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Visual working memory performance in aphantasia

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ABSTRACT

Aphantasia, i.e., the congenital inability to experience voluntary mental imagery, offers a new model for studying the functional role of mental imagery in (visual) cognition. However, until now, there have been no studies investigating whether aphantasia can be linked to specific impairments in cognitive functioning. Here, we assess visual working memory performance in an aphantasic individual. We find that she performs significantly worse than controls on the most difficult (i.e., requiring the highest degree of precision) visual working memory trials. Surprisingly, her performance on a task designed to involve mental imagery did not differ from controls', although she lacked metacognitive insight into her performance. Together, these results indicate that although a lack of mental imagery can be compensated for under some conditions, mental imagery has a functional role in other areas of visual cognition, one of which is high-precision working memory.

1. Introduction

Aphantasia refers to the inability to generate mental images (Zeman, Dewar, & Della Sala, 2015). Individuals affected by aphantasia cannot experience the sensory qualities of objects that are not physically presented to them. Although the phenomenon was already described nearly 150 years ago (Galton, 1880), it has recently (re)gained public and scientific interest (Zeman et al., 2010, 2015). A study by Zeman et al. described a case of acquired aphantasia as a result of a coronary angioplasty procedure (Zeman et al., 2010). They found that the patient behaved accurately on tasks of visual mental imagery and visual memory, from which they concluded that he must have utilized alternative cognitive processes, rather mental imagery, to perform these tasks. fMRI data showed that he relied more heavily on frontal brain areas, whereas in controls a posterior network of brain regions was more active, corroborating the idea that he made use of an alternative cognitive strategy. Another study described a group of twenty-one individuals who had never experienced voluntary mental imagery at any moment during their lifetime (Zeman et al., 2015). Many of these congenital aphantasics self-reported

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mood-related or cognitive difficulties. However, this study did not systematically examine the cognitive functioning of these individuals. Here, we examined the functioning of visual working memory in a case of congenital aphantasia.

Visual working memory and mental imagery are two processes that both depend on the representation and manipulation of visual mental content not driven by current visual input. Even though they share this important feature, within the field of cognitive psychology the two processes have been mostly researched independently (e.g., Tong, 2013), although some investigations on the link between visual working memory and visual imagery have been published. Early work did not find a positive relationship between the two cognitive processes (Heuer, Fischman, & Reisberg, 1986; Reisberg, Culver, Heuer, & Fischman, 1986; Reisberg & Leak, 1987), but more recently, strength of mental imagery was found to correlate with visual working memory performance (Keogh & Pearson, 2011), and working memory capacity (Keogh & Pearson, 2014). In addition, both processes have shown to be sensitive to visual interference by task-irrelevant visual input (Baddeley & Andrade, 2000; Keogh & Pearson, 2011, 2014, although see; Borst, Niven, & Logie, 2012), especially when the participants were strong-imagers (Keogh & Pearson, 2011, 2014), indicating that this subset of participants most likely adopts a cognitive strategy involving mental imagery when executing visual working memory tasks. At the same time, this would mean that for many individuals mental imagery is of no functional relevance for working memory. Thus even if (strong) imagery might be beneficial to visual working memory, it is not a prerequisite for adequate performance. On the other hand, there are studies showing that mental imagery relies on the same cognitive structures underlying visual working memory. Baddeley and Andrade (2000) have shown that disruption of the visuospatial sketchpad, one of working memory's so-called slave systems, reduces the vividness of mental images representing information retrieved from long-term memory. A close correspondence between representations underlying visual working memory and visual imagery has been demonstrated, both cognitive (Borst, Ganis, Thompson, & Kosslyn, 2012), and neural (Albers, Kok, Toni, Dijkerman, & De Lange, 2013; Slotnick, Thompson, & Kosslyn, 2012). Clinical work with schizophrenic patients demonstrated that even though this patient group suffers from working memory impairments, they are faster at mental image generation than matched controls (Matthews, Collins, Thakkar, & Park, 2014). However, the same study also showed that the enhanced mental imagery capacity could be abolished by increasing the concurrent working memory load.

Here, we further examine this functional relationship by examining the working memory performance of an individual, who in her own experience is incapable of mental image generation since birth. We investigated multiple aspects of (visual) working memory, i.e., visual working memory capacity, metacognitive performance for remembered information, and the role of feature binding in visual working memory. We also carried out a general working memory capacity battery to control for any differences in working memory performance that are not specific to visual information. In a similar effort to rule out generic differences between our control sample and the individual under study, IQ was measured in all participants as well. We designed a spatial working memory task which tested participants' memory for the contours of geometric shapes after a 4-sec delay period, and we included an equivalent mental imagery task that required participants to generate a mental representation of the same stimuli. We hypothesized that the aphantasic individual would perform worse than controls on the mental imagery version of the task. If mental imagery is essential to visual working memory, she would show impaired performance also on the working memory version. Alternatively, she could have developed compensatory strategies for those tasks in which typical individuals would resort to mental imagery. In that case, her performance pattern across visual working memory tasks could diverge from that of the typical individuals in any possible way. Finally, if there are no differences between the aphantasic individual and the control group, the parsimonious conclusion would be that mental imagery does not seem instrumental to visual working memory altogether.

We also included the change detection task designed by Wheeler and Treisman (2002) to measure visual working memory performance for feature-bound objects as opposed to single-feature working memory. Mental imagery involves the generation of integrated, featured-bound visual images, but single visual features, like color or shape, can be passively and unconsciously stored in working memory without the need to be integrated into object-like representations. We therefore hypothesized that if the aphantasic individual shows visual working memory deficits, these might be limited to working memory for feature-bound stimuli, while leaving single-feature memory unaffected.

2. Methods

2.1. Participants

2.1.1. *Aphantasic individual*

The aphantasic individual (AI, not actual initials) was a female 31y9m of age. At the time of testing she was a PhD student. She had recently come across aphantasia through communications about the phenomenon in popular media, and found that her personal experiences were similar to the experiences described there. She contacted our research group to offer to volunteer in further research on the phenomenon of aphantasia. Her vision was corrected-to-normal. She was compensated for her participation through gift vouchers.

2.1.2. *Control participants*

11 control participants were included in the study. All of them were female and their average age was 31y0m (SD = 28 m). All control participants were in possession of at least a Master's degree and had varying vocational backgrounds (7 graduate students or academics, 3 individuals working in business, 1 graphic designer). As average IQ scores did not match AI's, we selected a subgroup of 4 participants with matching IQs to additionally compare her with (see Section 3.2). This subgroup had a mean age of 31y5m of age and consisted of 2 women working in industry and 2

graduate students. All control participants had normal or corrected-to-normal vision and were compensated for participation through gift vouchers.

2.2. Behavioral tasks

Behavioral testing was split over 3 separate sessions of about 1.5–2 h each. Task order was identical across all participants to ensure that any learning/fatigue effects were equivalent for AI and the control participants. See Table 1 for an overview of task order across sessions.

2.2.1. Vividness of Visual Imagery Questionnaire (VVIQ)

The VVIQ (Marks, 1973) is a questionnaire that assesses the strength of visual mental imagery. On each of its four components, the participant is instructed to visualize a particular scene (e.g., "*think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye*") and to subsequently rate the vividness of four different aspects of the created mental image (e.g., "*the exact contour of face, head, shoulders and body*") on a scale from 1 ("*No image at all, you only "know" that you are thinking of the object*") to 5 ("*Perfectly clear and lively as real seeing*"). Minimum and maximum scores on the VVIQ are therefore 16 and 80, respectively. In all recent studies on the phenomenon of aphantasia (Zeman et al., 2015; Zeman et al., 2010) the VVIQ is the diagnostic tool used to identify individual cases of aphantasia.

2.2.2. Wechsler Adult Intelligence Scale-IV (WAIS-IV)

The U.K. Version of the WAIS-IV (Pearson PLC, London, UK) was administered to assess overall IQ of all participants in order to match control participants' IQ to that of the aphantasic individual. The full-scale IQ is based on the individuals' scores on 10 separate tasks tapping into a variety of skills. Based on the grouped scores of particular selections of the 10 tasks four separate subscales can be calculated: verbal comprehension (VCI; combined scores on Similarity, Vocabulary, and Information tasks), working memory (WMI; combined scores on the Digit Span and Arithmetic tasks), perceptual reasoning (PRI; combined scores on the Block Design, Matrix Reasoning, and Visual Puzzles tasks), and processing speed (PSI; combined scores of Symbol Search and Coding tasks). WMI is calculated from the combined scores on a digit span task and arithmetic task, neither of which explicitly tests *visual* working memory performance.

2.2.3. Working Memory Capacity (WMC) battery

To assess working memory capacity, we used the tests developed and validated by Lewandowsky, Oberauer, Yang, and Ecker (2010). This WMC battery consists of four tasks: 1) memory updating; 2) operation span; 3) sentence span; 4) spatial working memory. A brief description of each of the tasks is given below. For more details, we refer to the original study (Lewandowsky et al., 2010).

1) Memory updating (MU; Fig. 1a): at the start of each trial the black outline of 3, 4 or 5 empty boxes (placeholders) appeared on a white background, after which single digits were presented sequentially in each of the placeholders for 1000 msec. The digits could range from 1 to 9 and the participant was instructed to remember which number had appeared in which placeholder. After this initial encoding phase, sequential arithmetic operations were presented within (a subset of) the placeholders. The operations could be anything from "−7" to "+7", except "0". The participants were required to perform each arithmetic operation on the digit they had encoded for that placeholder, and from then on remember the outcome (i.e., memory updating) as the new digit for that spatial position. Each operation was presented for 1300 msec and the overall number of arithmetic operations varied between 2 and 6 per trial. Multiple arithmetic operations could appear within a single placeholder. At the end of the trial, sequential question marks in each of the placeholders prompted the participant to enter the last digit they remembered for each location. Total number of trials was 15.

2) Operation span (OS; Fig. 1b): participants were asked to judge whether or not simple, centrally presented equations were correct (an example of an incorrect equation is "$5 + 1 = 7$"). Each time after they had indicated through button press whether an equation was correct or not, a consonant would appear on screen. After a 1000 msec interval the next equation appeared. At the end of a trial a question mark prompted participants to report the letters they had memorized on that trial in the correct order. The number of equations/letters per trial varied between four and eight. Total number of trials was 15.

3) Sentence span (SS; Fig. 1c): identical to the OS task, except now instead of equations participants were asked to judge whether simple statements were true or false (an example of an untrue statement is "Every flower is a rose"). The sentences consisted of 8–11 words and the number of presented sentences varied between 3 and 7. Total number of trials was 15.

4) Spatial short-term memory (SSTM; Fig. 1d): at the start of each trial a grid of 10×10 cells appeared on screen. In one of the cells a solid black dot appeared for 900 msec and then disappeared again, after which a dot appeared and disappeared in a different cell, and so on. The length of the dot sequence varied from 2 to 6. At the end of the trial, participants were asked to "*reconstruct the dots*". At this stage, participants recreated the pattern of dots that was presented to them, not necessarily in the original order of representation. A mouse click in any of the cells generated a black dot in that cell. Participants were instructed that the relative distance between the dots was more important than their precise individual locations. Total number of trials was 30.

Table 1 – Order in which task were administered for all participants.

Session 1	Session 2	Session 3
Vividness of Visual Imagery Questionnaire (VVIQ)	Visual Working Memory (WM) task	Imagery (IM) task
Wechsler Adult Intelligence Scale – IV (WAIS – IV)	Working Memory Capacity (WMC) battery	Change detection (CD) task

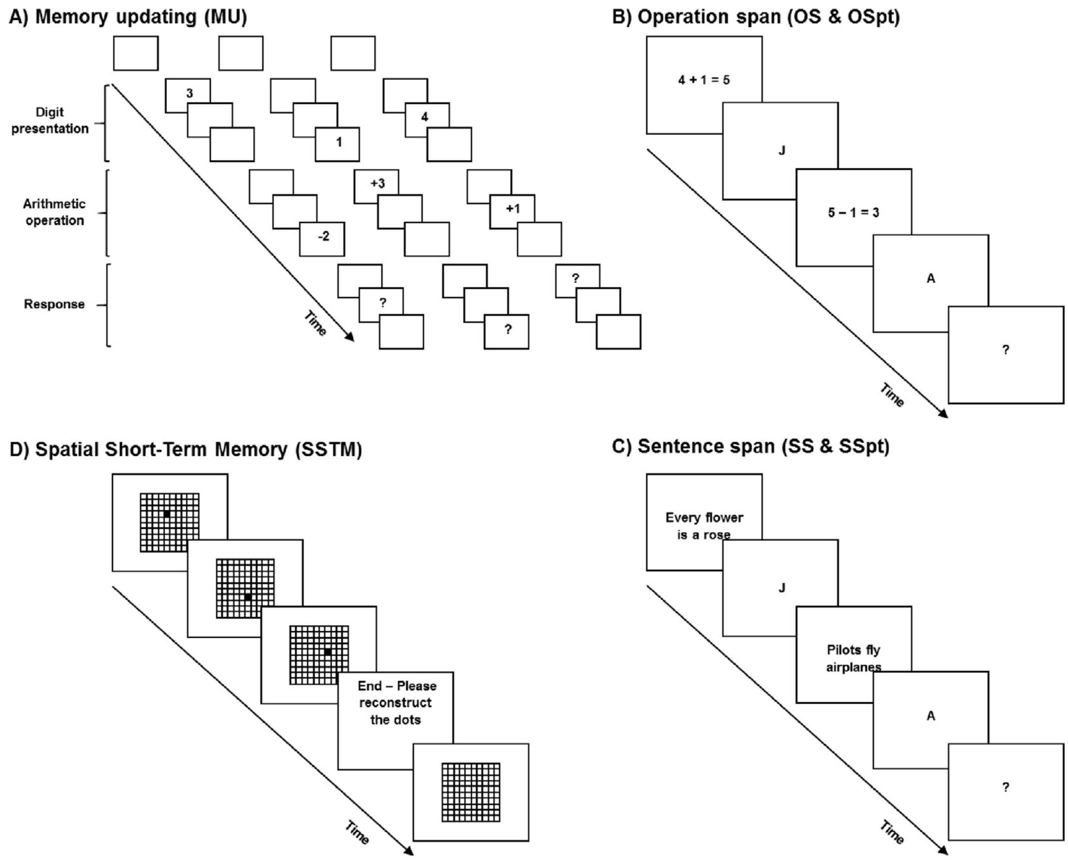

Fig. 1 — The Working Memory Capacity (WMC) battery. A) An example trial for the Memory Updating (MU) task. During the digit presentation phase of the task, the digits are presented within the predefined placeholders sequentially. After the digit presentation phase, arithmetic operations are sequentially presented within the placeholders. Participants applied such operations to their current working memory representation for the placeholder in question and then updated this representation with the resultant numerical value. At the response stage participants were prompted to enter the current memory representation for each of the placeholders. B) An example trial for the Operation Span (OS) task. Participants indicated whether sequentially presented visual equations were correct or incorrect. After each equation, they were presented with a letter, which they were instructed to memorize. At the end of each trial, participants were prompted to reproduce the remembered letter string in the correct order of presentation. C) An example trial for the Sentence Span (OS) task. Participants indicated whether sequentially presented visual sentences made sense or not. After each equation, they were presented with a letter, which they were instructed to memorize. At the end of each trial, participants were prompted to reproduce the remembered letter string in the correct order of presentation. D) An example trial for the Spatial Short-Term Memory (SSTM) task. Participants were presented with a 10 × 10 grid. Black dots appeared sequentially in some of the grid cells. At the end of each trial, participants were asked to reconstruct the pattern of the dots by mouse clicking in the corresponding cells. (see Lewandowsky et al., 2010 for more information the WMC battery).

All stimuli were presented on an 22″ CRT monitor (p1230; HP, Palo Alto, CA) at 85 Hz refresh rate and run in Matlab v2009a (The MathWorks Inc., Natick, MA) with PsychToolbox v3.0.9. Accuracy data were analyzed with the SPSS syntax file (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY) provided by the developers of the toolbox. Execution of this syntax file converted the individual's data as recorded in the Matlab logfiles into a single value representing the mean proportion of correctly recalled items for the MU, OS, and SS task. For the SSTM task the value would represent the mean of the dot-to-dot similarities divided by the full-match similarity (see original paper by Lewandowsky et al. (2010) for further details on scoring).

2.2.4. *Visual Working Memory (WM) and Imagery (IM) tasks*

We designed this set of tasks in order to compare (meta-cognitive) performance on a visual working memory task and a matched mental imagery task. In the Visual Working Memory (WM; Fig. 2) version of the task, each trial started with the presentation of the name of a geometric shape (i.e., *diamond*, *triangle* or *parallelogram* — we chose these shapes, because they are easy to construct on the basis of the four placeholders demarcating the visual field area) for 500 msec, after which the corresponding geometric shape was presented in the center of the screen for 1500 msec. A square noise mask appeared on screen for 200 msec to prevent the generation of an afterimage. After a 4000 msec delay period, a small (2 × 2

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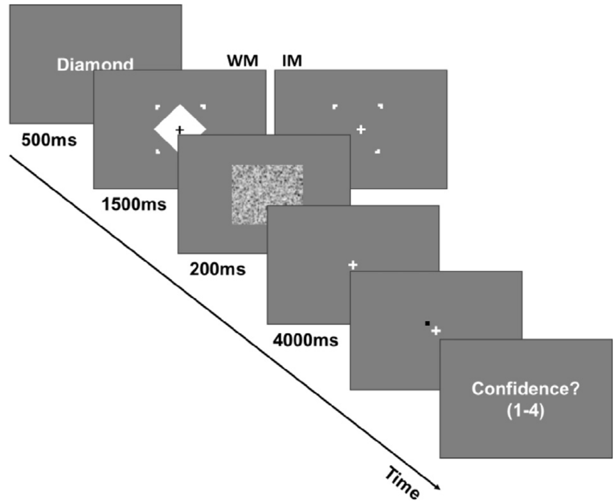

Fig. 2 – Visual Working Memory (WM) and Mental Imagery (IM) tasks. The name of one of three geometric shapes (i.e., diamond, parallelogram, or triangle) appeared on screen for 500 msec. In the working memory version of the task (left), the corresponding shape was visually presented within four placeholders for 1500 msec. In the imagery version (right), only the place holders were shown and participants were instructed to construct the mental image of the shape within the area of the visual field demarcated by the place holders. A random noise stimulus masked any potential afterimages. After a 4000 msec delay period, a target dot appeared on screen. Participants were instructed to indicate by button press whether the target stimulus appeared within the boundaries of the original (WM) or constructed (IM) stimulus. They subsequently rated how confident they felt about this response on a 1–4 scale.

pixels) black dot appeared on screen. Pre-defined difficulty levels were created by varying the distance between the boundaries of the (imagined) geometric shape and the location of black target dot. We included three levels of difficulty in our design (thus the target dot could appear at three different distances from shape stimulus boundaries). Within a difficulty condition, potential target dot locations were all equally distant from the geometric shape's boundary. Participants were instructed to indicate by button press whether they believed the dot to be within or outside of the boundaries of the original geometric shape. After they had given their initial responses, participants were prompted to indicate on a 1–4 scale how confident they felt about the response they had just given (1 = "low confidence"; 2 = "low to moderate confidence"; 3 = "moderate to high confidence", 4 = "high confidence"). The Imagery (IM; Fig. 2) version of the task was identical to the WM task in every aspect, apart from the stimulus presentation stage. Instead of actually showing the geometric shape, only the four placeholders, which marked the area of the visual field in which the stimuli had to be imagined, were offered to the participants forcing them to construct a mental image of the geometric shape based exclusively on the initial verbal instruction. The shapes (i.e., triangle, diamond or parallelogram) were specifically chosen so that they only occupied half of the area of the visual field demarcated by the placeholder, so that the target dot can appear within the demarcated area, but still fall outside the contours of the imagined geometric shape. Task instructions were varied slightly for participant AI (from "*you are to imagine*" to "*you are to retrieve*"), because she would not be able to execute the instruction to mentally imagine a visual object and just asking her to retrieve it from memory gave her the freedom to do that in whatever preferred way.

2.2.5. *Change detection task*

In order to examine whether inability to engage in imagery affects working memory for feature-bound percepts, we slightly modified one of the tasks described in Wheeler and Treisman (2002), which was specifically designed to compare visual working memory for separate features versus bound objects. The task is fundamentally a change detection task (Fig. 3). At the start of each trial participants were presented with a stimulus display consisting of three, four or five simple shapes in different colors for 150 msec. After a delay of 900 msec a test display would appear containing the same number of colored shapes. All shapes always changed spatial position from initial to test display, but their potential new location was limited to those spatial locations at which a stimulus had also been presented on the initial display. Participants were to indicate via button press whether the stimuli on the initial and test display were identical. Test stimuli

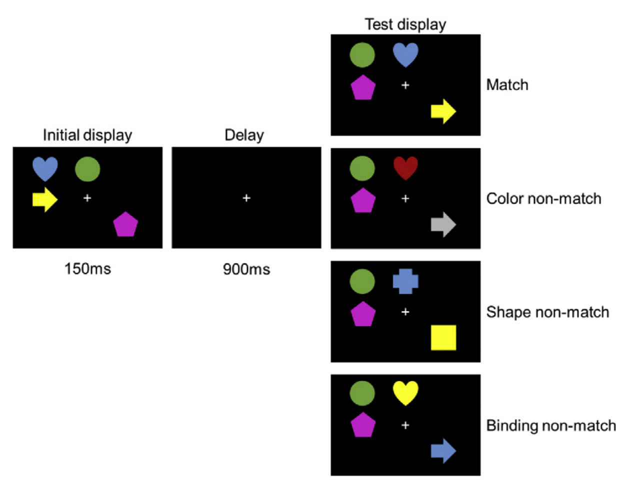

Fig. 3 – Change detection task. An initial display of multiple stimuli of different colors and shapes appeared for 150 msec. After a 900 msec delay period, a second test display appeared with the same number of stimuli presented in the same locations on screen. Participants were to indicate whether the test display contained the same colored shapes as the initial display (location-matching impossible, because the stimuli would swap always swap positions from initial to test display). Non-matches could results from two colors being replaced by new ones (color non-match), two shapes being replaced by new ones (shape non-match) or two shapes swapping color (binding non-match). Conditions were blocked, so participants were aware that they were to detect color changes, shape changes, color-or-shape changes, or binding non-matches in each block.

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could be different in a number of ways. In the *color* condition, the color of two stimuli changed into new colors, which were not present on the initial display. In the *shape* condition, two stimuli changed into new shapes, which were not present on the initial display. These conditions were blocked so the participants knew beforehand whether to pay attention to colors or shapes presented in the initial display. There was a third, *either* condition, which consisted of blocks in which either feature could change from initial to test display. Finally, in the *binding* condition all the initial colors and shapes were present in the test display, but two shapes had swapped color. Each block consisted of 48 trials and was repeated once, thus adding up to 384 trials in total. The order of blocks was pseudorandomised for the first participant and the resulting block order was then used for all other participants. Participants were instructed to repeat the words "Coca-Cola" throughout the experiment to prevent them falling back on verbal encoding of the stimuli (i.e., articulatory suppression). Participants received feedback on their performance on a trial-by-trial basis.

2.3. Data analyses

We report effect sizes and the outcome of significance tests on the differences between AI and the control participants. Crawford and Garthwaite (2012) have recently compared different commonly used methods for significance testing in single-case studies. They recommend calculation and report of the t-statistic for the single case under the estimated t-distribution of the control sample based on their mean, standard deviation, and sample size (i.e., degrees of freedom), which also allows comparison of the corresponding *p*-value to a critical alpha value as a test for statistical significance. In addition, they strongly suggest reporting the z-value as an indicator of estimated effect size, as it reflects the average difference (in standard deviations) between the control group's mean and the case's score irrespective of sample size. We decided to follow their recommendations and report all these statistics, including their 95% confidence intervals, in an effort to objectify the described results. In order to calculate these values, we used the software package (Singlims_ES) designed for this purpose by Crawford and Garthwaite and available online (http://homepages.abdn.ac.uk/j.crawford/pages/dept/Single_Case_Effect_Sizes.htm). Because we hypothesized AI to perform worse than controls on the experimental tasks, all the reported *p*-values are one-tailed, unless otherwise specified.

3. Results

3.1. VVIQ

Consistent with her self-acknowledged complete lack of mental imagery, AI gave her mental images the lowest possible score of 16. The control participants' VVIQ scores were in a much higher range [mean = 61.1, SD = 7.6; $t_{(10)} = -5.66$, $p < .01$.; Fig. 4]. The control participant with the lowest score had an overall score of 51, which is an average of 3.2 per item. A rating of 3 corresponds to having a "*moderately clear and lively*" mental image. The subgroup (N = 4) of IQ-matched controls had an average VVIQ score of 59.8 [SD = 5.91; $t_{(3)} = -6.62$, $p < .01$]. Based on these VVIQ scores, we conclude that we are indeed comparing a genuinely aphantasic individual to a group of control participants with unimpaired visual mental imagery.

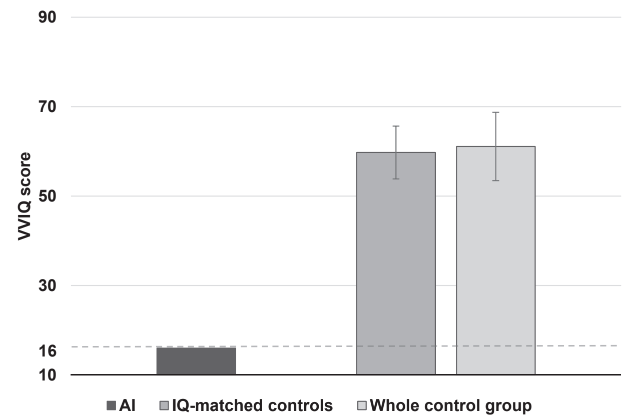

Fig. 4 – Vividness of Visual Imagery Questionnaire (VVIQ) scores. VVIQ scores of the aphantasic individual (AI; left; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray). Error bars represent standard deviations. Sixteen is the minimal score (dotted line).

3.2. WAIS-IV

AI's full-scale IQ was 126, whereas the average IQ of our control group was 116 (SD = 9.9). Within the control group there were four participants with a full-scale IQ of above 120, and an average full-scale IQ of exactly 126 (SD = 8.1). For all of the experimental tasks, as described in the next sections, we will compare the AI's score to both the whole control group, as well as the sub-group of the four IQ-matched control participants. AI's WMI score (122) was 10 points higher than that of IQ-matched controls. Thus, we conclude that AI's general working memory abilities are unimpaired.

3.3. Working Memory Capacity (WMC)

AI's performance was superior to the performance of the control group on nearly all tasks (see Table 2). However, as WM and IQ are inherently related and the control group's overall mean IQ is lower than AI's, it is more informative to compare her performance to that of the IQ-matched control group. Reflecting this relationship between working memory capacity and IQ, the difference in performance between AI and the sub-group of participants matched for IQ is much less pronounced (see Table 3). The only sub-test on which AI underperforms compared to controls is the sentence judgment part of the SS task (i.e., SSpt); AI shows about 10–12 percent worse performance (.80) than the IQ-matched [mean = .92; $t_{(3)} = -1.45$, $p = .12$] and general control group [mean = .90; $t_{(10)} = -1.60$, $p = .071$], respectively, but these differences did not reach statistical significance. This finding is in line with the pattern of results on the WAIS-IV in which

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Table 2 – Descriptives, significance tests, and effect sizes for the comparison between AI and the overall control group.

Task	Control group			AI	Significance test		Effect size		
	n	Mean	SD		t	*p* (1-tailed)	ES	Lower	Upper
VVIQ	11	61.09	7.63	16	−5.66	>.01 (*)	−5.91	−8.51	−3.29
WAIS Subscales									
VCI	11	119.91	9.38	110	−1.01	.17			
PRI	11	113.09	10.99	125	1.04	.84			
WMI	11	104.54	11.27	122	1.48	.92			
PSI	11	110.36	11.39	127	1.40	.90			
WMC battery									
MU	11	.59	.15	.70	.70	.75			
OS	11	.66	.12	.77	.88	.80			
OSpt	11	.86	.07	.93	.96	.82			
SS	11	.69	.11	.75	.52	.69			
SSpt	11	.90	.06	.80	−1.60	.071			
SSTM	11	.84	.04	.88	.96	.82			
WM/IM									
Accuracy									
WM	11	.90	.04	.87	−.65	.26			
IM	11	.89	.04	.85	−.91	.19			
Confidence									
WM	10	3.01	.54	3.13	.22	.58			
IM	10	2.95	.49	3.05	.20	.57			
Metacognitive accuracy									
WM	10	.75	.43	1.10	.78	.77			
IM	10	.64	.50	.75	.21	.58			
CD									
Accuracy									
Color	11	.86	.09	.92	.61	.72			
Shape	11	.73	.06	.73	−.08	.47			
Either shape	11	.70	.07	.81	1.39	.90			
Either Color	11	.79	.09	.96	1.84	.95			
Binding	11	.64	.08	.73	1.12	.86			

Asterisk indicates *p*-value smaller than alpha (.05).

AI outperformed controls on all but the verbal subscale (see Table 2). In summary, AI's general working memory capacity is unimpaired with the possible exception of verbal working memory potentially due to a general impairment in verbal information processing.

3.4. *WM and IM tasks*

Control participants performed well on both the WM as well as the IM version of the task (means of 90 and 89%, respectively). Accuracy on both the WM and the IM version of the task was slightly higher (2–3%) in the control group than was AI's performance, but none of these differences were (close to) significant ($p > .40$; Fig. 5). This result is quite striking, as we would expect that AI's absence of mental imagery would give her a disadvantage, at least in the imagery condition in which participants had to mentally construct the visual stimuli themselves. However, her performance on neither task appears to suffer from her aphantasia. Confidence data were also very similar between the controls and AI (Confidence ratings were not recorded in one participant and we therefore had to exclude their data from these analyses). Confidence levels were generally high, with an average confidence rating of approximately 3 (out of 4) in both versions of the task (see Tables 2 and 3). Thus, AI's aphantasia did neither affect accuracy nor confidence in a negative way.

We then calculated the average confidence for trials on correct versus incorrect trials, and subsequently subtracted these numbers. The resulting statistic reflects metacognitive accuracy, i.e., how adequately a participant can distinguish between their correct and incorrect responses. When comparing AI to the IQ-matched controls on this measure, an interesting dissociation appears. There is no difference in metacognitive accuracy for working memory, but AI's metacognitive accuracy is significantly reduced for the IM version of the task [$t_{(2)} = -3.15$, $p = .044$; Fig. 6]. This is driven by a significant difference in average rating for the inaccurate trials [$t_{(2)} = 4.579$, $p = .045$, two-tailed], which AI endorses with a higher confidence rating (2.41) than IQ-matched controls (mean = 1.95).

Data was also investigated per level of difficulty. In the most difficult condition, AIs performance (67% correct) was worse than controls in the working memory version, but not in the imagery version of the task, both when compared to the overall control group [80% correct; $t_{(10)} = -2.11$, $p = .031$; effect size $z = -2.20$ (CI = −3.31: −1.07)] as well as when compared to the IQ-matched controls although this difference did not quite reach statistical significance [83% correct; $t_{(3)} = -2.20$, $p = .058$; effect size $z = -2.46$ (CI = −4.55: −.35); Fig. 7]. There were no significant differences or trends towards differences between AI and controls in the easier conditions, and there were no difficulty effects on the confidence ratings or metacognitive

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Table 3 – Descriptives, significance tests, and effect sizes for the comparison between AI and the IQ-matched control group.

Task	Control group			AI	Significance test		Effect size		
	n	Mean	SD		t	*p* (2-tailed)	ES	Lower	Upper
VVIQ	4	59.75	5.91	16	−6.62	<.01 (*)	−7.40	−13.14	−1.87
WAIS Subscales									
VCI	4	127.00	4.08	110	−3.73	.017 (*)	−4.16	−7.47	−.92
PRI	4	121.50	9.15	125	.34	.62			
WMI	4	111.50	7.55	122	1.24	.85			
PSI	4	119.25	12.82	127	.54	.69			
WMC battery									
MU	4	.70	.09	.70	.05	.52			
OS	4	.70	.12	.77	.52	.68			
OSpt	4	.92	.04	.93	.23	.58			
SS	4	.73	.10	.75	.22	.58			
SSpt	4	.92	.07	.80	−1.45	.12			
SSTM	4	.87	.03	.88	.28	.60			
WM/IM									
Accuracy									
WM	4	.91	.05	.87	−.75	.26			
IM	4	.89	.06	.85	−.60	.30			
Confidence									
WM	3	3.08	.44	3.13	.11	.54			
IM	3	3.00	.18	3.05	.26	.58			
Metacognitive accuracy									
WM	3	.92	.18	1.10	.87	.76			
IM	3	1.15	.11	.75	−3.15	.044 (*)	−3.64	−7.13	−.29
CD									
Accuracy									
Color	4	.93	.04	.92	−.23	.42			
Shape	4	.78	.05	.73	−.93	.21			
Either shape	4	.74	.08	.81	.81	.76			
Either color	4	.86	.07	.96	1.26	.85			
Binding	4	.66	.09	.73	.66	.72			

Asterisks indicate *p*-values smaller than alpha (.05).

performance either. This result might reflect control participants resorting to mental imagery when the target dot appears too close to the original image contours, a strategy which is unavailable to AI. To test this hypothesis, we calculated the linear correlation between WM accuracy and VVIQ scores in our control sample. The resultant Pearson's linear correlation coefficient showed a positive trend (Pearson's $r = .55$; $p = .079$, uncorrected) (Fig. 8). We also calculated correlations with VVIQ for accuracies in the other difficulty conditions and for accuracies in the different levels of the IM version of the task. None of these showed any trends towards significance (all *p*-values >.17, uncorrected).

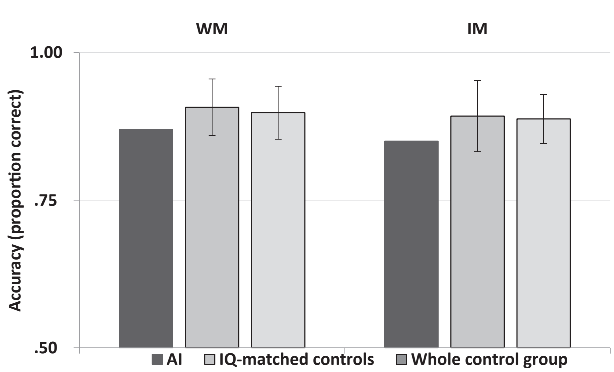

Fig. 5 – Performance on Visual Working Memory (WM) and Mental Imagery (IM) tasks. Proportion of correct trials per task (left: WM; right: IM) for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray). Error bars represent standard deviations. .5 is chance level.

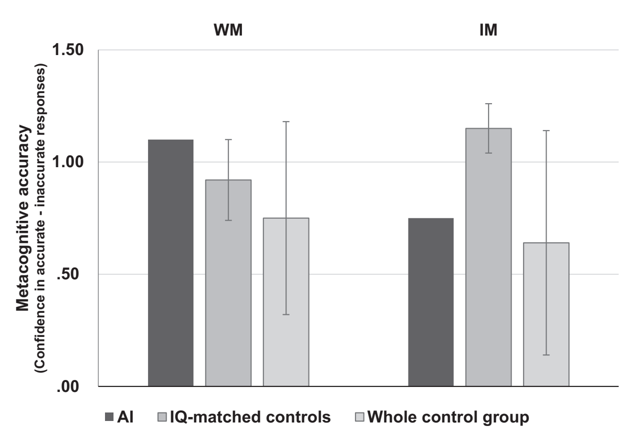

Fig. 6 – Metacognitive accuracy. Difference scores between the average confidence rating for correct and the average confidence rating for incorrect trials split out for the Visual Working Memory (WM) and Mental Imagery (IM) tasks. Bars represent differences scores for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 3; intermediate gray), and the overall control group (N = 10; light gray). Error bars represent standard deviations.

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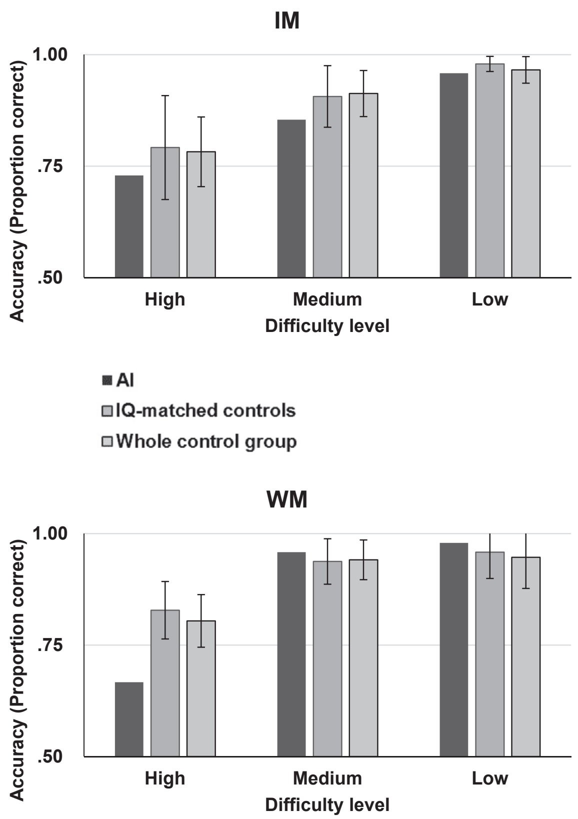

Fig. 7 – Performance on Visual Working Memory (WM) and Mental Imagery (IM) tasks split out for difficulty level. Proportion of correct trials per task (lower panel: WM; upper panel: IM) for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray) per level of difficulty (left: high; middle: medium; right: low). Difficulty was based on the relative difference between the boundary of the geometric shape and the location of the target stimulus. Error bars represent standard deviations. .5 is chance level.

Altogether, we conclude that even though overall task performance on neither one of the tasks is any different for AI than for control participants, her metacognitive accuracy is lower when a task involves mental imagery, but not when it simply requires visual working memory. Surprisingly, however, AI's visual working memory seems to be less precise than controls', as reflected by her performance drop in the most difficult condition; a property which does not transfer to the mental imagery version of the task.

3.5. *Change detection task*

The accuracy data for the overall control group closely resemble the data pattern as reported in the original paper by Wheeler and Treisman (2002) with color conditions being easier than shape conditions, single-feature conditions being easier than *either* conditions (in which participants did not know beforehand whether the color or shape were changing on non-match trials) and the binding condition being the hardest. However, AI's performance pattern is deviant. As in controls, AI performs worst in the binding condition and color conditions are harder than shape conditions, but unlike controls, AI performs better in the either conditions, rather than in the single feature conditions. We investigated this pattern further by computing difference scores between both color conditions and both shape conditions for all participants and running our significance tests on these values. For the color feature, there is no significant difference between AI and the controls (ps > .20, two-tailed; Fig. 9). However, there was a trend in the direction of better performance in the *either* blocks for the shape conditions both for the overall control group [$t_{(10)} = -1.881$, $p = .090$, two-tailed], and the IQ matched controls [$t_{(3)} = -2.957$, $p = .060$, two-tailed; Fig. 10]. These analyses were all run on the data collapsed across load. There were no load-specific effects in the data.

4. Discussion

In order to investigate the functional role of mental imagery in visual working memory, we compared performance of a congenitally aphantasic individual to that of a group of age-matched controls on a number of different (visual) working memory aspects. The first surprising result was that her performance in the mental imagery task did not differ from controls. However, her metacognitive performance on this task was lower than that of controls; specifically, she overestimated her own performance on inaccurate trials. Thus, although she was able to perform a task that was designed to require mental imagery, she lacked insight into her performance. Secondly, we found that when visual working memory required a high level of precision, her performance was worse than that of control participants. Furthermore, within our control sample high-precision working memory tended to correlate with self-rated imagery vividness. Together, these results indicate that although a lack of mental imagery can be compensated for under some conditions, it may be important for high precision WM as well as metacognition.

4.1. *Intact performance on a mental imagery task*

Because the intact performance of AI on the mental imagery task is in essence a null result, we need to be careful in our interpretations of this (lack of a) finding. But since it touches upon the essential question of the functional relevance of mental imagery, it deserves to be discussed nonetheless.

Unimpaired performance on an imagery task in an aphantasic individual, who by definition cannot engage in mental image generation, could mean either of two things; 1) the task does not qualify as a mental imagery task, in the sense that non-aphantasic participants do not utilize mental imagery when executing it, or 2) even though control participants do employ mental imagery, our aphantasic participant has developed an alternative strategy in order to achieve decent performance levels. We consider the second explanation to be the most plausible.

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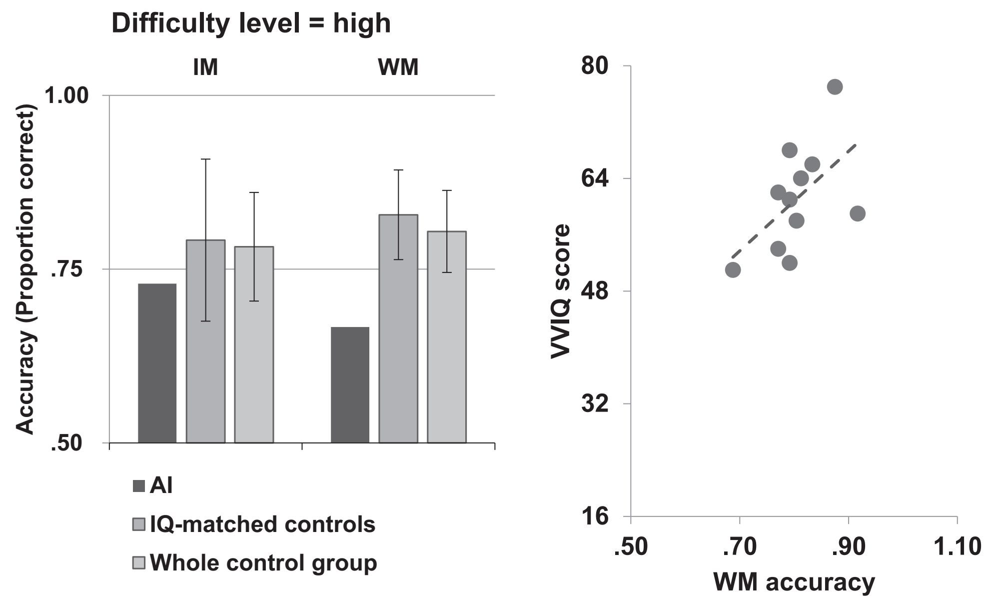

Fig. 8 – Performance on Visual Working Memory (WM) and Mental Imagery (IM) tasks for the most difficult condition. Left panel: Proportion of correct trials per task (right: WM; left: IM) for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray) for the most difficult condition only. Right panel: Scatterplot depicting the relation between average WM accuracy on the most difficult trials and Vividness of Visual Imagery Questionnaire (VVIQ) score within the control group. The slope of the dotted trend line is .55 (Pearson's R).

The mental imagery task was designed in such a way that participants were never physically presented with the information they based their responses on, i.e., the contours of the geometric shape they were instructed to imagine. This is the fundamental difference from the working memory version of the task. However, instead of generating a mental image at the start of each trial and actively keeping it on-line during the delay interval, participants simply might have remembered the spatial location of the place holders and created the mental image only at the test stage of the trial. In doing so they would have knowingly disregarded task instructions, but they might have resorted to this strategy nonetheless if it were less effortful or exhausting. In either case, control participants engaged in mental imagery at some point during task execution and their behavioral performance therefore reflects a series of cognitive processes involving mental imagery.

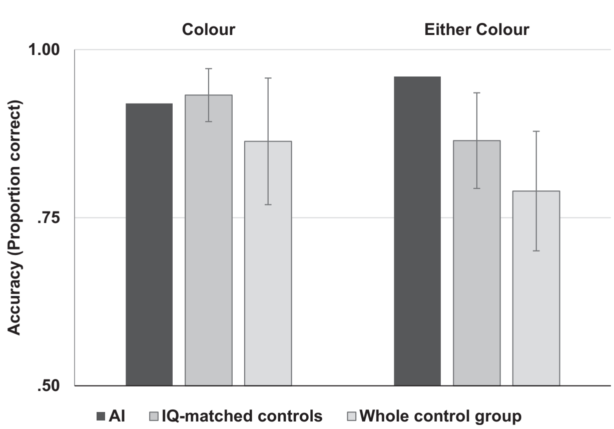

Fig. 9 – Performance for single feature and multi-feature color trials. Proportion of correct trials for the single feature color condition (Color; left) and multi-feature color condition (Either Color; right) for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray) per level of difficulty (left: high; middle: medium; right: low). Error bars represent standard deviations. .5 is chance level.

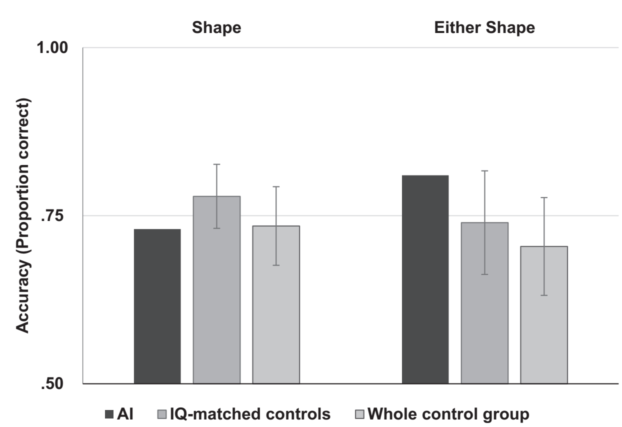

Fig. 10 – Performance for single feature and multi-feature shape trials. Proportion of correct trials for the single feature shape condition (Shape; left) and multi-feature shape condition (Either Shape; right) for the aphantasic individual (AI; darkest gray), IQ-matched controls (N = 4; intermediate gray), and the overall control group (N = 11; light gray) per level of difficulty (left: high; middle: medium; right: low). Error bars represent standard deviations. .5 is chance level.

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Also, not all behavioral measures showed such similarities, as the metacognitive performance of controls was much better than that of AI. This does not fit well with the view that AI and controls use identical cognitive strategies, and therefore we consider it most likely that controls were in fact engaging in mental imagery while AI found an alternative way of reaching high performance levels, but at the cost of metacognitive insight. Zeman et al. (2010) also reported fairly intact mental imagery performance, but with unusual overall patterns of behavior, in a case of acquired aphantasia, which they also take as evidence for alternative strategy employment by their patient. They suggested that he might have generated mental representations in a propositional, verbal code, rather than as an actual perceivable image. This idea originates from the work of Zenon Pylyshyn who proposed that mental imagery is not identical to visual perception, but that the visual experiences which typically accompany imagery are in fact the result of people inferring what they would see if they were to witness the stored information (Pylyshyn, 1973, 2003a,b). Our aphantasic participant's introspective reports are in line with the concept of mental imagery being a form of ‘knowledge’ rather than ‘perception’, because she reports simply ‘knowing’ what the correct answer is on this or any other (everyday) task requiring mental imagery. This does not necessarily imply knowledge stored verbally, but could also involve a ‘spatial’ code, which represents the spatial relations between the presented visual items during the encoding stage.

A more speculative explanation is that aphantasic individuals in fact use mental imagery to perform mental imagery tasks, but without conscious awareness of the resultant mental representation. A distinction has been made between the underlying structure of the representation and its conscious experience. In some views, the term “imagery” does not refer to subjective experience, but, rather, to a hypothetical picture-like representation (or inner representation of any sort) in the mind and brain that can give rise to quasi-perceptual conscious experience (Block, 1983). Possibly, aphantasic individuals are capable of the former but not the latter.

4.2. *Impaired high-precision working memory*

In the working memory experiment, the encoding and maintenance stages were identical across trials of all difficulty levels. Rather, trials differed at the retrieval stage, because task difficulty was defined by the spatial location of the target stimulus (which needed to be compared to the outer contours of the memory item). The selective deficit for high-precision working memory in our aphantasic individual thus could not have arisen from strategy adjustment at trial onset. It either resulted 1) from an overall difference in strategy that only emerged behaviorally on difficult trials, or 2) from a cognitive difference that only arose after target stimulus presentation. In the former case, controls might have utilized mental imagery when performing the visual working memory task, whereas AI created a different type of representation (e.g., propositions, spatial or verbal code, see previous section). Assuming that images can be maintained with a higher level of detail compared to other types of mental representation, on easy trials the non-pictorial representation would offer enough quality to adequately perform the working memory task, but when high-precision is required, its coarseness will have a measurable, negative effect on performance. The very high levels of accuracy on the intermediate and difficult trials for both controls and AI could indeed indicate ceiling effects, which explains the lack of any performance difference in these conditions. However, this fails to explain why these difficulty effects are specific to the working memory task.

Alternatively, on those difficult WM trials, controls may have begun to use visual imagery at the test phase (i.e., they may have constructed a mental image in order to perform the task more effectively). The use of this additional cognitive process was not available to AI due to her inability to engage in imagery – she had to rely solely on WM processes. In other words, the ability of controls (but not of AI) to use imagery to boost performance on difficult trials may underlie AI's worse performance on those trials. This is supported by the finding that for controls, imagery vividness correlated with WM performance for difficult trials. In the imagery task, there would have been no such possibility for the controls to engage in an additional cognitive process to enhance performance (as they were already engaged in imagery as per task requirement). If AI adopted the same strategy for both tasks, measures of her performance across the two tasks could be prone to learning effects. Indeed, the current effect appeared to be driven by AI's better performance on the mental imagery than on the working memory task (note that task order was working memory session followed by mental imagery session across all participants; see Table 1). On the other hand, varied cognitive operations between high-precision working memory and mental imagery tasks can explain the absence of a similar learning effect in controls.

So far, we have considered what role mental imagery potentially plays in working memory, but in fact the association could be reversed. Then the mental imagery difficulties that AI experiences would originate from a visual working memory deficit. According to Robert Logie (2003), mental image generation relies on the so-called central executive; a non-sensory system that drives the phonological and visuo-spatial slave systems in which information is actually maintained. However, if impaired executive processing would underlie aphantasia, then instead of only affecting high-precision visual working memory, AIs scores on other (working memory) tasks would have been hampered as well. But both her score on the working memory subscale of the WAIS-IV (WMI) and her working memory capacity proved similar or better than controls'. This leaves the visuo-sketchpad as the potential working memory component affected in aphantasia. There is indeed evidence showing mental image formation is prevented by loading the visuo-spatial sketchpad with dynamic visual noise (Baddeley & Andrade, 2000). Moreover, AI could have relied on the other slave system, i.e., the phonological loop, while executing the working memory tasks of the WAIS-IV and the working memory capacity battery. Still, the specificity of AIs working memory deficits and the lack of any mental imagery impairments seem to be at odds with the broad functionality of the visuo-spatial sketchpad. The visuo-spatial sketchpad has been suggested to consist of two sub-

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components with different functionalities: a passive visual cache which stores information about shape and color, and an inner scribe which stores motion and spatial information and is involved in active short-term memory processing (Logie, 1995, 2003). Perhaps aphantasia is linked to difficulties in either one of these subsystems specifically. Unfortunately, we did not isolate the related visual memory processes with any of the tasks we included, so we cannot look to our data to shed light on this issue.

Recent studies on individual differences of visual working memory and mental imagery have demonstrated a relation with primary visual cortex (V1) size. Bergmann, Genc, Kohler, Singer, & Pearson, (2016b) found that individuals with a smaller V1 experience more vivid, but less precise mental imagery. Conceivably, mental imagery vividness is a continuously distributed population variable, which suggests AI could be one of the individuals at the lower end of the spectrum with a corresponding larger V1. Inconsistent with the mental imagery findings of Bergmann et al. (2016b) however, she also shows a lower *precision* of visual working memory. A similar study on visual working memory has so far shown a positive correlation between working memory capacity and V1 size (Bergmann, Genc, Kohler, Singer, & Pearson, 2016a), but memory precision was not varied in this design. Future MRI work is needed to elucidate the relation between V1 size and different aspects of visual cognition in aphantasic individuals. Specifically, such studies could shed light on whether the (neuroanatomical) difference between imagers and non-imagers is qualitatively different or not.

4.3. *Single-feature versus multi-feature memory*

We originally included the Wheeler and Treisman (2002) task because we were interested in the binding condition particularly. Based on our earlier theoretical work (Jacobs & Silvanto, 2015) in which we link mental imagery to feature-binding, we hypothesized that feature-binding might be more effortful in aphantasic individuals. However, we did not find a negative effect of aphantasia on binding. If anything, AI performed better than controls in this condition (see Tables 2 and 3). Furthermore, AIs visual working memory is less sensitive to the number of to-be-remembered features than controls. This could mean that she applies a form of chunking, i.e., items are remembered as integrated objects, not as a collection of separate features (Luck & Vogel, 1997), whereas controls store all features separately. Performance in the binding condition should have benefited from chunking. Although there is a significant drop in AI's performance from the four other conditions to the binding condition, she still outperforms controls (see Tables 2 and 3). However, we did not statistically test for this positive effect, because it was not part of our a priori hypotheses. Also, there is no apparent reason as to why aphantasia would be associated with chunking in visual working memory. Alternatively, as participants knew before the start of each block whether it was going to be a single-feature or multi-feature block, they could have increased motivation or put more effort into these blocks to compensate for increased difficulty. Since trial-by-trial feedback was given as well, participants were well aware of their relative performance across conditions. But, again, there does not seem to be an evident reason why AI's motivation would surpass controls'.

5. Conclusion

What do these results tell us about the functional role of mental imagery in visual working memory? First, that for many tasks that supposedly involving mental imagery there are alternative cognitive strategies that lead to equally successful behavior. This by no means implies that mental imagery has no part to play in working memory whatsoever; there are circumstances in which the visual experience of stored content contributes to working memory. Here we have identified high-precision task demands as one of them, but there might be others. In more general terms, this study has shown the potential of using aphantasia as a model for studying the functional relevance of mental imagery for visual cognition.

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