

1 Quantifying Aphantasia through drawing: Those without visual imagery  
2 show deficits in object but not spatial memory

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20 **Author Contributions**

21 W.A.B., Z.P., and C.I.B. conceived the study. W.A.B. and Z.P. collected and analyzed the data. All  
22 authors wrote the manuscript.

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26

## Abstract

27

28           Congenital aphantasia is a recently characterized experience defined by the inability to  
29 form voluntary visual imagery, in spite of intact semantic memory, recognition memory, and  
30 visual perception. Because of this specific deficit to visual imagery, aphantasia serves as an ideal  
31 population for probing the nature of representations in visual memory, particularly the  
32 interplay of object, spatial, and symbolic information. Here, we conducted a large-scale online  
33 study of aphantasics and revealed a dissociation in object and spatial content in their memory  
34 representations. Sixty-one aphantasics and matched controls with typical imagery studied real-  
35 world scene images, and were asked to draw them from memory, and then later copy them  
36 during a matched perceptual condition. Drawings were objectively quantified by 2,795 online  
37 scorers for object and spatial details. Aphantasics recalled significantly fewer objects than  
38 controls, with less color in their drawings, and an increased reliance on verbal scaffolding.  
39 However, aphantasics showed incredibly high spatial accuracy, equivalent to controls, and  
40 made significantly fewer memory errors. These differences between groups only manifested  
41 during recall, with no differences between groups during the matched perceptual condition.  
42 This object-specific memory impairment in aphantasics provides evidence for separate systems  
43 in memory that support object versus spatial information.

44

45 Keywords: Mental imagery; Object Information; Spatial Information; False Memory; Memory  
46 Recall

47

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## Introduction

49

50           Visual imagery, the ability to form visual mental representations, is a common human  
51 cognitive experience, yet it has been hard to characterize and quantify. What is the nature of  
52 the images that come to mind when forming visual representations of objects or scenes? What  
53 might these representations look like if one lacks this ability? *Aphantasia* is a recently  
54 characterized experience, defined by an inability to create voluntary visual mental images,

55 although semantic memory and vision remain intact (Zeman, Dewar, & Della Sala, 2015; Keogh  
56 & Pearson, 2017). Aphantasia is still largely uncharacterized, with many of its studies based on  
57 case studies or employing small sample sizes. Here, using an online crowd-sourced drawing task  
58 designed to quantify the content of visual memories (Bainbridge, Hall, & Baker, 2019), we  
59 examine the nature of aphantasics' mental representations of visual images within a large  
60 sample, and reveal evidence for separate object and spatial systems in human imagery.

61 Although some cases reporting an absence of mental imagery were first identified in the  
62 19<sup>th</sup> century (Galton, 1880), the term *aphantasia* has only recently been defined and  
63 investigated, within fewer than a dozen studies (Zeman et al., 2015; Keogh & Pearson, 2017;  
64 Jacobs, Schwarzkopf, & Silvanto, 2018; Brons, 2019; Wicken, Keogh, Pearson, Unpublished  
65 results). This is arguably because most individuals with aphantasia can lead functional,  
66 professional lives, with many individuals realizing their imagery experience differed from the  
67 majority only in adulthood. The current method for identifying if an individual has aphantasia is  
68 through subjective self-report, using the Vividness of Visual Imagery Questionnaire (Marks,  
69 1973). However, recent research has begun quantifying the experience using objective  
70 measures such as priming during binocular rivalry (Keogh & Pearson, 2017) and skin  
71 conductance during reading (Wicken et al., Unpublished results). Since its identification, several  
72 prominent figures have come forth describing their experience with aphantasia, including  
73 economics professor Nicholas Watkins (Watkins, 2018), Firefox co-creator Blake Ross (Ross,  
74 2016), and former Pixar Chief Technology Officer Ed Catmull (Gallagher, 2019), leading to  
75 broader recognition of the experience.

76 Like congenital prosopagnosia (Behrmann & Avidan, 2005), in the absence of any brain  
77 damage or trauma, aphantasia is considered to be congenital (although it can also be acquired  
78 through trauma; Zeman et al., 2010; Thorudottir et al., 2020). However, beyond this, little  
79 research has examined the nature of aphantasia and the impact on imagery function and  
80 cognition more broadly. A single-participant aphantasia case study found no significant  
81 difference from controls in a visual imagery task (judging the location of a target in relation to  
82 an imagined shape) nor its matched version of a working memory task, except at the hardest  
83 level of difficulty (Jacobs et al., 2018). However, aphantasics show significantly less imagery-

84 based priming in a binocular rivalry task (Keogh & Pearson, 2017; Pearson, 2019), and show  
85 diminished physiological responses to fearful text as compared with controls (Wicken et al.,  
86 Unpublished results). While these studies have observed differences between aphantasics and  
87 controls, the nature of aphantasics' mental representations during visual recall is still unknown.  
88 Understanding these differences in representation between aphantasics and controls could  
89 shed light on broader questions of what information (visual, semantic, spatial) makes up a  
90 memory, and how this information compares to the initial perceptual trace. In fact, the  
91 existence of aphantasia serves as key evidence against the hypothesis that visual perception  
92 and imagery rely upon the same neural substrates and representations (Dijkstra, Bosch, & van  
93 Gerven, 2019), and also suggests a dissociation of visual recognition and recall (as aphantasia  
94 only affects the latter). Examination into aphantasia thus has wide-reaching potential  
95 implications for the understanding of the way we form mental representations of our world.

96         The nature and content of our visual imagery has proved incredibly difficult to quantify.  
97 Several studies in psychology have developed tasks to objectively study the cognitive process of  
98 mental imagery through visual working memory or priming (e.g., Marks, 1973; Marmor &  
99 Zaback, 1976; Brandt & Stark, 1997). One of the long-standing debates within the imagery  
100 literature has been over the nature of images, and specifically whether visual imagery  
101 representations are depictive and picture-like in nature (Kosslyn, 1980; Kosslyn 2005) or  
102 symbolic, "propositional" representations (Pylyshyn, 1981; Pylyshyn, 2003). Neuropsychological  
103 research, especially in neuroimaging, has led to large leaps in our understanding of visual  
104 imagery. Studies examining the role and activation of the primary visual cortex during imagery  
105 tasks have been interpreted as supporting the depictive nature of imagery (Ishai, Ungerleider, &  
106 Haxby, 2000; Kosslyn, Ganis, & Thompson, 2001; Schacter et al., 2012; Pearson & Kosslyn, 2015).  
107 However, neuropsychological studies have identified patients with dissociable impairments in  
108 perception versus imagery (Behrmann, 2000; Bartolomeo, 2008), and recent neuroimaging  
109 work has suggested there may be systematically related yet separate cortical areas for  
110 perception and imagery, and that the neural representation during recall may lack much of the  
111 richer, elaborative processing of the initial perceptual trace (Xiao et al., 2017; Silson et al., 2019;  
112 Bainbridge, Hall, & Baker, Unpublished results). Combined with research identifying situations

113 where propositional encoding dominates spatial imagery (e.g., Stevens & Coupe, 1978),  
114 researchers have concluded that there is a role for both propositional and depictive elements in  
115 the imagery process (e.g., Denis & Cocude, 1989). In their case study, Jacobs and colleagues  
116 (2018) argue that differences in performance between aphantasic participant *AI* and  
117 neurotypical controls may result from different strategies, including a heavier reliance on  
118 propositional encoding, relying on a spatial or verbal code. Thus, ideally a task that measures  
119 both depictive (visual) and propositional (semantic) elements of a mental representation could  
120 directly compare the strategies used by aphantasics and controls. In a recent study, impressive  
121 levels of both object and spatial detail could be quantified by drawings made by neurotypical  
122 adults in a drawing-based visual memory experiment (Bainbridge et al., 2019). Such drawings  
123 allow a more direct look at the information within one's mental representation of a visual  
124 image, in contrast to verbal descriptions or recognition-based tasks. Thus, a drawing task may  
125 allow us to identify what fundamental differences exist between aphantasics and individuals  
126 with typical imagery, and in turn inform us of what information exists within imagery.

127 In the current study, we examine the visual memory representations of congenital  
128 aphantasics and individuals with typical imagery (controls) for real-world scene images.  
129 Through online crowd-sourcing, we leverage the power of the internet to identify and recruit  
130 large numbers of both aphantasic and controls for a memory drawing task. We also recruit over  
131 2,700 online scorers to objectively quantify these drawings for object details, spatial details,  
132 and errors in the drawings. We discover a selective impairment in aphantasics for object  
133 memory, with significantly fewer visual details and evidence for increased semantic scaffolding.  
134 In contrast, for the items that they remember, aphantasics show spatial accuracy at the same  
135 high level of precision as controls. Aphantasics also show fewer memory errors and memory  
136 correction as compared to controls. These results may point to two systems that support object  
137 information versus spatial information in memory.

138

## 139 Materials and Methods

140

### 141 **Participants**

142 N=123 adults participated in the main online drawing recall experiment, while 2,795  
143 adults participated in online scoring experiments on Amazon Mechanical Turk (AMT) of the  
144 drawings from the main experiment. Aphantasic participants for the main experiment were  
145 recruited from aphantasia-specific online forums, including “Aphantasia (Non-Imager/Mental  
146 Blindness) Awareness Group”, “Aphantasia!” and Aphantasia discussion pages on Reddit.  
147 Control participants for the main experiment were recruited from the population at the  
148 University of Westminster, online social media sites such as Facebook and Twitter pages for the  
149 University of Westminster Psychology, and “Participate in research” pages on Reddit. Scoring  
150 participants were recruited from the general population of AMT.

151 Aphantasic participants were identified by their score on the Vividness of Visual Imagery  
152 Questionnaire (VVIQ), a self-report measure of the vividness of one’s visual mental images  
153 (Marks, 1973). The VVIQ currently serves as the main tool for identifying aphantasia (although  
154 there are other methods, see Keogh & Pearson, 2017). Scores on the VVIQ range from 16 to 80,  
155 with aphantasics defined by VVIQ scores  $\leq 25$  and control VVIQ scores  $\geq 40$ . Eight participants  
156 were removed from the analyses for having scores between 26 and 39, and two participants  
157 were removed for skipping more than  $\frac{1}{4}$  of the questions in the VVIQ. Of the remaining  
158 participants, there were 61 aphantasics and 52 control participants.

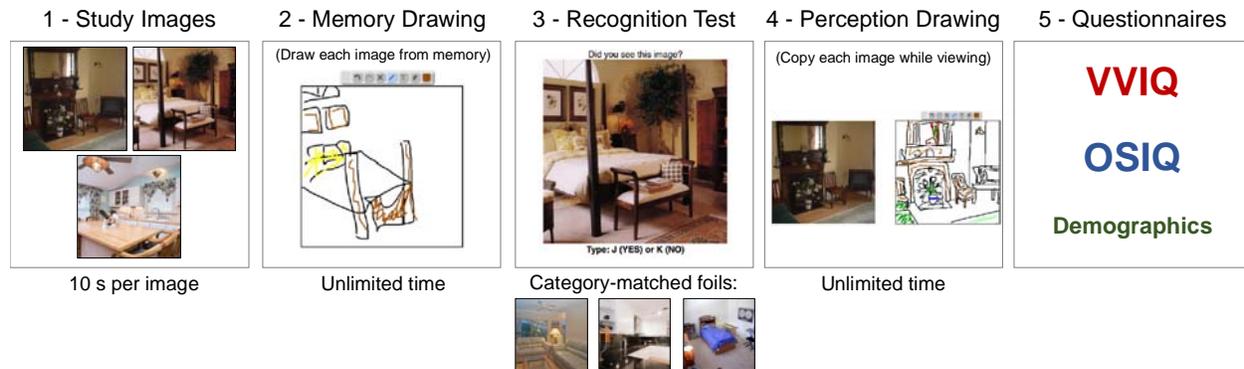
159 No personally identifiable information was collected from any participants, and  
160 participants had to acknowledge participation in order to continue, following the guidelines  
161 approved by the University of Westminster Psychology Ethics Committee (ETH1718-2345) and  
162 the National Institutes of Health Office of Human Subjects Research Protections (18-NIMH-  
163 00696).

164

### 165 **Main Experiment: Drawing Recall Experiment**

166 The Drawing Recall Experiment was a fully online memory experiment that consisted of  
167 five sections ordered: 1) study phase, 2) recall drawing phase, 3) recognition phase, 4) copied  
168 drawing (perception) phase, and 5) questionnaires and demographics. The methods of the  
169 experiment are summarized in Fig. 1.

170



171

172 **Fig. 1.** The experimental design of the online experiment. Participants 1) studied three separate scene  
173 photographs presented sequentially, 2) drew them from memory, 3) completed a recognition task, 4) copied  
174 the images while viewing them, and then 5) filled out the VVIQ and OSIQ questionnaires in addition to  
175 demographics questions. The whole experiment took approximately 30 minutes.

176

177 First, for the study phase, participants were told to study three images in as much detail  
178 as possible. The images were presented at 500 x 500 pixels. They were shown each image for  
179 10 s, presented in a randomized order with a 1 s interstimulus interval (ISI). These three images  
180 (see Fig 1a) were selected from a previously validated memory drawing study (Bainbridge et al.,  
181 2019), as the images with the highest recall success, highest number of objects, and several  
182 unique elements compared to a canonical representation of its category. For example, the  
183 kitchen scene does not include several typical kitchen components such as a refrigerator,  
184 microwave, or stove, and does include more idiosyncratic objects such as a ceramic chef, zebra-  
185 printed chairs, and a ceiling fan. This is important as we want to assess the ability to recall  
186 unique visual information beyond just a coding of the category name (e.g., just drawing a  
187 typical kitchen). Participants were not informed what they would do after studying the images,  
188 to prevent targeted memory strategies.

189

190 Second, the recall drawing phase tested what visual memory representations  
191 participants had for these images through drawing. Participants were presented with a blank  
192 square with the same dimensions as the original images and told to draw an image from  
193 memory in as much detail as possible using their mouse. Participants drew using an interface  
194 like a simple paint program. They could draw with a pen in multiple colors, erase lines, and  
undo or redo actions. They were given unlimited time and could draw the images in any order.

195 They were also instructed that they could label any unclear items. Once a participant finished a  
196 drawing, they then moved onto another blank square to start a new drawing. They were asked  
197 to create three drawings from memory, and could not go back to edit previous drawings. As  
198 they were drawing, their mouse movements were recorded to track timing and erasing  
199 behavior. These drawings were later quantified by online scorers in a series of separate  
200 experiments (see Online Scoring Experiments below).

201 Third, the recognition phase tested whether there was visual recognition memory for  
202 these specific images. Participants viewed images and were told to indicate whether they had  
203 seen each image before or not. The images consisted of the three images presented in the  
204 study phase as well as three new foil images of the same scene categories (kitchen, bedroom,  
205 living room). Matched foils were used so that recognition performance could not rely on  
206 recognizing the category type alone. All images were presented at 500 x 500 pixels. Participants  
207 were given unlimited time to view the image and respond, and a fixation cross appeared  
208 between each image for 200 ms.

209 Fourth, the copied drawing phase had participants copy the drawings while viewing  
210 them, in order to see how participants perceive each image in the absence of a memory task.  
211 This phase gives us an estimate of the participant's drawing ability and ability to use this  
212 drawing interface with a computer mouse to create drawings. This phase also measures the  
213 maximum information one might draw for a given image (e.g., you won't draw every plate  
214 stacked in a cupboard). Participants saw each image from the study phase presented next to a  
215 blank square. They were instructed to copy the image in as much detail as possible. The blank  
216 square used the same interface as the recall drawing phase. When they were done, they could  
217 continue onto the next image, until they copied all three images from the study phase. The  
218 images were tested in a random order, and participants had as much time as they wanted to  
219 draw each image, but could not go back to any completed drawings.

220 Finally, participants filled out three questionnaires at the end. They completed the  
221 previously mentioned VVIQ (Marks, 1973), which was mainly used to determine participant  
222 group membership. Participants also completed the more recent Object and Spatial Imagery  
223 Questionnaire (OSIQ) (Blajenkova, Kozhevnikov, & Motes, 2006), which measures visual

224 imagery preference for object information and spatial information, providing a score between  
225 15-75 for each subscore (object, spatial). Finally, participants provided basic demographics,  
226 basic information about their computer interface, and their experience with art. In these final  
227 questions, they indicated which component of the experiment was most difficult, and were  
228 able to write comments on why they found it difficult.

229

### 230 **Online Scoring Experiments**

231 In order to objectively and rapidly score the 692 drawings produced in the Drawing  
232 Recall Experiment, we conducted online crowd-sourced scoring experiments with a set of 2,795  
233 participants on AMT, an online platform used for crowd-sourcing of tasks. None of these  
234 participants took part in the Drawing Recall Experiment. For all online scoring experiments,  
235 scorers could participate in as many trials as they wanted, and were compensated for their time.

236 *Object Selection Study.* AMT scorers were asked to indicate which objects from the  
237 original images were in each drawing. This allows us to systematically measure how many and  
238 what types of objects exist in the drawings. They were presented with one drawing and five  
239 photographs of the original image with a different object highlighted in red. They had to click  
240 on all object images that were contained in the original drawing. Five scorers were recruited  
241 per object, with 909 unique scorers in total. An object was determined to exist in the drawing if  
242 at least 3 out of 5 scorers selected it.

243 *Object Location Study.* For each object, AMT scorers were asked to place and resize an  
244 oval around that object in the drawing, in order to get information on the location and size  
245 accuracy of the objects in the drawings. AMT scorers were instructed on which object to circle  
246 in the drawing by the original image with the object highlighted in red, and only objects  
247 selected in the Object Selection Study were used. Five scorers were recruited per object, with  
248 1,310 unique scorers in total. Object location and size (in both the x and y directions) were  
249 taken as the median pixel values across the five scorers.

250 *Object Details Study.* AMT scorers here indicated what details existed in the specific  
251 drawings. In a first AMT experiment, five scorers per object (N=304 total) saw each object from  
252 the original images and were asked to list 5 unique traits about the object (e.g., shape, material,

253 pattern, style). A list of unique traits was then created for each object in the images. In a second  
254 AMT experiment, scorers were then shown each object in the drawings (highlighted by the  
255 ellipse drawn in the Object Location Study), and had to indicate whether that trait described  
256 the drawn object or not. Five scorers were recruited per trait per drawn object, with 777  
257 unique scorers in total.

258 *False Objects Study.* AMT scorers were asked to indicate “false objects” in the  
259 drawings—what objects were drawn in the drawing that didn’t exist in the original image?  
260 Scorers were shown a drawing and its corresponding image and were asked to write down a list  
261 of all false objects. Nine scorers were recruited per drawing, with 337 unique scorers in total.  
262 An object was counted as a false object if at least three scorers listed it.

263

#### 264 **Additional Drawing Scoring Metrics and Analyses**

265 In addition to the Online Scoring Experiments, other attributes were collected for the  
266 drawings. A blind scorer (the corresponding author) went through each drawing presented in a  
267 random order (without participant or condition information visible) and had to code *yes* or *no*  
268 for if the drawing 1) contained any color, 2) contained any text, and 3) contained any erasures.  
269 Erasures were quantified by viewing the mouse movements used for drawing the image, to see  
270 if lines were drawn and then erased, and did not make it into the final image.

271 Throughout this manuscript, whenever parametric statistical tests were used to  
272 compare groups, we first confirmed the measures were not significantly different from a  
273 normal distribution, using the Kolmogorov-Smirnov test of goodness-of-fit.

274

#### 275 Results

276

277 With these memory and perceptual drawings, we can then make direct comparisons in  
278 the types of detail, amounts of detail, and types of errors that may differ between aphantasics  
279 and controls. First, we examine the demographic measures between the two groups, such as  
280 age, gender, art ability, and ratings on the OSIQ. Second, we turn to objective quantification of  
281 the drawings, and explore differences in the objects drawn by aphantasics and controls and

282 text-based strategies. Third, we compare spatial accuracy in the drawings between these two  
283 groups. Finally, we compare the presence of memory errors, quantifying the number of falsely  
284 inserted additional objects.

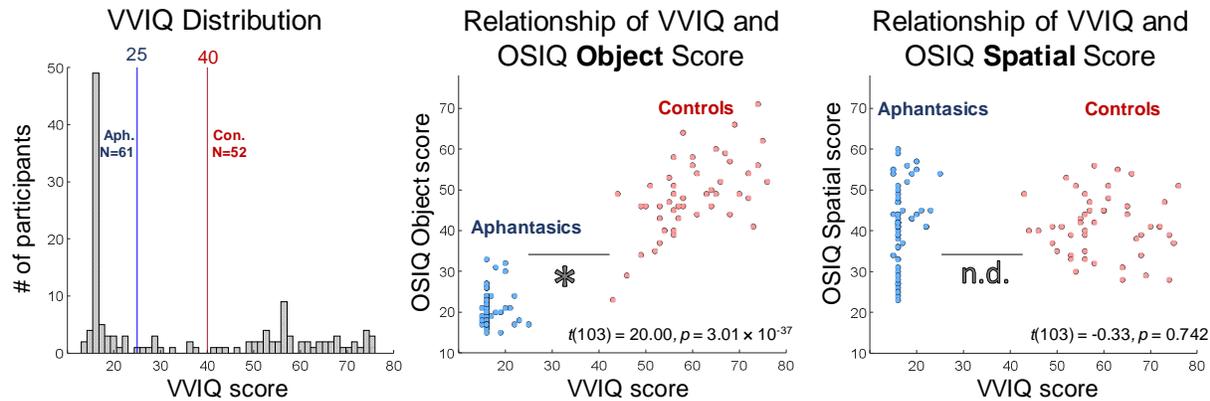
285

### 286 **No demographic differences between groups, but reported differences in object and spatial** 287 **imagery**

288 First, we analyzed whether there were demographic differences between the groups.  
289 There was a significant difference in age between groups with aphantasics generally older than  
290 controls (aphantasic:  $M=41.88$  years,  $SD=13.88$ ,  $Range=18$  to 74 years; control:  $M=32.12$  years,  
291  $SD=15.26$ ,  $Range=18$  to 75 years;  $t(107)=3.49$ ,  $p=6.95 \times 10^{-4}$ ). There was no significant  
292 difference in gender proportion between the two groups (aphantasic: 62.3% female; control:  
293 59.6% female; Pearson's chi-square test for proportions:  $\chi^2=0.08$ ,  $p=0.771$ ), even though a  
294 previous study reported a sample comprising of predominantly males (Zeman et al., 2015).

295 Second, we investigated the relationship of the VVIQ score and OSIQ (Fig. 2), a  
296 questionnaire developed to separate abilities to perform imagery with individual objects versus  
297 spatial relations amongst objects (Blajenkova et al., 2006). Controls scored significantly higher  
298 on the OSIQ than aphantasics ( $t(103) = 12.70$ ,  $p=8.55 \times 10^{-23}$ ). There was a significant  
299 correlation between VVIQ score and OSIQ score for control participants ( $M=89.73$ ,  $SD=10.97$ ;  
300 Spearman rank-correlation test:  $\rho=0.54$ ,  $p=7.70 \times 10^{-5}$ ), but only marginally for aphantasics  
301 (OSIQ  $M$  score= $62.88$ ,  $SD=10.65$ ;  $\rho=0.26$ ,  $p=0.052$ ). When broken down by OSIQ subscale, there  
302 was a significant difference between groups in questions relating to object imagery  
303 ( $t(103)=20.00$ ,  $p=3.01 \times 10^{-37}$ ), but not spatial imagery ( $t(103)=-0.33$ ,  $p=0.742$ ). Indeed, a 2-way  
304 ANOVA (participant group  $\times$  subscale) reveals a main effect of participant group  
305 ( $F(1,206)=154.97$ ,  $p \sim 0$ ), subscale ( $F(1,206)=40.11$ ,  $p=1.48 \times 10^{-9}$ ), and a significant interaction  
306 ( $F(1,206)=167.94$ ,  $p \sim 0$ ), confirming a difference in self-reported ratings for object imagery and  
307 spatial imagery respectively. This difference in self-reported object imagery and spatial imagery  
308 has been reported a previous study (Keogh & Pearson, 2017), and suggests a potential  
309 difference between the two imagery subsystems.

310



311

312 **Figure 2. Experimental paradigm and basic demographics.** a) b) (Left) A histogram of the distribution of  
313 participants across the VVIQ. Aphantasics were selected as those scoring 25 and below (N=61) and controls  
314 were selected as those scoring 40 and above (N=52), while those in between were removed from the  
315 analyses (N=8). While the range of the VVIQ is from 16 to 80, some participants (N=10 out of 121 total)  
316 skipped 1-3 questions, leading to some participants scoring below 16. These skipped questions did not affect  
317 group membership. (Middle) A scatterplot of total VVIQ score plotted against total OSIQ Object component  
318 score for participants meeting criterion. Each point represents a participant, with aphantasics in blue and  
319 controls in red. There was a significant difference in OSIQ Object score between the two groups. (Right) A  
320 scatterplot of total VVIQ score plotted against OSIQ Spatial component score. There was no difference in  
321 OSIQ Spatial score between the two groups. Both the OSIQ Object component and Spatial components have  
322 a range of 15 to 75 points.

323

324 Third, we investigated whether aphantasics and controls reported different levels of  
325 comfort or familiarity with art, which may influence their drawing performance. When asked to  
326 rate their artistic abilities on a scale from 1 (very poor) to 5 (very good), aphantasics and  
327 controls showed no significant difference in their ratings (aphantasic:  $M=2.30$ ,  $SD=1.34$ ; control:  
328  $M=2.52$ ,  $SD=0.99$ ; non-parametric Wilcoxon rank sum test:  $Z=1.23$ ,  $p=0.219$ ). Both aphantasic  
329 and control participants also reported taking art classes in the past (39.34% of aphantasic  
330 participants, 37.74% of controls). Many aphantasics (13.11%) also reported being employed  
331 within industries involving artistic abilities, such as sculpting, visual arts, makeup art, and  
332 interior decoration. Thus, aphantasics and controls did not show strong differences in their  
333 propensity for, or interest in, art.

334 Finally, given the focus of the current experiment on visual recall, we also compared  
335 measures of visual recognition performance. Both groups performed near ceiling at visual  
336 recognition of the images they studied, with no significant difference between groups in  
337 recognition hit rate (controls:  $M=0.96$ ,  $SD=0.12$ ; aphantasics:  $M=0.97$ ,  $SD=0.12$ ; Wilcoxon rank-  
338 sum test:  $Z=1.09$ ,  $p=0.274$ ), or false alarm rate (controls:  $M=0.02$ ,  $SD=0.12$ ; aphantasics:  $M=0$ ,  
339  $SD=0$ ; Wilcoxon rank-sum test:  $Z=1.10$ ,  $p=0.273$ ). These results indicate that there is no obvious  
340 deficit in aphantasics for recognizing images, even with lures from the same semantic scene  
341 category.

342

### 343 **Diminished object information for aphantasics**

344 Next, we turned to analyzing the drawings made by the participants to reveal objective  
345 measures of the mental representations of these two groups. Looking at overall number of  
346 drawings made, while a small number of participants could not recall all three images, there  
347 was no significant difference between groups in number of images drawn from memory  
348 (control:  $M=2.92$ ,  $SD=0.27$ ; aphantasic:  $M=2.89$ ,  $SD=0.37$ ; Wilcoxon rank-sum test:  $Z=0.42$ ,  
349  $p=0.678$ ). To evaluate the drawings, 2,795 unique workers from the online experimental  
350 platform Amazon Mechanical Turk (AMT) scored the drawings on a variety of metrics including  
351 object information, spatial accuracy, and memory errors, using methods previously established  
352 for quantifying memory drawings (Bainbridge et al., 2019). Importantly, each participant  
353 completed both a memory drawing (i.e., drawing an image from memory for an unlimited time  
354 period) and a perception drawing (i.e., copying from a drawing for an unlimited time period) for  
355 each image, allowing us to compare for each participant what is in memory versus what that  
356 individual would maximally draw given an image without memory constraints (refer to Fig. 3 for  
357 example drawings). This comparison allows us to control for differences in effort and drawing  
358 ability, which we should expect to be reflected in both types of drawings.

359



360

361 **Figure 3. Example drawings.** Example drawings made by aphantasic and control participants from memory  
362 and perception (i.e., copying the image) showing the range of performance. The memory and perception

363 drawings connected by arrows are from the same participant, and every row is from a different participant.

364 Low memory examples show participants who drew the fewest from memory but the most from perception.

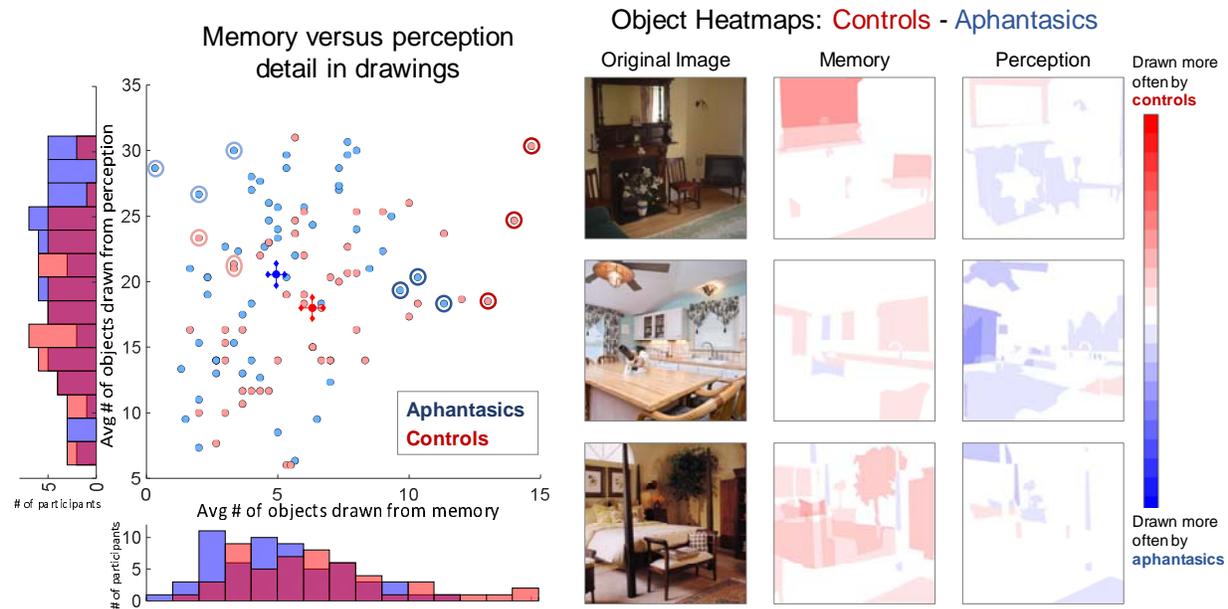
365 High memory examples show participants who drew the highest amounts of detail from both memory and

366 perception. These examples are all highlighted in the scatterplot of Fig. 4. The key question is whether there  
367 are meaningful differences between these two sets of participants' drawings.

368

369 To score level of object information, AMT workers (N=5 per object) identified whether  
370 each of the objects in an image was present in each drawing of that image (Fig. 4). A 2-way  
371 ANOVA of participant group (aphantasic / control) × drawing type (memory / perception  
372 drawing, repeated measure) looking at number of objects drawn per image showed no  
373 significant overall effect of participant group ( $F(1,223)=0.26, p=0.613$ ), but a significant effect of  
374 drawing type ( $F(1,223)=507.03, p\sim 0$ ), and more importantly, a significant statistical interaction  
375 ( $F(1,223)=9.25, p=0.0029$ ). Targeted post-hoc independent t-tests revealed that when drawing  
376 from memory, controls drew significantly more objects ( $M=6.32$  objects per image,  $SD=3.07$ )  
377 than aphantasics ( $M=4.98, SD=2.54; t(111)=2.53, p=0.013$ ) across the experiment. In contrast,  
378 when copying a drawing (perception drawing), aphantasics on average drew more objects from  
379 the images than controls, but with no significant difference (controls:  $M=18.00$  objects per  
380 image,  $SD=5.81$ ; aphantasics:  $M=20.07, SD=7.26; t(111)=1.74, p=0.085$ ). These results suggest  
381 that aphantasics are showing a specific deficit in recalling object information during memory.

382



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384

385 **Figure 4. Comparison of object information in drawings between aphantasics and controls.** (Left) A  
386 scatterplot of each participant as a point, showing average number of objects drawn from memory across the  
387 three images (x-axis), versus average number of objects drawn from perception across the three images (y-  
388 axis). Aphantasics are in blue, while controls are in red. The bright blue circle indicates average aphantasic  
389 performance, while the bright red circle indicates average control performance, with crosshairs for both  
390 indicating standard error of the mean for memory and perception respectively. Histograms on the axes show  
391 the number of participants who drew each number of objects. Controls drew significantly more objects from  
392 memory, although with a tendency towards fewer from perception. The highlighted light blue and red points  
393 are the participants with the lowest memory performance shown in Fig. 3, while the highlighted dark blue  
394 and red points are the participants with the highest memory performance shown in Fig. 3. (Right) Heatmaps  
395 of which objects for each image tended to be drawn more by controls (red) or aphantasics (blue). Pixel value  
396 represents the proportion of control participants who drew that object in the image subtracted by the  
397 proportion of aphantasics who drew that object (with a range of -1 to 1). Controls remembered more objects  
398 (i.e., there is more red in the memory heatmaps), even though aphantasics tended to copy more objects (i.e.,  
399 there is more blue in the perception heatmaps).

400

401 Given that some participants tended to draw few objects even when copying from an  
402 image, we also investigated a corrected measure, taken as the number of objects drawn from  
403 memory divided by the number of objects drawn from perception, for each image for each  
404 participant. Drawings from perception with fewer than 5 objects were not included in the

405 analysis, to remove any low-effort trials. Aphantasics drew a significantly smaller proportion of  
406 objects from memory than control participants (aphantasic:  $M=0.261$ ,  $SD=0.165$ ; control:  
407  $M=0.369$ ,  $SD=0.162$ ; Wilcoxon rank-sum test:  $Z=4.09$ ,  $p=4.24 \times 10^{-5}$ ). We also investigated the  
408 correlation within groups between the number of objects drawn from memory and the number  
409 drawn from perception. There was a significant correlation for both groups, where the more  
410 one draws from perception, the more one also tends to draw from memory (Pearson  
411 correlation; aphantasics:  $r=0.34$ ,  $p=0.0075$ ; controls:  $r=0.40$ ,  $p=0.0035$ ).

412 We also assessed the relationship between performance in the task and self-reported  
413 object imagery in the OSIQ. Across groups, there was a significant correlation between  
414 proportion of objects drawn from memory and OSIQ object score (Spearman's rank correlation:  
415  $\rho=0.33$ ,  $p=7.18 \times 10^{-4}$ ), although these correlations were not significant when separated by  
416 participant group ( $p>0.10$ ).

417 Next, we examined whether there was a difference in visual detail within objects, by  
418 quantifying differences between groups in color and amount of time spent on the drawings.  
419 Significantly more memory drawings by controls contained color than those by aphantasics  
420 (control: 38.2%, aphantasics: 21.6%; Pearson's chi-square test for proportions:  $\chi^2=10.09$ ,  
421  $p=0.0015$ ), while there was no significant difference for perception drawings (control: 46.2%,  
422 aphantasic: 39.4%,  $\chi^2=1.46$ ,  $p=0.227$ ). Control participants also spent significantly longer time  
423 on their memory drawings than aphantasics (control:  $M=119.41$  s per image,  $SD=68.88$  s;  
424 aphantasics:  $M=71.22$  s,  $SD=49.17$  s;  $t(110) = 4.31$ ,  $p=3.56 \times 10^{-5}$ ), implying more attention to  
425 detail in their drawings. For the perception drawings, there was no significant difference  
426 between groups in the amount of time they spent on their drawings (control:  $M=272.33$  s,  
427  $SD=214.17$  s; aphantasic:  $M=295.18$  s,  $SD=304.54$  s;  $p = 0.654$ ). These differences in time spent  
428 on memory drawing could reflect controls spending more time because they drew more objects  
429 from memory. However, even if we normalize total drawing time by number of objects drawn  
430 to get an estimate of average time spent per object, controls spent significantly more time per  
431 object than aphantasics when drawing from memory (Wilcoxon rank sum test:  $Z=2.09$ ,  $p=0.037$ ),  
432 but not when drawing during perception ( $Z=0.75$ ,  $p=0.454$ ). This implies that aphantasics not  
433 only spent less time per drawing, but also less time on the details for each object. Finally, we

434 investigated other forms of object detail, by having AMT workers (N=777) judge whether  
435 different object descriptors (e.g., material, texture, shape, aesthetics; generated by 304  
436 separate AMT workers) applied to each drawn object. This task did not identify differences  
437 between groups for the memory drawings ( $t(110)=0.21, p=0.833$ ), although objects were  
438 significantly more detailed when copied than when drawn from memory for both aphantasics  
439 (memory:  $M=42.4\%$  descriptors per object applied,  $SD=5.1\%$ ; copied:  $M=45.9\%$ ,  $SD=4.1\%$ ;  
440  $t(119)=4.12, p=6.92 \times 10^{-5}$ ) and control participants (memory:  $M=42.2\%$ ,  $SD=5.6\%$ ; copied:  
441  $M=47.0\%$ ,  $SD=3.9\%$ ;  $t(100)=5.06, p=1.92 \times 10^{-6}$ ). However, it is possible this task may have  
442 asked for too fine-grained information than can be measured from these drawings (e.g., judging  
443 the material and texture of a drawn chair).

444 In sum, these results present concrete evidence that aphantasics recall fewer objects  
445 than controls, and these objects contain less visual detail (i.e., color, less time spent for drawing)  
446 within their memory representations.

447

#### 448 **Aphantasics show greater dependence on symbolic representations**

449 While aphantasics show decreased object information in their memory drawings, they  
450 are still able to successfully draw some objects from memory (4.98 objects per image on  
451 average). Do these drawings reveal evidence for alternative, non-visual strategies that may  
452 have supported this level of performance? To test this question, we quantified the amount of  
453 text used to label objects included in the participants' drawings. Note that while labeling was  
454 allowed (the instructions stated: "Please draw or label anything you are able to remember"), it  
455 was effortful as it required drawing the letters with the mouse. We found that significantly  
456 more memory drawings by aphantasics contained text than those by controls (aphantasic:  
457 29.6%, control: 16.0%;  $\chi^2=7.57, p=0.0059$ ). Further, there was no significant difference between  
458 groups for perception drawings (aphantasic: 2.9%, control: 0.8%;  $\chi^2=1.77, p=0.184$ ). These  
459 results imply that aphantasics may have relied upon symbolic representations to support their  
460 memory.

461 One question is whether aphantasics just prefer writing over drawing, and so prioritized  
462 time or effort on writing text over drawing objects. To elaborate, it is possible that aphantasics

463 expend their effort on writing text, and then do not want to spend further time on drawing  
464 objects even if they might have object information in memory. If this were the case, then  
465 drawings that contain text should contain fewer objects. However, we found there was no  
466 significant difference in number of objects between aphantasic memory drawings with text and  
467 without (independent samples t-test by drawing:  $t(174)=0.07$ ,  $p=0.947$ ). There was also no  
468 significant difference for their drawings made during perception ( $t(171)=0.35$ ,  $p=0.726$ ), nor  
469 were there differences for controls (memory drawings:  $t(150)=0.004$ ,  $p=0.997$ ; perception  
470 drawings:  $t(152)=1.50$ ,  $p=0.135$ ). These results indicate that the usage of text was not a trade-  
471 off with object memory; aphantasics preferred to include text in their memory drawings  
472 regardless of how many objects they recalled.

473         Comments by aphantasics at the end of the experiment supported their use of symbolic  
474 strategies. When asked what they thought was difficult about the task, one participant noted,  
475 “Because I don’t have any images in my head, when I was trying to remember the photos, I  
476 have to store the pieces as words. I always have to draw from reference photos.” Another  
477 aphantasic stated, “I had to remember a list of objects rather than the picture,” and another  
478 said, “When I saw the images, I described them to myself and drew from that description, so I...  
479 could only hold 7-9 details in memory.” In contrast, control participants largely commented on  
480 their lack of confidence in their drawing abilities: e.g., “I am very uncoordinated so making  
481 things look right was frustrating”; “I can see the picture in my mind, but I am terrible at  
482 drawing.”

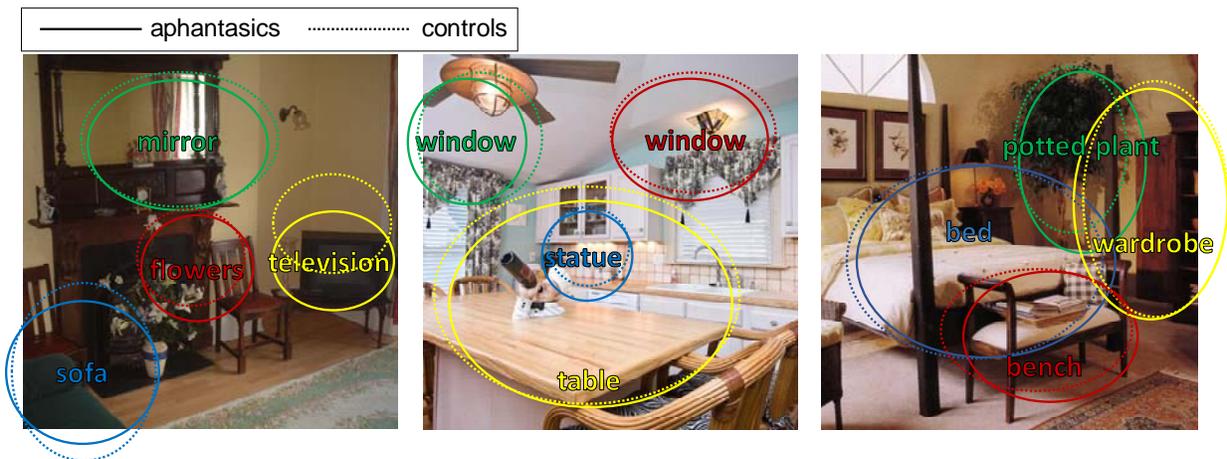
483

#### 484 **Aphantasics and controls show equally high spatial accuracy in memory**

485         While aphantasics show an impairment in memory for object information, do they also  
486 show an impairment in spatial placement of the objects? To test this question, AMT workers  
487 (N=5 per object) drew an ellipse around the drawn version of each object, allowing us to  
488 quantify the size and location accuracy of each drawn object (Fig. 5). When drawing from  
489 memory, there was no significant difference between groups in object location error in the x-  
490 direction (aphantasic:  $M$  pixel error=63.86,  $SD=31.59$ ; control:  $M=60.63$ ,  $SD=28.45$ ;  $t(111)=0.57$ ,  
491  $p=0.572$ ) nor the y-direction (aphantasic:  $M=65.43$ ,  $SD=29.89$ ; control:  $M=69.10$ ,  $SD=29.72$ ;

492  $t(111)=0.65, p=0.515$ ). However, this lack of difference was not due to difficulty in spatial  
493 accuracy; both groups' drawings were incredibly spatially accurate, with all average errors in  
494 location less than 10% of the size of the images themselves. Similarly, there was also no  
495 significant difference in drawn object size error in terms of width (aphantasic:  $M$  pixel  
496 error=23.00,  $SD=10.95$ ; control:  $M=24.89, SD=13.58$ ;  $t(111)=0.82, p=0.413$ ) and height  
497 (aphantasic:  $M=26.75; SD=14.15$ ; control:  $M=22.82; SD=11.05$ ;  $t(111)=1.62, p=0.107$ ), and these  
498 sizes were incredibly accurate in both groups (average errors less than 4% of the image size).  
499 There was no correlation between a participant's level of object location or size error and  
500 ratings on the OSIQ spatial questions (all  $p>0.30$ ). In all, these results show that both  
501 aphantasics and controls have highly accurate memories for spatial location, with no  
502 observable differences between groups.  
503

### Average object locations for memory drawings



504  
505 **Figure 5. Average object locations and sizes recalled by aphantasics and controls.** Average object locations  
506 and sizes for memory drawings of four of the main objects from each image, made by aphantasics (solid lines)  
507 and controls (dashed lines). Even though these objects were drawn from memory, their location and size  
508 accuracy was still very high. Importantly, aphantasics and controls showed no significant differences in object  
509 location or size accuracy.

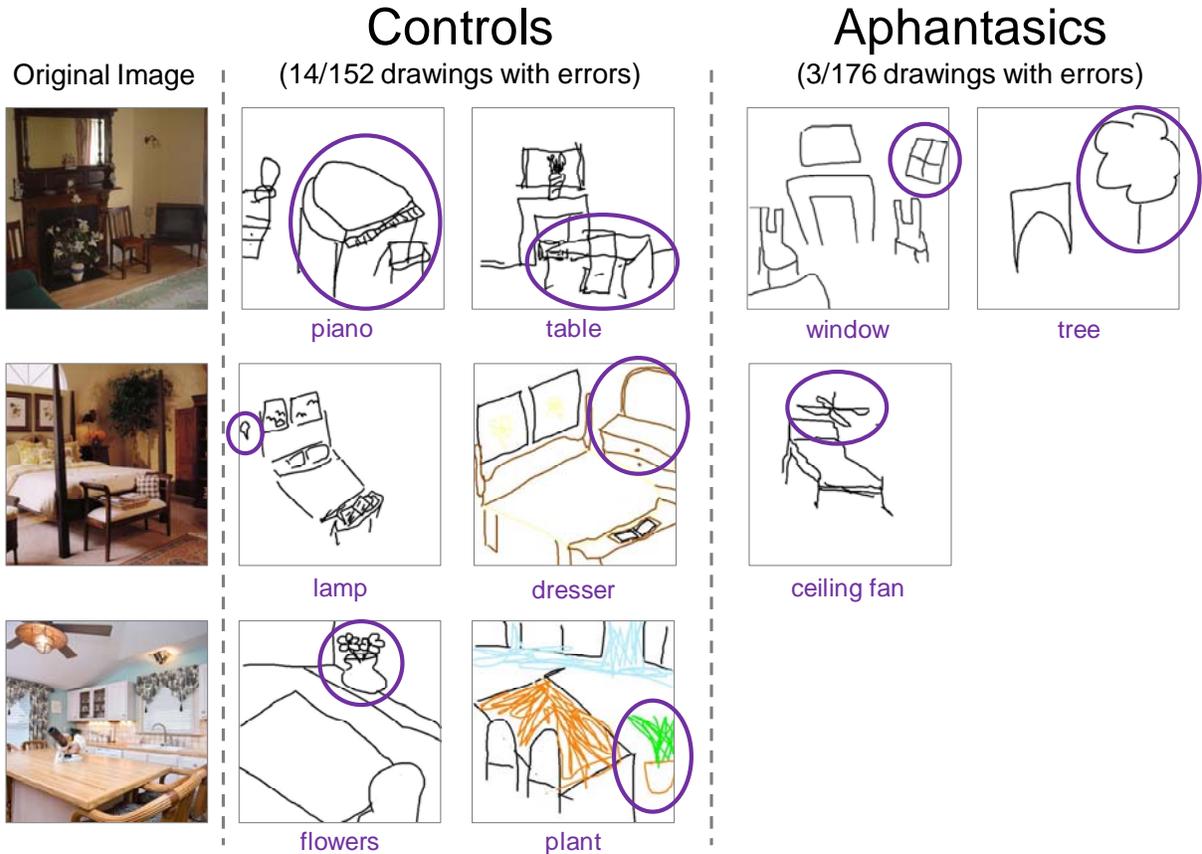
510

511

512 **Aphantasics draw fewer false objects than controls**

513 Finally, we quantified the amount of error in participants' drawings from memory by  
514 group. AMT workers (N=5 per drawing) viewed a drawing and its corresponding image and  
515 wrote down all objects in the drawings that were not present in the original image (essentially  
516 quantifying false object memories). Significantly more memory drawings by controls contained  
517 false objects than drawings by aphantasics (controls: 14 drawings, aphantasics: 3 drawings;  
518 Pearson chi-square test:  $\chi^2=9.35$ ,  $p=0.002$ ); examples can be seen in Fig. 6. This is not just  
519 because controls drew more objects overall and were thus more likely to draw false objects. If  
520 we also look at proportion of total objects drawn by group that were false objects, significantly  
521 more objects drawn by controls were false objects than those drawn by aphantasics ( $\chi^2=6.37$ ,  
522  $p=0.012$ ). This indicates that control participants were making more memory errors, even after  
523 controlling for the fewer number of objects drawn overall by aphantasics. Interestingly, all  
524 aphantasic errors (see Fig. 6) were transpositions from another image and drawn in the correct  
525 location as the original object (a tree from the bedroom to the living room, a window from the  
526 kitchen to the living room, and a ceiling fan from the kitchen to the bedroom). In contrast,  
527 several false memories from controls were objects that did not exist across any image but  
528 instead appeared to be filled in based on the scene category (e.g., a piano in the living room, a  
529 dresser in the bedroom, logs in the living room). No perception drawings by participants from  
530 either group contained false objects.

531 As another metric of memory error, we also coded whether a drawing was edited or not,  
532 based on tracked mouse movements. A drawing was scored as edited if at least one line was  
533 drawn and then erased during the drawing. Significantly more memory drawings by control  
534 participants had editing than those by aphantasic participants (aphantasic: 28.4%, control:  
535 46.6%;  $\chi^2=10.72$ ,  $p=0.0011$ ). There was no significant difference in editing between groups for  
536 the perception drawings (aphantasic: 37.6%, control: 47.7%;  $\chi^2=3.17$ ,  $p=0.075$ ), indicating these  
537 differences are likely not due to differences in effort.



538

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**Figure 6. False object memories in the drawings.** Examples of the false object memories made by

540

participants in their memory drawings, with the inaccurate objects circled. Control participants made

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significantly more errors, with only 3 out of 176 total aphantasic drawings containing a falsely remembered

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object. Note that all aphantasic errors were also transpositions from other images.

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### Discussion

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Through a drawing task with a large online sample, we conducted an in-depth

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characterization of the mental representations held by congenital aphantasics, a recently

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identified group of individuals who self-report the inability to form voluntary visual imagery.

550

We discover that aphantasics show impairments in object memory, drawing fewer objects,

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containing less color, and spending less time drawing details. Further, we find evidence for

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greater dependence on symbolic information in the task, with more text in their drawings and

553 common self-reporting of verbal strategies. However, aphantasics show no impairments in  
554 spatial memory, positioning objects at accurate locations with the correct sizes. Further,  
555 aphantasics show significantly fewer errors in memory, with fewer falsely recalled objects, and  
556 less correction of their drawings. Importantly, we observe no significant differences between  
557 controls and aphantasics when drawing directly from an image, indicating these differences are  
558 specific to memory and not driven by differences in effort, drawing ability, or perceptual  
559 processing. Indeed, aphantasics reported an equal confidence in their art abilities compared to  
560 controls, and many had experience with art classes and art-based careers.

561 Collectively, these results point to a dissociation in imagery between object-based  
562 information and spatial information. In addition to selective deficits in object memory over  
563 spatial memory, aphantasics subjectively report a lower preference for object imagery  
564 compared to spatial imagery in the OSIQ. This supports subjective self-report in the smaller  
565 dataset (N=15) of Keogh & Pearson (2017), which first reported differences in OSIQ measures.  
566 Further, in the current study, participants' reported object imagery abilities correlated with the  
567 number of objects they drew from memory. These consistent results both confirm the OSIQ as  
568 a meaningful measure, while also demonstrating how such deficits can be captured by a  
569 behavioral measure such as drawing. While a similar dissociation between object and spatial  
570 memory has been observed in other paradigms and populations (Farah & Hammond, 1988), the  
571 current study provides further evidence for this dissociation in a population of individuals in the  
572 absence of trauma or changes in brain pathology. Cognitive decline from aging and dementia  
573 have shown selective deficits in object identification versus object localization (Reagh et al.,  
574 2016), owing to changes in the medial temporal lobe, where the perirhinal cortex is thought to  
575 contribute to object detail recollection, while the parahippocampal cortex contributes to scene  
576 detail recollection (Staresina, Duncan, & Davachi, 2011). The neocortex is also considered to be  
577 organized along separate visual processing pathways, with ventral regions primarily coding  
578 information about visual features, and parietal regions coding spatial information (Farah,  
579 Hammond, Levine, & Calvanio, 1988; Ungerleider & Haxby, 1994; Corballis, 1997; Carlesimo,  
580 Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001; Kravitz, Saleem, Baker, & Mishkin, 2011).  
581 These findings also suggest interesting parallels between the imagery experience of individuals

582 with aphantasia and individuals who are congenitally blind, who perform similarly to typically  
583 sighted individuals on a variety of spatial imagery tasks (Kerr, 1983; Zimler & Keenan, 1983;  
584 Eardley & Pring, 2007; Cattaneo et al., 2008). Neuroimaging of aphantasics will be an important  
585 next step, to see whether these impairments are manifested in decreased volume or  
586 connectivity of regions specific to the imagery of visual details, such as anterior regions within  
587 inferotemporal cortex (Ishai et al., 2000; O'Craven & Kanwisher, 2000; Lee, Kravitz, & Baker,  
588 2012; Bainbridge et al., Unpublished results) or medial parietal regions implicated in memory  
589 recall (Buckner, Andrews-Hanna, & Schacter, 2008; Vilberg & Rugg, 2008; Ranganath & Ritchey,  
590 2012; Silson et al., 2019).

591 Further investigations on aphantasics will also provide critical insight on the nature of  
592 imagery, and how it compares to different forms of memory. While aphantasics show an  
593 impairment at recall performance, no evidence has shown impairments in visual recognition,  
594 and indeed our study also observes near-ceiling recognition performance. These results support  
595 other converging evidence pointing towards a neural dissociation in the processes of quick,  
596 automatic visual recognition and slower, elaborative visual recall (Jacoby, 1991; Holdstock et al.,  
597 2002; Staresina & Davachi, 2006; Barbeau, Pariente, Felician, & Puel, 2011; Bainbridge et al.,  
598 2019). That being said, the recognition task in the current experiment had relatively low  
599 difficulty, testing foil images of the same semantic category, but without other matched detail  
600 (e.g., identities of objects). Future work could study whether aphantasics are impaired at more  
601 fine-grained recognition tasks, where object and spatial detail within an image are selectively  
602 manipulated. Aphantasics also report fully intact verbal recall abilities, and our results suggest  
603 that they may be using semantic strategies, in combination with accurate spatial  
604 representations, to compensate for their lack of visual imagery. In fact, in the current study,  
605 aphantasics' drawings from memory contained more text than those of controls, potentially  
606 indicating a semantic propositional coding of their memories to perform the task. Imagery of a  
607 visual stimulus thus may not necessarily be visual in nature; while forming a visual  
608 representation of the scene or object may be one way to undertake the task, there may be  
609 other, non-visual strategies to complete the task. Even in neurotypical adults, imagery-based  
610 representations in the brain may differ from perceptual representations of the same items

611 (Bainbridge et al., Unpublished results). Further neuroimaging investigations will lead to an  
612 understanding of the neural mechanisms underlying these different strategies.

613 Further, aphantasics' lower errors in memory (e.g., fewer falsely recalled objects  
614 compared to controls) could possibly reflect higher accuracy in semantic memory versus  
615 controls, to compensate for visual memory difficulties. Aphantasics may serve as an ideal  
616 population to probe the difference between visual and semantic memory and their interaction  
617 in both behavior and the brain. Additionally, while aphantasia has thus far only been quantified  
618 in the visual domain, preliminary work suggests that the experience may extend to other  
619 modalities (Zeman et al., 2015). Using a multimodal approach, researchers may be able to  
620 pinpoint neural differences in aphantasics across other sensory modalities, for instance, the  
621 auditory domain which has been shown to have several characteristics similar to the visual  
622 domain (Halpern, 1988; Clarke, Bellmann, Meuli, Assal, & Steck, 2000; Bunzeck, Wuestenberg,  
623 Lutz, Heinze, & Jancke, 2005).

624 Finally, these results serve as essential evidence to suggest that aphantasia is a valid  
625 experience, defined by the inability to form voluntary visual images with a selective impairment  
626 in object imagery. Previous work has shown relatively intact performance by aphantasics on  
627 imagery and visual working memory tasks (Jacobs et al., 2018), and some researchers have  
628 proposed aphantasia may be more psychogenic than a real impairment (de Vito & Bortolomeo,  
629 2016). However, in the current study, we observe evidence for a selective impairment in object  
630 imagery for aphantasics in comparison to controls. Importantly, if such an impairment were  
631 caused by intentional efforts to demonstrate an impairment, we would expect decreased  
632 performance in spatial accuracy, decreased performance in the perceptual drawing task, or low  
633 ratings in all questions of the OSIQ rather than solely the object imagery component. However,  
634 in all of these cases, aphantasics performed identically with controls. In fact, aphantasics even  
635 showed higher memory precision than controls on some measures, including significantly fewer  
636 memory errors and fewer editing in their drawings. Further, the correlations between the VVIQ,  
637 OSIQ, and drawn object information lend validity to the self-reported questionnaires in  
638 capturing true behavioral deficits. This being said, while we observed a deficit in object memory  
639 for aphantasics, it was not a complete elimination of object memory abilities. Aphantasics were

640 still able to draw five objects per image from memory. While this moderate performance could  
641 be due to some preserved ability at object memory, this performance could also reflect the use  
642 of verbal lists of objects combined with intact, accurate spatial memory to reconstruct a scene.  
643 Future work will need to directly compare visual and verbal strategies, and push the limits to  
644 see what occurs when there is more visual detail than can be supported by verbal strategies.

645 In conclusion, leveraging the wide reach of the internet, we have conducted an in-depth  
646 and large scale study of the nature of aphantasics' mental representations for visual images.  
647 Aphantasics have a unique mental experience that can provide essential insights into the nature  
648 of imagery, memory, and perception. Their drawings reveal a complex, nuanced story that  
649 show impaired object memory, with a combination of semantic and spatial strategies used to  
650 reconstruct scenes from memory. Collectively, these results suggest a dissociation in object and  
651 spatial information in visual memory.

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