, $p = .90$). There was, however, a significant *switch status* x *test perspective* interaction ($\beta = -1.55$, $SE =$

0.49, $t(135) = -3.18$, $p = .002$), but no significant *imagery group* x *switch status* ($\beta = 0.35$, $SE = 0.49$, $t(135) = 0.71$, $p = .48$) or *imagery group* x *test perspective* ($\beta = -0.04$, $SE = 0.49$, $t(135) = -0.09$, $p = .93$) interactions. Finally, the *imagery group* x *switch status* x *test perspective* interaction was significant ($\beta = -1.28$, $SE = 0.49$, $t(135) = -2.63$, $p = .010$). Excluding outlier participants ($n = 3$) did not change the pattern of results. See Table 3 below for descriptive statistics of all spatial memory measures.

Table 3. Mean (SD in brackets) spatial memory vividness and performance measures.

Condition	Controls			Aphantasics		
	Vividness	MS	RT	Vividness	MS	RT
First person						
Stay	47.86 (15.63)	0.75 (0.09)	5.31 (1.51)	25.44 (27.18)	0.77 (0.11)	5.03 (1.60)
Switch	52.50 (18.91)	0.78 (0.13)	5.53 (1.72)	28.10 (29.53)	0.81 (0.11)	5.16 (1.76)
Third person						
Stay	52.65 (19.64)	0.85 (0.10)	4.06 (1.79)	26.26 (27.92)	0.85 (0.12)	3.64 (1.46)
Switch	47.29 (16.32)	0.76 (0.09)	4.16 (1.88)	26.83 (27.20)	0.78 (0.11)	3.64 (1.30)

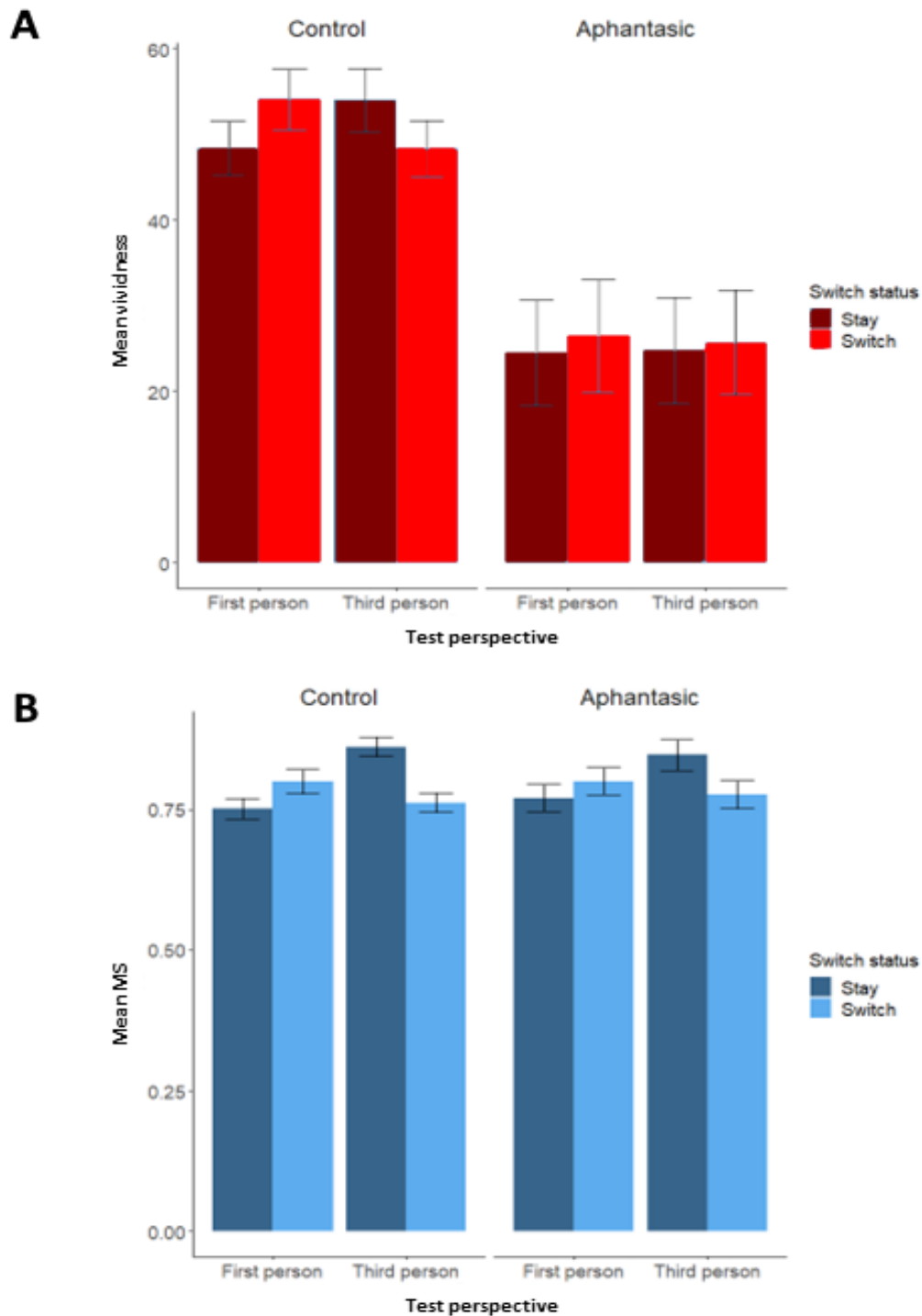


Figure 5. Mean spatial memory vividness ratings (A) and MS (B) across imager groups and switch status and test perspective task conditions. Error bars denote SEM.

To decompose the significant three-way interaction in the analysis of spatial memory vividness, the simple effects of *imagery group*, conditioned on *switch status* x *test perspective*, were initially investigated. Relative to the aphantasic participants, control participants had significantly higher vividness ratings in both stay first person ($\beta = 30.30$, *SE*

= 6.72, $t(46) = 4.50$, $p < .001$) and switch first person ($\beta = 34.90$, $SE = 6.72$, $t(46) = 5.19$, $p < .001$) trials. Likewise, control participants rated their vividness significantly higher than aphantasics in both stay third person trials ($\beta = 34.70$, $SE = 6.72$, $t(46) = 5.16$, $p < .001$) and switch third person trials ($\beta = 28.9$, $SE = 6.72$, $t(46) = 45.80$, $p < .001$).

The simple effects of *test perspective*, conditioned on *imagery group* and *switch status*, were then examined. Stay first person vividness ratings were significantly lower than stay third person vividness ratings in control participants ($\beta = -5.63$, $SE = 1.88$, $t(114) = -2.99$, $p = .003$) but not aphantasic participants ($\beta = -1.20$, $SE = 2.71$, $t(114) = -0.44$, $p = .66$). In comparison, switch first person vividness ratings were significantly higher than switch third person vividness ratings in control participants ($\beta = 5.71$, $SE = 1.88$, $t(114) = 3.03$, $p = .003$) but not aphantasic participants ($\beta = -0.26$, $SE = 2.71$, $t(114) = -0.10$, $p = .92$).

Finally, the simple effects of *switch status*, conditioned on *imagery group* and *test perspective*. Vividness ratings in stay first person trials were significantly lower than in switch first person trials in control participants ($\beta = -5.71$, $SE = 1.88$, $t(114) = -3.04$, $p < .003$), whereas this difference was not significant in aphantasic participants ($\beta = -11.11$, $SE = 2.71$, $t(114) = -0.410$, $p = .68$). In contrast, stay third person vividness ratings were significantly higher than switch third person vividness ratings in control participants ($\beta = 5.62$, $SE = 1.88$, $t(114) = 2.99$, $p = .003$) but not in aphantasic participants ($\beta = -0.17$, $SE = 2.71$, $t(114) = -0.06$, $p = .95$). Considering the results of the simple effects analyses together, a crossover interaction is apparent in the control group but not the aphantasic group. More specifically, spatial memory vividness is higher in those with typical imagery when object locations are studied in third person versus first person, irrespective of the test perspective. On the other hand, those with atypical imagery have lower spatial memory vividness in general.

Memory score. The model on spatial memory score (see Figure 4B) revealed significant main effects of *switch status* ($\beta = 0.01$, $SE < 0.01$, $t(135) = -3.13$, $p = .024$) and *test perspective* ($\beta = -0.02$, $SE < 0.01$, $t(135) = -3.13$, $p = .002$), but not *imagery group* ($\beta < -0.01$, $SE = 0.01$, $t(45) = -0.20$, $p = .85$). There was a significant *switch status* x *test perspective* interaction ($\beta = -0.03$, $SE < 0.01$, $t(135) = -6.19$, $p < .001$) but not *imagery group* x *switch status* ($\beta < 0.01$, $SE < 0.01$, $t(135) = 0.28$, $p = .78$) or *imagery group* x *test perspective* ($\beta < -0.01$, $SE < 0.01$, $t(135) = -0.49$, $p = .62$). The *imagery group* x *switch status*

x test perspective interaction was not significant ($\beta < 0.01$, $SE < 0.01$, $t(135) = -1.18$, $p = .24$). Excluding outlier participants ($n = 2$) did not influence the results.

The significant *switch status x test perspective* interaction in the analysis of spatial memory score was decomposed by examining the simple effects of *test perspective*, conditioned on *switch status*, and averaged over *imagery group*. As predicted, stay first person MS was significantly lower than stay third person MS ($\beta = -0.09$, $SE = 0.01$, $t(135) = -6.59$, $p < .001$), suggesting that spatial memory accuracy is generally less accurate when studied and tested in first person versus third person. In comparison, however, switch first person MS was significantly higher than switch third person MS ($\beta = 0.03$, $SE = 0.01$, $t(135) = 2.16$, $p = .032$). Together, these results indicate that a third person perspective, whether encoded as such or adopted during subsequent retrieval, enhances spatial memory accuracy.

Response time. Lastly, in the model on spatial memory RTs (see Table 3), the main effect of *imagery group* was not significant ($\beta = 0.26$, $SE = 0.22$, $t(45) = 1.21$, $p = .23$) but the main effect of *test perspective* was ($\beta = 0.73$, $SE = 0.05$, $t(135) = 13.50$, $p < .001$). There was no significant main effect of *switch status* ($\beta = -0.07$, $SE = 0.05$, $t(135) = -1.21$, $p = .23$), nor were there significant interactions of *switch status x test perspective* ($\beta = -0.4$, $SE = 0.05$, $t(135) = -0.74$, $p = .46$), *imagery group x switch status* ($\beta = -0.02$, $SE = 0.05$, $t(135) = -0.37$, $p = .71$), *imagery group x test perspective* ($\beta = -0.02$, $SE = 0.05$, $t(135) = -0.37$, $p = .71$), or *imagery group x switch status x test perspective* ($\beta = -0.02$, $SE = 0.05$, $t(135) = -0.38$, $p = .71$). Three outlier participants were detected, but their exclusion did not affect the results.

Effects of total aphantasia on task performance

The aphantasic sample in the present study had a mean VVIQ score of 17.70, which is in line with other studies (e.g., Pounder et al., 2022). However, $n = 7$ of these aphantasic participants had VVIQ scores indicating a limited degree of mental imagery experience (range = 16 – 28), which might have reduced potential group differences in the object and spatial memory task. To explore this possibility, the main analysis was re-run to include only those reporting a complete absence of mental imagery (i.e., total aphantasia) in the aphantasic group ($n = 13$). The overall pattern of results did not change as there were no significant main effects or interactions involving imagery group on any of the object or spatial memory performance measures (all $ps \geq .19$). Furthermore, there were no significant main effects or interactions involving imagery group in the re-analysis of object memory RT (all $ps \geq .23$), although a significant *imagery group x test perspective* interaction was revealed in the re-

analysis of spatial memory RT ($\beta = 0.12$, $SE = 0.06$, $t(114) = 2.0$, $p = .048$). This interaction was decomposed by examining the simple effects of *test perspective*, conditioned on *imagery group*, and averaged over *switch status*. No significant group differences emerged for spatial memory RT under the first person ($\beta = 0.75$, $SE = 0.54$, $t(41.7) = 1.39$, $p = .171$) and third person ($\beta = 0.29$, $SE = 0.54$, $t(41.7) = 0.54$, $p = .594$) test conditions. However, it should be cautioned that these null results may simply reflect a power issue due to the small size of the subgroup reporting total aphantasia.

Relationship between subjective and objective memory measures

As indicated by the apparent inconsistency between task-based subjective vividness ratings and objective performance in the aphantasic participants, some or all of those individuals might have a deficit in meta-cognitive awareness of mental imagery rather than in imagery itself (Pounder et al., 2022). To explore this possibility in the present data, correlations were run within groups on the memory task vividness ratings and performance measures to see whether their assumed relationship in control participants is reduced or absent in aphantasic participants. These analyses were run in R using the ‘psych’ package (Revelle, 2023). The number of tests was reduced by averaging across task conditions to obtain single measures of object and spatial memory vividness and performance. As the pattern of results in the main analysis of the object memory component of the task did not depend on the measure used (i.e., raw error, retrieval success, or retrieval precision), object memory performance was quantified here with the raw errors to further reduce the number of tests. By contrast, spatial memory performance remained characterised by MS.

First, the correlation between vividness ratings and performance in the memory task was examined. Rank-based Kendall correlations, which account for floor effects in the aphantasic vividness ratings, were run in both participant groups to ensure they were treated equally. In the control participants, the correlation between memory vividness and performance was significant and in the expected direction for both object memory ($\tau_b = -0.54$, $p < .001$; see Figure 6, top left) and spatial memory ($\tau_b = 0.28$, $p = .040$; see Figure 5, bottom left). In the aphantasic participants, this correlation was not significant for object memory ($\tau_b = -0.09$, $p = .58$; see Figure 5, top right) or spatial memory ($\tau_b = 0.26$, $p = .11$; see Figure 6, bottom right). These relationships were then compared between groups. Kendall’s formula was used to convert each tau value to a Pearson’s r correlation coefficient (Walker, 2003) before submitting their group difference, paired according to task component, to a Fisher z -transformation.

Relative to the aphantasic participants, control participants exhibited a significantly higher correlation between vividness ratings and memory performance in the object memory component of the task ($z = 2.65, p = 0.010$), but not in the spatial memory task component ($z = 0.13, p = 0.90$).

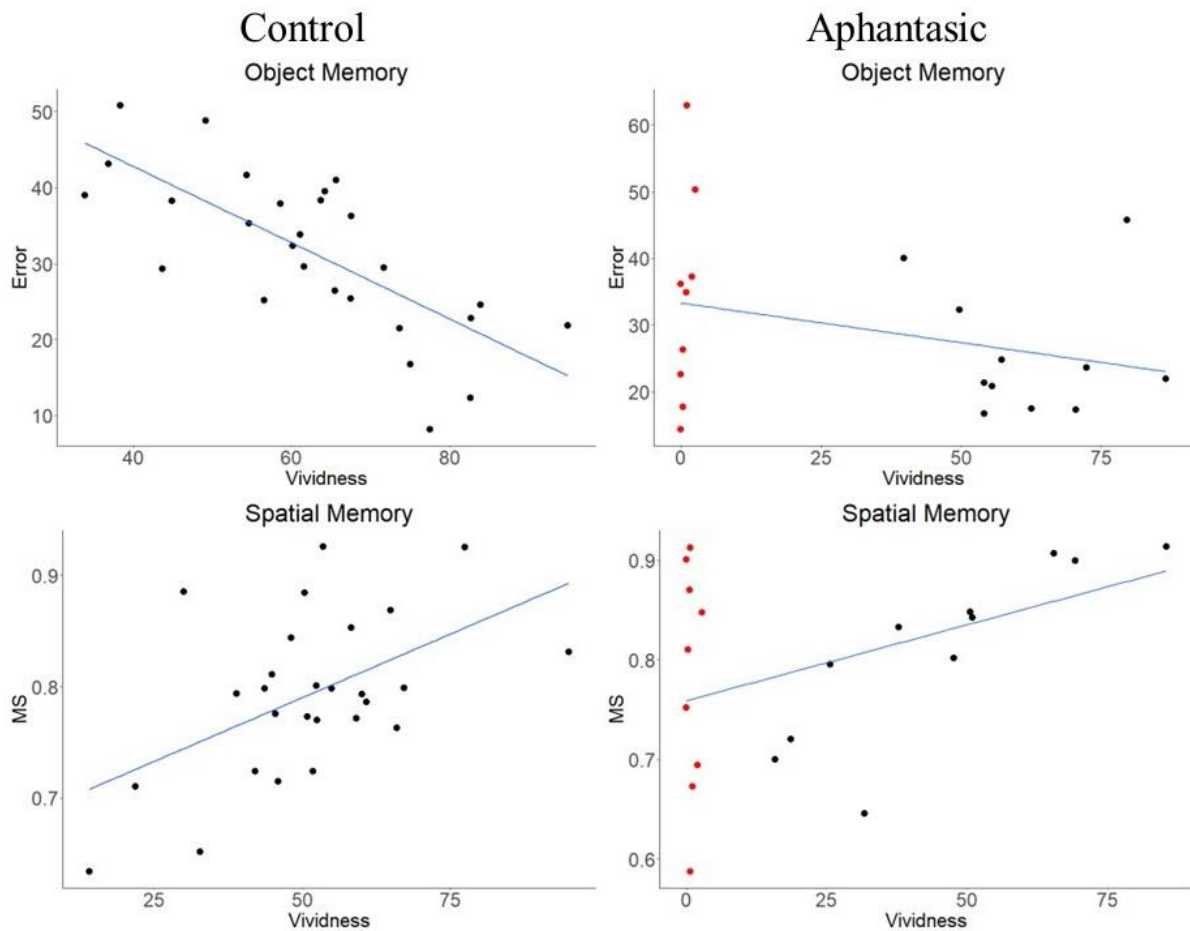


Figure 6. Plots showing the relationship between mean vividness ratings and performance for object (top) and spatial (bottom) memory features in control (left) and aphantasic participants (right). Red-highlighted datapoints denote the subgroup of aphantasic participants who rated their task-based memory vividness at floor.

As the correlations between overall object and spatial memory vividness ratings and performance were significant in the control participants (see Figure 6, left), these relationships were further broken down in this group by visuospatial perspective. Given the spread of task-based vividness ratings in the control participants, standard Pearson correlations were run in this exploratory analysis. These relationships were significant for object features studied both in first person ($r(25) = -0.79, p < .001$) and in third person ($r(25) = -0.60, p = .001$). All but the stay first-person condition of the spatial memory component of the task were significant (stay

first person: $r(25) = 0.25, p = .20$; switch first person: $r(25) = 0.64, p < .001$; stay third person $r(25) = 0.57, p = .002$; switch third person: $r(25) = 0.60, p = .001$).

Finally, two distinct clusters were evident in the aphantasic correlation plots (see Figure 6, right), with one subgroup ($n = 9$) rating their memory vividness at floor (vividness < 10) despite wide ranging performance and another subgroup ($n = 11$) rating their memory vividness and performance ostensibly more in line with controls. Additionally, it should be noted that those who rated their memory vividness for object features at floor did so too for spatial features. Accordingly, further exploratory Kendall's rank correlations were run in the latter aphantasic subgroup, which remained non-significant for object memory ($\tau_b = -0.09, p = .80$), but became significant for spatial memory ($\tau_b = 0.78, p < .005$).

Discussion

This study investigated objective and subjective aspects of episodic recall in people with aphantasia. To this end, a novel 3D object and spatial memory task manipulating visuospatial perspective was employed to assess visual and spatial imagery abilities in self-identified aphantasics and their influence on subjective and objective measures of episodic memory. Aphantasic participants showed no objective deficits in object or spatial memory performance in either perspective condition, despite rating the subjective vividness of both memory features lower than control participants. Furthermore, aphantasic participants did not differ from controls in their ability to manipulate visuospatial representations as indicated by the comparable levels of switch versus stay trial performance in both groups. The overall pattern of results did not change following an exploratory re-analysis restricting the aphantasic group to individuals reporting a complete lack of mental imagery (i.e., total aphantasia), although an RT difference emerged in the spatial memory task. Further exploratory correlation analysis revealed a significant relationship between objective task performance and subjective imagery vividness in the control participants but not in the aphantasic participants. Together, these results suggest that some aphantasics might have a deficit in conscious awareness of mental imagery rather than in imagery itself.

Contrary to our necessarily speculative predictions given the limited prior literature, there were no objective differences between aphantasic and control participants in spatial or object memory performance, regardless of perspective. The overall lack of objective memory deficits in the aphantasic participants is unlikely to reflect data insensitivity as the standard errors for all estimates were small across analyses. The lack of an objective object memory

deficit in the current aphantasic participants is particularly noteworthy given numerous previous subjective self-reports and some objective task-based evidence of selective object imagery deficits (Bainbridge et al., 2021; Dawes et al., 2020; Dawes et al., 2022). The lack of spatial memory deficits in the current aphantasic participants is consistent with previous findings that aphantasics typically self-report unimpaired spatial abilities (Dawes et al., 2020) and perform normally when these abilities are examined objectively using mental rotation tasks (Bainbridge et al., 2021; Zeman et al., 2015), despite potential measurement biases toward allocentric spatial processing. While a spatial subtype of aphantasia has recently been suggested (Palermo et al., 2022), the current use of the VVIQ to identify aphantasic participants more generally likely favours individuals with poor visual imagery.

It should be cautioned that there may have been sampling bias in the aphantasic group given that those with abnormally weak mental imagery ($VVIQ \leq 32$) were explicitly recruited. It is not uncommon for the majority of aphantasic participants to report a complete absence of mental imagery on the VVIQ (as in the present study), despite allowances for some degree of weak mental imagery (e.g., Dawes et al., 2020; Zeman et al., 2015). Yet, when recruitment biases are explicitly controlled for, total aphantasia has been indicated to be rarer in the general population than “moderate aphantasia” (0.8% versus 3.1%, respectively; Dance et al., 2022). Thus, the strength of any potential imagery-related memory deficits in the current aphantasic sample should have been overestimated rather than underestimated relative to the true aphantasic population, making the lack of objective deficits all the more puzzling. However, while clear objective imagery deficits have been previously found in small samples of aphantasics (e.g., $n = 15$; Keogh & Pearson, 2018), whether memory should be impaired to a similar extent is unclear given the paucity of objective memory studies (Bainbridge et al., 2021; Monzel et al., 2022; Pounder et al., 2022).

This study is not the first to find little to no objective evidence for memory differences in people with aphantasia, despite large sample self-report studies providing evidence to the contrary (Dawes et al., 2020; Milton et al., 2021; Zeman et al., 2020). A recent study by Pounder et al. (2022) found no accuracy differences between aphantasics and control participants on visuospatial working memory and verbal/visual pattern recognition memory tasks. Importantly, the visual pattern recognition task stimuli used by Pounder et al. were abstract and not easily represented verbally or symbolically, which might otherwise support good task performance when visual imagery is weak or absent. However, recognition memory task performance may also be supported by the vague sense of prior occurrence or

familiarity rather than detailed recollection (e.g., Addante et al., 2012), which is assumed to involve mental imagery in most individuals. Reliance on familiarity is less likely to explain the present data given the more complex, challenging, and continuous nature of memory assessment, although familiarity may have guided responses to some extent in the objective memory tasks due to the visual feedback they provided, thereby reducing potential group differences due to generative mental imagery. Indeed, it is noteworthy that Bainbridge et al. (2021) found a selective object memory deficit on their drawing task, which provided no such visual feedback. However, our measure of object memory retrieval precision derived from probabilistic mixture modelling has been shown to be highly sensitive to recollection-based memory differences (e.g., Korkki et al., 2020), and it is unlikely that familiarity alone supported task performance in the current study given the high level of precision in responses, which presumably required access to high fidelity memory representations.

Pounder et al. (2022) found no performance differences on any of their tasks when their analyses were restricted to individuals with total aphantasia, although some differences did emerge when RTs were examined (e.g., mental rotation). Based on this finding, Pounder et al. suggested that RT measures may be more informative than accuracy measures where alternative non-imagery-based task strategies are concerned. No significant RT differences were found in the main analysis of the present study, although an exploratory re-analysis restricted to the subgroup reporting total aphantasia revealed a significant imagery group by test perspective interaction for spatial memory RT. However, this result should be interpreted with caution given the small size of the subgroup with total aphantasia ($n = 13$). Moreover, it is unclear why RT differences proposed to reflect alternative strategy use would manifest on spatial tasks (see also Pounder et al.) when aphantasia is thought to reflect a primarily object imagery deficit. Indeed, the subgroup with total aphantasia did not significantly differ from controls on any of the other RT or performance measures including object memory retrieval precision, which should be the most sensitive to their characteristic mental imagery deficits. While it is difficult to imagine how the aphantasics participants might have completed the current memory task without the use of mental imagery, it is nevertheless possible that they did so using a strategy that has yet to be identified. Ruling out this possibility is of critical importance to future research on the question of unconscious mental imagery in aphantasics. To this end, non-invasive brain stimulation targeting imagery-related cortical regions in non-aphantasic participants might be one way to test whether the current task requires mental imagery. However, the present findings nevertheless suggest that some self-identified

aphantasics can perform normally on tasks typically thought to require mental imagery, regardless of the degree of their phenomenal imagery deficit.

The overall lack of significant objective memory deficits in the present aphantasics poses a challenge to the recent proposal that aphantasia might represent an episodic system condition rather than a mental imagery condition (Blomkvist, 2022). This theory extends the constructive episodic simulation hypothesis (Schacter & Addis, 2007, 2020), where episodic memory retrieval and imagery generation are held to involve common constructive and simulative processes (Hassabis et al., 2007; Hassabis & Maguire, 2007; Pearson, 2019), by adding hippocampally-based memory indices that point to the storage locations of individual episodic elements, multiple modality-specific episodic retrieval processes, and separate episodic and semantic spatial retrieval processes. Under this expanded cognitive architecture, Blomkvist distinguishes between aphantasics with voluntary mental imagery deficits and aphantasics with mental imagery deficits irrespective of volition. Specifically, Blomkvist argues that the former type of aphantasics reflects an impairment in activating the episodic system to generate mental imagery in a top-down manner only. By contrast, the latter type of aphantasics might be deficient at both top-down and bottom-up imagery generation (i.e., reflecting impaired access to the episodic system) or, alternatively, have an impaired episodic system on its own. Blomkvist notes that, in the case of more “complete” aphantasia, there is currently insufficient evidence to favour one possibility over the other. The present data (see also Pounder et al., 2022), particularly those from probabilistic mixture modelling indicating that aphantasics may have access to high fidelity visual memory representations, is inconsistent with the notion that aphantasia necessarily represents more fundamental episodic memory deficits. However, it is difficult to reconcile the present lack of objective task-based memory impairments and those found in other studies. For instance, Monzel et al. (2022) and Pounder et al. (2022) both employed similar complex visual pattern recognition memory tasks, yet only Monzel et al.’s aphantasic participants exhibited memory deficits. Findings are mixed even regarding more challenging memory tasks that separate object and spatial aspects of retrieval. For instance, Bainbridge et al. (2021) found aphantasics had selective object memory deficits in their drawing task whereas aphantasics in the present study exhibited normal performance in both categories. Therefore, future work should endeavour to identify potential task-related drivers of these divergences such as task difficulty or the manner of instruction.

One explanation for the present findings is that some aphantasics might retain a latent capacity for mental imagery, which they have no conscious awareness of, that nevertheless supports a normal level of task performance (see Jacobs et al., 2018; Nanay, 2021; Pounder et al., 2022). This would also be consistent with the view that, rather than reflecting a mental imagery-related metacognitive/introspective deficit, aphantasia might represent a disconnection syndrome, where sub-personal or representational mental imagery is proposed to remain intact but be inaccessible at the personal or experiential level (for discussion, see Lorenzatti, 2023). While the notion of unconscious mental imagery runs counter to the view that mental imagery is necessarily conscious (Farah, 1984; Kosslyn, 2005), more recent thinking has entertained this possibility (Brogaard & Gatzia, 2017; Nanay, 2021). Indeed, visual perception, which shows behavioural and neural overlap with visual mental imagery (for review see Pearson, 2019), has been suggested to occur without conscious awareness (Kiefer et al., 2011), although this notion is also controversial (Peters et al., 2017). For example, disrupted primary visual cortex function in blindsight patients (see Leopold, 2012 for review) or in neurologically healthy individuals with non-invasive brain stimulation (Boyer et al., 2005) can abolish the conscious experience of visual perception while preserving some ability to respond to visual stimuli.

More direct evidence for unconscious mental imagery is currently scarce, possibly due to assumptions about the nature of mental imagery. However, Kwok et al. (2019) recently showed that both the active imagining and successful imagery suppression of visual stimuli results in comparable levels of binocular rivalry priming in typical imagers. Critically, Kwok et al. showed the perceptual presentation of an irrelevant neutral luminous stimulus during active imagery and imagery suppression, which should interfere only with imagery-based priming in the active imagery condition, also affected priming in the imagery suppression condition. Using a similar imagery suppression paradigm, Koenig-Robert & Pearson (2020) were further able to decode the content of mental imagery using multivoxel pattern analysis visual brain areas despite subjects reporting successful imagery suppression. In another study using the same analytical methods, both the contents and vividness of mental imagery could be decoded from activity patterns in primary visual cortex up to 11 seconds before making conscious mental imagery-based judgements (Koenig-Robert & Pearson, 2019). Finally, Weber et al. (2023) found that working memory-related visual information is represented similarly in the early visual cortex of both strong and weak imagers including in a subset of participants classed as aphantasic.

Consistent with the interpretation of unconscious mental imagery, some of the current aphantasic participants ($n = 4$) remarked on the surprising ease with which they completed the object and/or spatial memory components of the task, despite not being able to say how they did so. Other aphantasic participants ($n = 7$) could describe the strategies they used, which included verbal or symbolic strategies (e.g., verbally encoding the colour of objects or assigning object positions to numbers on a clockface), but these strategies did not differ from those used by control participants. Moreover, exploratory correlation analyses revealed no significant relationship between object memory vividness ratings and performance in the aphantasic participants. Further exploratory analysis likewise revealed no such relationship in the subset of aphantasics who rated their general memory vividness above floor (vividness ≥ 10), although a significant correlation between spatial memory vividness and performance did emerge in that subgroup. However, the strongest evidence indicating unconscious mental imagery in these aphantasics comes from the high level of precision of their object memory, which was comparable to that of the control participants. While alternative strategy use has been favoured in previous studies as an explanation for unimpaired performance on tasks thought to require mental imagery by aphantasics (Jacobs et al., 2018; Keogh et al., 2021; Zeman et al., 2010), none until now have used probabilistic mixture modelling to investigate the visual fidelity of their memory representations, which should be particularly sensitive to the strength of visual imagery. Alternative probabilistic mixture models to the one used here can be applied to continuous report data (e.g., Bays, 2014), but two-component models describe this type of data well and have previously been used to separate long-term memory retrieval success and precision (Brady et al., 2013; Cooper et al., 2017, 2019; Harlow & Yonelinas, 2016; Korkki et al., 2020, 2023; Richter et al., 2016; Stevenson et al., 2018; Sutterer & Awh, 2016). Moreover, it should be noted that the current results did not change when a model-free measure of object memory performance, raw angular colour deviation, was analysed. Thus, the present data is among the first to show high-fidelity visual representations may be intact and support episodic memory in some aphantasics, apparently without their conscious awareness.

Many individuals with aphantasia report experiencing involuntary mental imagery, either as flashes during wakefulness or during dreaming (Dawes et al., 2020; Milton et al., 2021; Palermo et al., 2022; Zeman et al., 2015, 2020), making the separation of involuntary and unconscious mental imagery a challenge. Moreover, the VVIQ typically used to identify aphantasia explicitly requires respondents to intentionally generate mental images and thus

fails to distinguish those who can form involuntary unconscious mental imagery. Tasks involving the intentional generation of imagery may obscure this latent capacity in some aphantasics. Indeed, aphantasics have been shown to perform normally on imagery-based visual working memory tasks when instructed to “retrieve” rather than “imagine” object features (Jacobs et al., 2018), similar to how the current participants were instructed to remember object and spatial features. At surface, this view is harder to reconcile with frequent reports made by aphantasics of presumably imagery-related deficits in ABM, the contents of which are often spontaneously recalled (Berntsen, 2021). These differences might reflect the way ABM is probed, which sometimes involves the intentional recall of specific events (e.g., Dawes et al., 2020, 2022). However, aphantasics also report deficits on the SAM questionnaire, which assesses ABM more generally, and indicate less frequent involuntary memory intrusions than typical imagers (Dawes et al., 2020). Finally, it should be cautioned that individuals may generally be less willing or confident to report conscious imagery that is weak or dim because it is near the threshold for consciousness (Deroy, 2020). While the debate over the precise nature of aphantasia is far from resolved, the condition may be best characterised by differences in imagery phenomenology rather than capability. However, future studies of aphantasia should endeavour to include an objective measure of mental imagery (e.g., Kay et al., 2022; Keogh & Pearson, 2018; Wicken et al., 2021).

Finally, concerning episodic memory more generally, the greater precision of first-person versus third-person object memory retrieval in both imagery groups is intriguing. This difference was not significant when raw object memory errors or overall retrieval success were analysed separately, suggesting a first-person perspective might specifically enhance the fidelity of episodic memory retrieval. While the overall level of vividness for spatial memory features was lower than that for object memory features, and further exploratory correlation analysis revealed both first-person and third-person object memory recall performance to be significantly related to vividness ratings in the control participants with normal imagery awareness, this relationship was comparatively stronger for object features studied in first person. By contrast, the same relationship for spatial memory features was significant for all trial types, except for those studied and tested in a first-person perspective (i.e., stay first person trials). This pattern of correlations for the spatial memory component of the task may be due to stay first person trials reflecting egocentric spatial representations in their purest form, which may lead to worse spatial memory performance and less vivid spatial recall in comparison to allocentric representations. When considered together, these results suggest

that episodic memory reliving may be promoted more by the greater quality representations of scene contents formed when experienced in first person, rather than by a first-person (egocentric) perspective on its own. This interpretation is broadly consistent with that of Aydin (2018), who suggested object imagery to be recruited in ABM tasks requiring self-reflective processing, whereas spatial imagery might support direct retrieval of episodic details. However, further work is needed to disentangle the relative contributions of object versus spatial imagery as well as retrieval perspective to subjective episodic memory re-experiencing.

To conclude, this study is among the first to investigate episodic memory in aphantasics using objective and subjective measures. A novel 3D object and spatial memory task that manipulated visuospatial perspective was employed, but no evidence for impairment in either aspect of memory was found. This adds to recently emerging evidence for one possible subtype of aphantasia (among potentially many) in which mental imagery may be intact and support accurate task performance without conscious awareness (see also Pounder et al., 2022). However, further research is required to distinguish metacognitive/introspective and disconnection accounts of aphantasia, which differ in the proposed mechanisms by which phenomenal imagery may be lost (Lorenzatti, 2023). More work is also needed to address the possibly heterogenous nature of the condition, although the study of individuals with atypical imagery experience and/or ability offers the promise of gaining further important insights into the factors necessary for subjective episodic memory re-experiencing (Simons et al., 2022; Zaman & Russell, 2022). Finally, further work should endeavour to systematically rule out the potential confound of alternative strategy use by aphantasics on putatively imagery-based tasks.

Data Availability

Anonymized data will be made openly available on acceptance.

Author Contributions

Michael Siena: Conceptualization; Methodology; Software; Formal analysis; Investigation; Data curation; Writing – Original draft, Visualization, Project administration. **Jon Simons:** Conceptualization; Supervision; Writing – Review & editing; Funding acquisition.

Acknowledgements

We are grateful to the funders of this work as well as the research subjects who took part in it. We would also like to thank the reviewers of this manuscript for their helpful comments and suggestions. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

Funding Information

This research was carried out within the University of Cambridge Behavioural and Clinical Neuroscience Institute, funded by a joint award from the Medical Research Council and the Wellcome Trust.

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