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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 44(44)

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Publication Date
2022

Peer reviewed

Memory without Imagery: No Evidence of Visual Working Memory Impairment in People with Aphantasia

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Abstract

Visual working memory and visual mental imagery both involve the use of internal visual representations, and they likely have overlapping neural substrates. However, research on people with "aphantasia," or a lack of visual imagery, has not found any evidence that aphantasics are impaired on visual working memory tasks, possibly because they can use non-visual strategies. We designed a task intended to prevent compensatory strategies, and also to explore what happens when aphantasics are required to shift the focus of attention between items in working memory. We found that aphantasics were not significantly different from controls, either when maintaining or shifting the focus of attention. Explanations include non-visual memory strategies, but also the possibility that aphantasics can store information in visual working memory without conscious awareness. Future research should combine behavioral methods with neuroimaging to investigate how aphantasics encode working memory representations.

Keywords: aphantasia; visual working memory; visual mental imagery; attention

Introduction

Working memory is a temporary store for the maintenance and manipulation of information that is relevant to a present task (Baddeley, 2003; Ma, Husain, & Bays, 2014). According to the sensory recruitment theory, working memory arises out of a network of brain areas, and requires several cognitive functions, including memory and attention (D'Esposito & Postle, 2015). In the case of visual working memory, domain general attention controlled by the prefrontal and parietal cortices modulates representations encoded in the early visual cortex (Cowan, 2016; D'Esposito & Postle, 2015). It has been proposed that through this modulation of attention, information in visual working memory can exist in one of two representational states (Postle, 2015; Stokes, 2015). The first is the focus of attention, where items are prioritized and directly relevant to the task at hand (Oberauer, 2002; Trübutschek et al., 2017), and are likely maintained within conscious awareness (Trübutschek et al., 2019). Using multivoxel/multivariate pattern analysis (MVPA), these items can be decoded from the activity of the early visual cortex (LaRocque et al., 2013; Lewis-Peacock et al., 2012). The second state is the "passive encoding" state (Stokes, 2015). Items in this state are likely outside conscious awareness (Trübutschek et al., 2017; Trübutschek et al., 2019), and cannot be decoded from the early visual cortex, although they can later be retrieved and become decodable (LaRocque et al., 2013; Lewis-Peacock et al., 2012).

Visual mental imagery, meanwhile, refers to visual representations generated internally, in the absence of perception (Bartolomeo, 2008). Visual imagery ability can be measured by the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973), which asks respondents to rate the quality of their mental pictures. Studies using the VVIQ (e.g. Zeman et al., 2020) have found that visual imagery vividness varies across the population with some reporting lifelike imagery while others report severely deficient visualization. According to these studies roughly two to three percent of the population reports having little-to-no visual imagery (Faw, 2009; Zeman et al., 2020), a condition dubbed "aphantasia" (Zeman, Dewar, & Della Sala, 2015).

Visual Working Memory and Visual Imagery

Although generally treated as separate functions (Tong, 2013), visual working memory and visual imagery seem closely related. After all, both involve the creation, use, and manipulation of internal visual representations. Some (e.g. Tong, 2013) have even argued that visual imagery and visual working memory are merely two names for one cognitive function. As a result, if visual working memory recruits the early visual cortex, we should expect that visual imagery does also. Indeed, the same areas of the brain associated with visual working memory, particularly the prefrontal, parietal, and visual cortices, are also active during the use of visual imagery (Pearson, 2019). Variations in reported visual imagery vividness are positively correlated with variations in the activity of these areas (Dijkstra, Bosch, & van Gerven, 2017), and the contents of visual imagery can be decoded from activity in the early visual cortex (Naselaris et al., 2015).

In J. Culbertson, A. Perfors, H. Rabagliati & V. Ramenzoni (Eds.), *Proceedings of the 44th Annual Conference of the Cognitive Science Society*.

Aphantasia has also been found to affect performance on some perceptual and cognitive tasks. Using a binocular rivalry paradigm where participants were shown red and green Gabor patches, Keogh and Pearson (2018) observed that when participants were first instructed to visualize a particular patch (such as the red one), this significantly increased the probability that normal imagers, but not aphantasics, would perceive that same patch during the subsequent binocular rivalry trial, which supports an overlap between visual imagery and visual perception mechanisms. More recently, Bainbridge et al. (2021) found that aphantasics had significantly lower object memory scores than normal imagers when shown a visual scene and then asked to draw it from memory, although there was no difference in spatial memory.

Given then that visual imagery and visual working memory seem to overlap on both conceptual and neural levels, and that aphantasia can influence memory and perception, one might expect that individuals with aphantasia would be impaired on visual working memory tasks. Evidence is currently extremely limited; however, what evidence there is does not support a straightforward relationship between visual working memory ability and aphantasia. One case study, by Jacobs, Schwarzkopf, and Silvanto (2017), found that an aphantasic individual was not significantly different from a group of controls in terms of overall performance on a visual working memory task, although she was significantly worse on the hardest trials. Another case study, Zeman et al. (2010), found that an aphantasic individual had normal accuracy on a mental rotation task albeit with unusual response times, lacking the linear increase in times as rotation increased. Finally, Keogh, Wicken, and Pearson (2021) compared a group of aphantasics to a group of controls. They found that aphantasics and controls were not significantly different on a task measuring visual working memory capacity, and that aphantasics were actually significantly *better* than controls on visual working memory accuracy. In short, what little evidence we have seems to indicate that aphantasics are not impaired on visual working memory.

One possible explanation for these findings is that individuals with aphantasia are using visual working memory without conscious awareness. This explanation is relatively unlikely, however—studies of visual imagery show that subjective experiences of imagery vividness are related to observable differences in the activity of the visual cortex (e.g. Dijkstra et al., 2017). Similarly, behavioral evidence such as Keogh and Pearson (2018) shows that differences in self-reported imagery are linked to measurable differences in perceptual priming, while the response time findings from Zeman et al. (2010) indicated that the aphantasic individual was taking an unusual approach to the task. This brings us to a second possible explanation: that people with different imagery abilities use different memory strategies. Individuals with normal-to-vivid visual imagery might encode a visual image of the stimulus, while individuals with no visual imagery might use non-visual, propositional strategies such as remembering a verbal description. In other words, perhaps aphantasics seem normal on visual working memory tasks because these tasks are not adequately designed to prevent the use of non-visual compensation.

Limitations of Previous Research

One aspect of design that might allow aphantasics to substitute other forms of working memory is stimulus display times. In Jacobs et al. (2017), items to be remembered in the visual working memory task were displayed for 1500 ms, followed by a visual mask, while in Keogh et al. (2021), items in the memory tasks were displayed for 1000 - 1500 ms depending on the task, with no subsequent visual masks. Finally, in Zeman et al. (2010), stimuli remained on screen until participants responded, with no time limit for responses. This means that participants had at least a second of stimulus presentation time, plus the length of iconic memory on tasks without visual masks, to encode the stimulus using some non-visual, propositional mnemonic strategy. It is possible that a non-visual approach, which presumably requires perceiving a stimulus, identifying a key to-be-remembered feature (such as the orientation of a line), and then transforming and encoding that feature into some sort of non-visual memory, will be slower than a visual strategy that simply requires maintaining the stimulus in the same form as it was initially perceived, using the same neural mechanisms. As a result, viewing times of 1000 ms or longer may be too long to prevent the use of non-visual working memory, but shorter viewing times could potentially impact aphantasics' performance.

In addition to these long viewing times, all three studies of aphantasia and visual working memory (Jacobs et al., 2017; Keogh et al., 2021; Zeman et al., 2010) used two-alternative forced choice response scales. This raises the possibility that previous studies are simply not sensitive enough to capture differences in performance. An alternate approach such as method-of-adjustment probes, where participants manipulate a probe to match some item in memory, can yield continuous data and might detect subtler differences in recall accuracy.

Aphantasia and the Representational States of Working Memory

Beyond these limitations in methods, previous studies on visual working memory and visual imagery have not investigated the two representational states of working memory. As a result it is unclear whether aphantasics can redirect attention between representational states. This question of attentional modulation is of interest because if aphantasics have impaired visual working memory it might be possible to pinpoint a specific subcomponent of visual working memory that is impaired. Aside from findings that prosopagnosics are more likely to have unusually low quality visual imagery (Grüter et al., 2009), there is currently no evidence that aphantasics have any difficulties with perception. They certainly do not have any sort of broad visual agnosia. Instead, they are capable of perceiving and identifying stimuli, such as people and places (Milton et al., 2021). As a result, aphantasics appear able to encode and maintain visual representations. This raises the possibility that aphantasia is related to a specific problem with the top-down modulation of attention, which prevents aphantasics from retrieving visual representations in the absence of bottom-up perceptual activity. It would therefore be interesting to examine what happens when aphantasics are forced to retrieve information from the passive encoding state, and how that compares to information consistently maintained in the focus of attention.

One established method for measuring performance in both working memory states is the retro-cue (Souza & Oberauer, 2016). In a retro-cue task, participants are shown two items and then one of the items is cued (Griffin & Nobre, 2003). On the majority of trials, participants are then asked to recall the item that was cued. On a minority of trials, however, participants are asked to recall the uncued item. This leads to the "retro-cue effect," where items maintained consistently in the focus of attention are recalled with greater accuracy than uncued items (e.g. Zokaei et al., 2014). However, this method relies on participants complying with the cue and voluntarily shifting the focus of attention between items. As a result, it might not be suitable for comparing two groups, one of which is expected to have greater difficulty on the task, as participants who find the task harder might be more likely to miss or ignore the cue, thereby changing the nature of the task. Instead, it might be necessary to use some sort of "interrupting" task, presenting another task in the middle of some trials, to force participants to direct the focus of attention away from, then back towards, an item in memory.

The Present Study

The present study, then, was conducted with two goals in mind. The first was to test whether task design could prevent the use of non-visual compensation strategies, thereby allowing us to directly observe visual working memory impairments in aphantasics. The second goal was to investigate how shifting attention between working memory states affects the performance of aphantasics. We conducted an online study that combined changes to make the task harder for aphantasics (shorter stimulus viewing times, visual masks after the stimuli, and method of adjustment probes), as well as an interrupting task on half the trials to force participants to modulate attention.

We expected that aphantasics would have greater error than normal imagers when maintaining information consistently in the focus of attention. We also tentatively predicted that aphantasics would have more pronounced difficulty retrieving items once they have left the focus of attention, consistent with the hypothesis that aphantasics have greater difficulty with the top-down modulation of attention to visual stimuli (see Figure 1 for an illustration).

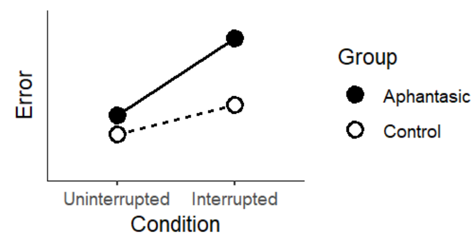

Figure 1: The expected pattern of results for the visual working memory task.

Method

Participants

Twenty aphantasic participants (12 female, 8 male) were recruited from a database of individuals with aphantasia. All 20 had a VVIQ score of 16, the lowest possible score, representing a total lack of reported visual imagery. Aphantasic participants' ages ranged from 19 to 36 (*M* = 26.35, *SD* = 4.75). Control participants, meanwhile, were recruited from a database of individuals who had previously completed the VVIQ. We recruited 22 control participants (14 female, 7 male, and 1 who preferred not to say) with ages ranging from 19 to 36 (*M* = 25.7, *SD* = 4.1). VVIQ scores for the control group ranged from 50 to 65 (*M* = 59.2, *SD* = 3.5), indicating that they had average visual imagery vividness (Zeman et al., 2020). Consent was obtained, and the procedure was approved by the Psychology Ethics Committee at the University of Exeter. All participants were paid for their time with Amazon vouchers.

Materials

The study took place entirely online. Consent and demographic information were collected and task instructions were given via Qualtrics (www.qualtrics.com). The visual working memory task was created using PsychoPy (2021.1.4) and hosted on Pavlovia (www.pavlovia.org).

Working Memory Task

To measure the effect of visual imagery on items in the focus of attention and the passive encoding state, we conducted a visual working memory task measuring participants' ability to remember the orientations of Gabor patches (Figure 2). On half the trials, participants were asked to recall these orientations after a long delay, while on the other half of the trials the long delay was replaced by a dot matrix task (adapted from Alloway, 2007) which was intended to force participants to move the focus of attention away from the Gabor patch and towards different information in visual memory, before then moving the focus of attention back to the Gabor patch so they could recall its orientation at the end of the trial.

Stimuli Stimuli for the experiment were displayed on a grey background. The memory array consisted of a single Gabor patch, 6.5° of visual angle in diameter when viewed from a distance of 50 cm, which was displayed in the center of the screen. The visual mask was 6.5° width by 6.5° height and made up of random noise, and the fixation crosses were black and 1.5° tall by 1.5° wide. The probe was a red (255, 0, 0) circle subtending 1.5° and displayed in the center of the screen, while the response wheel was made up of a circle 6.5° in diameter, with two “handles” or smaller circles each subtending 1° shown at diametrically opposite points on the larger circle to illustrate the wheel’s orientation. Feedback consisted of two additional red handles showing the correct orientation of the patch. For interrupted trials, participants were shown a four by four matrix of cells (16 cells in total, 12° by 12° overall). The memory array consisted of red dots 1.5° diameter. For the probe, a red circle 1.5° diameter was shown in one of the cells with a number 1° tall inside it.

Procedure After receiving task instructions, but before the practice trials, participants were asked to complete a standardization procedure designed to measure the size of their computer screens and adjust the size of the stimuli so that all participants saw stimuli of the same size. Based on a procedure from Morys-Carter (2021), each participant placed a bank card against their computer screen and then used the arrow keys to adjust an image of a bank card so that it was the same size as their real card. They then pressed the spacebar to record the size of the card and move on to the main experiment.

For the trials in the uninterrupted condition, a randomly-oriented Gabor patch was displayed for 250 ms. Immediately following the Gabor patch, a random noise mask appeared for 1000 ms. This mask was intended to disrupt the use of iconic memory so that aphantasic participants could not use this time as part of any compensatory strategies. Following the mask there was a delay where a black fixation was displayed in the center of the screen for 9000 ms. The length of this delay was chosen following pilot testing, to ensure that uninterrupted and interrupted trials took the same length of time. After the delay, a red circle was displayed in the center of the screen. This circle acted as the probe, and signaled that it was time to report orientation of the Gabor patch. Participants were instructed to recall the orientation of the patch and then press the spacebar on their keyboard when they were ready to respond. Once they pressed the spacebar, participants were shown the response wheel. The response wheel was used instead of a second Gabor patch to reduce distraction or the distortion of the patch in memory as much as possible, particularly for the control group given our assumption that normal imagers likely maintain visual memoranda in the early visual cortex while aphantasics likely do not.

To report the orientation of the patch, participants rotated the wheel using the keyboard. Pressing the J key rotated the wheel to the right, and pressing the F key rotated the wheel to the left. Once the orientation of the response wheel matched the remembered orientation of the patch, participants pressed the spacebar to record their answer and receive feedback in the form of the correct answer overlaid in red on the response wheel. This feedback was displayed for 500 ms, followed by a 300 ms intertrial interval where only a fixation cross was shown.

Trials in the interrupted condition began the same way, however the long delay was replaced by a dot matrix task

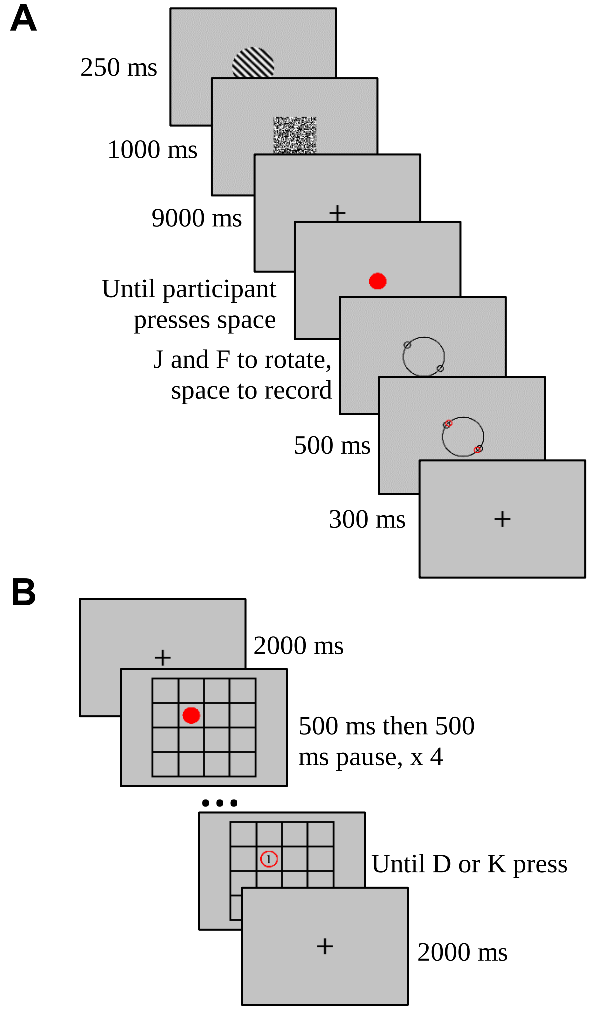

Figure 2. The visual working memory task. On half the trials there was a 9000 ms delay between the visual mask and the probe (A). On the other half of the trials, the 9000 ms delay was replaced by the dot matrix task (B).

intended to force participants to redirect the focus of attention. This task began with a 2000 ms delay where only a fixation cross was visible. Following this delay, the matrix appeared. Four red dots were displayed one at a time in random cells within the matrix. Each dot was displayed for 500 ms, with a 500 ms pause after each dot. Following all four dots, a circular outline with a number inside appeared in one of the matrix cells. This outline and number constituted the probe for the dot matrix task. The number referred to a particular dot in the sequence of four, based on the order in which the dots had appeared (1 referred to the first dot 2 to the second dot, and so on). When participants saw the probe, they were asked to think about that particular dot and decide whether the probe was in the cell where the dot had been shown. If the dot and the probe were in the same location, participants pressed the K key, and if they were in different locations, participants pressed the D key. After participants responded, the matrix disappeared and there was another

2000 ms delay where a fixation cross was shown. Following this delay, the trial continued on in the same way as trials in the uninterrupted condition: participants were shown a probe and asked to report the orientation of the Gabor patch, followed by feedback and then a 300 ms ITI.

Altogether participants completed one practice block and three test blocks. The practice block consisted of 16 trials, 8 interrupted and 8 uninterrupted, in random order, while the test blocks each contained 48 trials, 24 uninterrupted trials and 24 interrupted trials, again shown in random order. Across the three test blocks, this added up to a total of 72 trials in the uninterrupted condition and 72 trials in the interrupted condition. Within the interrupted condition, the dot and the probe were in the same location for 36 of the trials, and different locations for the other 36. Each position in the sequence (first dot, second dot, etc.) was probed an equal number of times.

Analysis and Results

Data were processed in MATLAB 2018a using the CircStat toolbox (Berens, 2009), and analyzed in SPSS 28.0.1. In the case of null results, we conducted follow-up Bayesian analyses to assess the strength of evidence in support of the null hypothesis. These analyses were conducted in JASP (www.jasp-stats.org), and models were compared to the null model. Given the lack of previous studies showing visual working memory deficits in aphantasics, JASP's default priors were used. In line with the JASP interpretation guidelines (van Doorn et al., 2021), a Bayes factor (BF_{01}) of less than .33 is considered at least moderate evidence for the alternate hypothesis, while a BF_{01} between .33 and 1 is considered weak evidence for the alternate hypothesis. A BF_{01} between 1 and 3 is weak evidence for the null hypothesis, while a BF_{01} between 3 and 10 is moderate evidence for the null.

The key outcome variable was the average error for each participant, error being the absolute value of the angular deviation between the orientation of the target patch and the participant's response, in radians. Once mean error was calculated for all participants, we observed that five of the control participants had unusually high average error (ranging from 0.59 to 0.78 in the uninterrupted condition, compared to a range of 0.16 to 0.38 for the rest of the controls). Further inspection of the data showed signs that these participants were likely responding at random or with minimal effort: four of the five participants recorded a response without rotating the response wheel on at least 33% percent of the trials (compared 4.5% on average for the rest of the controls), and three of the five had numerically below chance performance on the dot matrix task. All five participants with unusually high error showed at least one of the other two signs of responding at random. As a result, these participants' data were dropped from analysis.

Working Memory Task

With the remaining 20 aphantasics and 17 controls, we analyzed the results from the working memory task using a 2 x 2 mixed ANOVA with imagery ability (aphantasic or control) as the between-subjects factor and condition (uninterrupted or interrupted) as the within-subjects factor (Figure 3A). This ANOVA revealed a main effect of condition, $F(1, 35) = 56.52$, $p < .001$, $\eta_p^2 = .62$. Participants' mean error was greater when trials were interrupted by the dot matrix task ($M = 0.33$, $SD = 0.10$), compared to when trials were uninterrupted ($M = 0.23$, $SD = 0.06$). However, there was no main effect of group, $F(1, 35) = 0.75$, $p = .392$, $\eta_p^2 = .02$, $BF_{01} = 2.53$, and no significant interaction, $F(1, 35) = 1.63$, $p = .210$, $\eta_p^2 = .04$. The Bayes factor for the interaction was quite small, $BF_{01} = 1.99 \times 10^{-6}$, however, this was because the interaction model included the main effect of condition. Consequently, the Bayes factor increased when the main effects were removed, matched models exclusion BF = 1.68.

Dot Matrix Task

We also compared the accuracy of the two imagery groups on the dot matrix task. There was no significant difference between the groups, $t(35) = 0.62$, $p = .543$, $d = 0.20$, $BF_{01} = 2.70$ (Figure 3B).

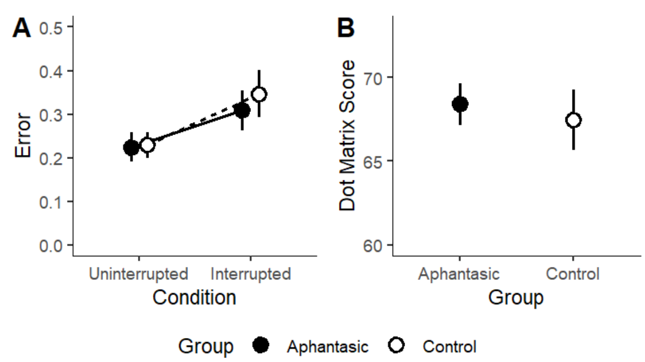

Figure 3: Mean error in radians for both imagery groups and task conditions for the main working memory task (A) and score on the interrupting dot matrix task for both imagery groups (B), with 95% confidence intervals.

Discussion

This study was conducted with two goals. The first was to test whether a visual working memory task could be designed to prevent aphantasics from using compensatory strategies. The second was to test whether aphantasics have difficulties redirecting attention between items in visual working memory. We expected first, that aphantasics would have greater error than normal imagers when consistently maintaining an item in the focus of attention, and second that aphantasics would have even more pronounced difficulty retrieving items from the passive encoding state. In reality, aphantasics did not have significantly greater error than controls, even though they only had 250 ms to view the stimuli and their performance was measured using a much more sensitive continuous scale, and we observed no differences between imagery groups on either the items consistently maintained in the focus of attention (the uninterrupted trials) or items retrieved from the passive encoding state (the interrupted trials).

Regarding our first hypothesis, the fact that we observed no significant differences between imagery groups has two possible explanations. The first is that contrary to previous research on visual working memory (Trübutschek et al., 2019), some people can maintain information in the focus of attention without conscious awareness of that information. It is also possible that there are as-yet-unidentified subtypes of aphantasia. Because we conducted this study online, we were unable to incorporate neuroimaging or replicate Keogh and Pearson's (2018) binocular rivalry findings, and so the present study does not directly provide evidence against this possibility. However it seems less likely in light of previous evidence. As discussed in the introduction, variations in visual imagery vividness are associated with variations in the activity of the early visual cortex (Dijkstra et al., 2017; Naselaris et al., 2015; Pearson, 2019), while Keogh and Pearson (2018) found that visual imagery influences perception in normal imagers but not aphantasics.

This brings us to the second possible explanation, that even with several modifications to the task design, aphantasics were still able to use non-visual compensatory strategies, perhaps some sort of verbal description such as a number representing the angle, or a time on a clock face. If this is the case, it has implications for the whole field of visual working memory research. It suggests that visual working memory tasks do not necessarily measure visual working memory: it is difficult to prevent participants from using whatever strategies they prefer, even when tasks are specifically designed to disrupt non-visual strategies. Because this was an online study, we were not able to examine the effects of articulatory suppression, but future lab-based research on visual imagery and visual working memory could use this method to disrupt verbal labelling strategies. Even if this is effective, however, it is probably not a practical long-term solution to ensure the validity of visual working memory tasks, and so tasks intended to measure visual working memory specifically may run the risk of being confounded by non-visual forms of memory. Although once again, our study does not directly support this possibility, as we cannot be sure that aphantasics used a non-visual strategy.

As it is unclear how aphantasics achieved normal performance on the working memory task, it is difficult to draw conclusions about our second hypothesis. Our results show that aphantasics can shift attention between different representational states within working memory. These results are interesting because they indicate that if aphantasics have impairments in visual working memory, other forms of working memory can nevertheless function normally, however they do not tell us anything specific about the ability to shift attention between *visual* representations.

In conclusion, the present study demonstrates that it is difficult to observe visual working memory impairments in people with aphantasia even with a task specifically designed to prevent compensation. Most likely, aphantasics are using non-visual strategies during these tasks, allowing them to appear normal in terms of behavior. However the possibility that aphantasics can store information in visual working memory without conscious awareness cannot be ruled out. One direction for future research is to combine behavioral methods with neuroimaging data to evaluate whether aphantasics are using visual working memory. Using MVPA, future studies could investigate whether visual working memory representations can or cannot be decoded from the early visual cortices of people with aphantasia during tasks where behavioral accuracy is equal to that of normal imagers.

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