CORTEX 105 (2018) 53–60

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Special issue: Research report

The blind mind: No sensory visual imagery in aphantasia

Rebecca Keogh * *and Joel Pearson*

School of Psychology, University of New South Wales, Sydney, Australia

ARTICLE INFO

Article history:
Received 30 January 2017
Reviewed 3 May 2017
Revised 27 June 2017
Accepted 15 October 2017
Published online 28 October 2017

Keywords:
Aphantasia
Visual imagery
Individual differences
Cognition
Mental imagery

ABSTRACT

For most people the use of visual imagery is pervasive in daily life, but for a small group of people the experience of visual imagery is entirely unknown. Research based on subjective phenomenology indicates that otherwise healthy people can completely lack the experience of visual imagery, a condition now referred to as aphantasia. As congenital aphantasia has thus far been based on subjective reports, it remains unclear whether individuals are really unable to imagine visually, or if they have very poor metacognition – they have images in their mind, but are blind to them. Here we measured sensory imagery in subjectively self-diagnosed aphantasics, using the binocular rivalry paradigm, as well as measuring their self-rated object and spatial imagery with multiple questionnaires (VVIQ, SUIS and OSIQ). Unlike, the general population, experimentally naive aphantasics showed almost no imagery-based rivalry priming. Aphantasic participants' self-rated visual object imagery was significantly below average, however their spatial imagery scores were above average. These data suggest that aphantasia is a condition involving a lack of sensory and phenomenal imagery, and not a lack of metacognition. The possible underlying neurological cause of aphantasia is discussed as well as future research directions.

> 'What does a person mean when he closes his eyes or ears (figuratively speaking) and says, "I see the house where I was born, the trundle bed in my mother's room where I used to sleep – I can even see my mother as she comes to tuck me in and I can even hear her voice as she softly says goodnight"? Touching, of course, but sheer bunk. We are merely dramatizing. The behaviourist finds no proof in imagery in all this. We have put these things in words long, long ago and we constantly rehearse those scenes verbally whenever the occasion arises'
>
> John B Watson

The study of visual imagery has been a controversial topic for many years, as the above quote from the behaviourist John Watson demonstrates. This quote exemplifies the long running imagery debate of the 1970s and 80's, which centred on the question of whether imagery can be depictive in the format of its representation (Kosslyn, 2005), or only symbolic or propositional in nature (Pylyshyn, 2003). However, in the last few decades psychologists and neuroscientists have made great strides in showing that visual imagery can be measured objectively and reliably, and indeed can be depictive/pictorial in nature, see Pearson and Kosslyn (2015) for a detailed

* *Corresponding author*. School of Psychology, University of New South Wales, Sydney, Australia.
E-mail address: rebeccalkeogh@gmail.com (R. Keogh).
https://doi.org/10.1016/j.cortex.2017.10.012
0010-9452/

discussion of the evidence. Research has shown that visual imagery, like weak perception, impacts subsequent perception in a myriad of ways (Ishai & Sagi, 1995; Pearson, Clifford, & Tong, 2008; Winawer, Huk, & Boroditsky, 2010; Zamuner, Oxner, & Hayward, 2017). For example, the effect of imagery on subsequent rivalry is specific in orientation and location space, showing strong evidence for a depictive representation (Pearson et al., 2008). Imagery has also been shown to activate early visual cortex and the content of imagery can be decoded in these areas using an encoding model based on low-level depictive visual features, such as spatial orientation and contrast (Naselaris, Olman, Stansbury, Ugurbil, & Gallant, 2015), and recently using features based on a multi-level convolutional neural network (Horikawa & Kamitani, 2017).

Additionally, visual imagery has been shown to be closely related to many cognitive functions such as visual memory (Albers, Kok, Toni, Dijkerman, & de Lange, 2013; Keogh & Pearson, 2011, 2014), spatial navigation (Ghaem et al., 1997), language comprehension (Bergen, Lindsay, Matlock, & Narayanan, 2007; Zwaan, Stanfield, & Yaxley, 2002), making moral decisions and making a decision to help others (Amit & Greene, 2012; Gaesser & Schacter, 2014). Visual imagery also appears to be elevated (stronger or more vivid) in some psychological and neurological disorders (Matthews, Collins, Thakkar, & Park, 2014; Sack, van de Ven, Etschenberg, Schatz, & Linden, 2005; Shine et al., 2015). Visual imagery has even been employed to assist in cognitive behavioural therapies such as imaginal exposure and imaginal rescripting (Arntz, Tiesema, & Kindt, 2007; Holmes, Arntz, & Smucker, 2007; Pearson, Naselaris, Holmes, & Kosslyn, 2015) and the use of visual imagery during cognitive behavioural therapy has been shown to be more effective than just verbal processing (Pearson et al., 2015).

With strong evidence that visual imagery can be a depictive cognitive mechanism, the question arises, were Watson, Pylyshyn and their ilk wrong? Or is it possible that they had a distinctly different experience of visual imagery that was not depictive, but more propositional or phonological in nature? Interestingly, a study investigated exactly this idea and found that those researchers who were more likely to have been on the 'imagery is depictive' side of the debate tended to report more vivid imagery, while those who reported weaker imagery were more likely to be on the imagery is propositional side of the debate (Reisberg, Pearson, & Kosslyn, 2003). One of the hallmarks of visual imagery is the large range of subjective reports in the vividness of an individual's imagery. For example, when people are asked to imagine the face of a close friend or relative some people report imagery so strong it is almost akin to seeing that person, whereas others report their imagery as so poor that, although they know they are thinking about the person, there is no visual image at all. Sir Francis Galton gave one of the earliest accounts of these subjective differences in visual imagery in 1883. Galton devised a series of questionnaires asking participants to imagine a specific object then describe the 'illumination', 'definition' and 'colouring' of the image. He found, to his surprise, that many of his fellow scientists professed to experience no visual images in their mind at all: 'To my astonishment, I found that the great majority of the men of science to whom I first applied protested that mental imagery was unknown to them, and they, looked on me as fanciful and fantastic in supposing that the words "mental imagery" really expressed what I believed everybody supposed them to mean. They had no more notion of its true nature than a colour-blind man, who has not discerned his defect, has of the nature of colour. They had a mental deficiency of which they were unaware, and naturally enough supposed that those who affirmed they possessed it, were romancing." In recent years very little attention has been given to the 'poor' or non-existent side of the visual imagery spectrum, outside of participants with neurological damage. Much research during the imagery debate of the 70's and 80's revolved around brain damaged participants who had lost their ability to imagine, but retained their vision, or vice versa (Farah, 1988). Recently the idea that some people are wholly unable to create visual images in mind, without any sort of neurological damage, psychiatric or psychological disorders, has seen a resurgence. A recent paper by Zeman, Dewar, and Della Sala (2015) coined a term for this phenomenon 'congenital aphantasia'. This study found that these aphantasics all scored very low on the vividness of visual imagery questionnaire (VVIQ). The VVIQ is a commonly used questionnaire to measure the subjective vividness of an individual's visual imagery, by asking them to imagine a friend or relative, as well as scenes and rate the vividness of these images on a Likert scale. However, a case study reported a 65-year-old male who became aphantasic after surgery (without any obvious neurological damage) and was still able to perform well on other measures of visual imagery, such as answering questions about the shape of animal's tails. The patient *was* also able to perform two types of mental rotation tasks (manikin and Shepard–Metzler tasks), which are commonly used test of imagery ability (A. Z. Zeman et al., 2010). Interestingly, his reaction times however, did not correspond to the rotation distance, which is the common finding in the literature. These reports suggest the possibility that aphantasic individuals do actually create images in mind that they are able to use to solve these tasks, however they are unaware of these images; that is they lack metacognition, or an inability to introspect.

Although the visual imagery tasks used in the Zeman et al. (2010) study are used extensively throughout the imagery literature, and in clinical settings to measure visual imagery, the validity of these tasks are somewhat unclear. For example, in the animal tails test it may be that subjects can use propositional semantic information about the images they are asked to imagine, instead of actually creating a visual image in mind. Additionally, the mental rotation task used (manikin and Shepard–Metzler tests) could be performed using spatial, or kinaesthetic imagery, rather than 'low-level' visual object imagery. A relatively new experimental imagery task, which exploits a visual illusion known as binocular rivalry, allows us to eliminate many of the issues related to these visual imagery measures (Pearson, 2014). Binocular rivalry is an illusion, or process, where one image is presented to the left eye and a different image to the right, which results in one of the images becoming dominant while the other is suppressed outside of awareness (see Fig. 1A for illustration). Previous work has demonstrated that presenting a very weak visual image of one of the rivalry patterns prior to the presentation of the binocular rivalry display, results in a higher probability of that

image being seen in the subsequent binocular rivalry presentation (Brascamp, Knapen, Kanai, van Ee, & van den Berg, 2007; Pearson et al., 2008). Interestingly, when someone imagines an image instead of being presented with a weak one, a very similar pattern of results emerges. In other words, imagery can prime subsequent rivalry dominance much like weak visual perception (Pearson, 2014; Pearson et al., 2008). Hence, this imagery paradigm has been referred to as a measure of the sensory strength of imagery, as it bypasses the need for any self-reports and directly measures sensory priming from the mental image.

If an individual is presented with a uniform and passive luminous background while they generate an image, the facilitative effect of their mental image is reduced (Chang, Lewis, & Pearson, 2013; Keogh & Pearson, 2011, 2014, 2017; Sherwood & Pearson, 2010). Previous work has shown that these disruptive effects are limited to visual tasks that require the use of depictive image generation (Keogh & Pearson, 2011, 2014) suggesting that the early visual areas of the brain are likely involved in the construction and maintenance of these images. Further, this priming effect is local in both retinotopic spatial-locations and orientation feature space (Bergmann, Genç, Kohler, Singer, & Pearson, 2015; Pearson et al., 2008), further suggesting the priming is contingent on early visual processes.

This measure of visual imagery also correlates with subjective ratings of visual imagery, both trial-by-trial and questionnaire ratings, suggesting that participants have insight into the strength of their own visual imagery (Bergmann et al., 2015; Rademaker & Pearson, 2012). Here we ran a group of self–described congenital aphantasics on the binocular rivalry visual imagery paradigm to measure the strength of their sensory imagery. If congenital aphantasia is a complete lack of visual imagery, we should expect no facilitative priming effects of visual imagery on subsequent rivalry. However, if congenital aphantasia is instead a lack of metacognition, or failed introspection, then we may expect to observe some priming, despite the subjective reports of no imagery. We further, tested the aphantasics on a range of standard questionnaires to probe the vividness and spatial qualities of their imagery.

1. Methods and materials

1.1. Participants

Fifteen (aged 21–68, 7 female) self-described aphantasic participants completed all experiments and questionnaires. The Aphantasics were recruited through a Facebook page, had emailed the lab regarding their aphantasia or were referred to us by Adam Zeman. All aphantasic participants indicated that they could not remember a time they could imagine and there was no injury that had led them to becoming aphantasic. We did not however do a full neurological exam of the participants. The control, or 'general population' group uses data that was collected over numerous experiments, some of which were published in a number of different journal articles (see Keogh & Pearson (2011, 2014); Shine et al. (2015)): while some are as yet unpublished, all using the same binocular rivalry visual imagery task, with the exact same stimuli and instructions, however not all of the studies included vividness ratings; the sample contains 209 different individuals. The age range of these 209 participants is from young adult (18 years +) to elderly (80's). All participants had normal or corrected to normal vision (i.e., wore glasses or contacts).

Fifteen control participants also completed the OSIQ (age range 18–35, 10 female).

1.2. Stimuli

All participants (in the aphantasic and general population) were tested in blackened rooms with the lights off, and their viewing distance from the monitor was 57 cm and was fixed with the use of a chin rest. The data for the general population were collected over several years and used several different computer monitors and testing rooms, as such the stimuli

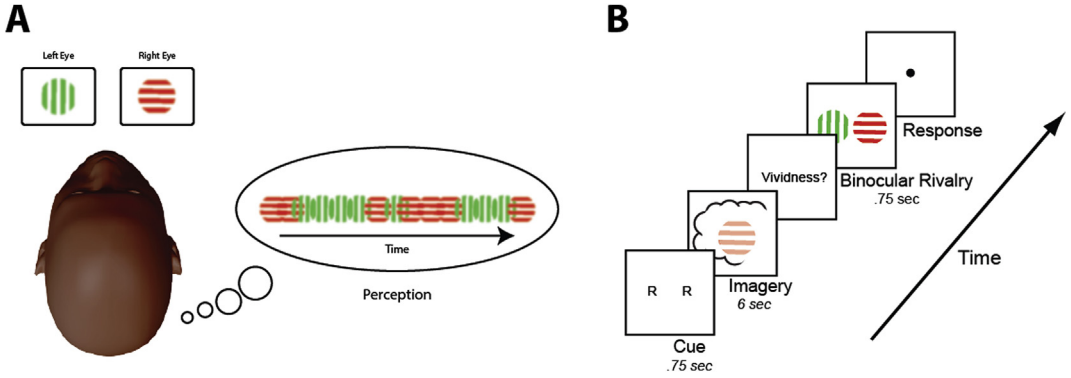

Fig. 1 – *Binocular rivalry and experimental timeline*. A. Illustration of an extended binocular rivalry presentation. Two separate images are presented, one to each eye, instead of seeing a mix of the two, perception alternates between the two images. Fluctuations only occur for prolonged viewing, not for our brief rivalry presentation. B. Binocular rivalry experimental timeline. Participants were cued to imagine one of two images (r = red-horizontal Gabor patch and g = green-vertical Gabor patch). Participants imagined this image for 6 sec, then after 6 sec they rated how vivid the image they created was on a scale of 1–4. After this they were presented with a very brief binocular rivalry display (750 msec) and had to report which colour they saw.

parameters will all be slightly different, due to monitor and graphics card differences. However, all the experiments were performed by the same experimenter (RK), who ran all participants in the aphantasia and general population studies. The following specific stimuli parameters described, are for the aphantasic participants of this study.

In the imagery task the binocular rivalry stimuli consisted of red horizontal (CIE x = .57, y = .36) and green vertical (CIE x = .28, y = .63) Gabor patterns, 1 cycle/°, Gaussian $\sigma = 1.5°$. Gabor patterns are sinusoidal gratings with a Gaussian envelope applied. The patterns were presented in an annulus around the fixation point and both Gabor patterns had a mean luminance of 4.41 cdm^2. The background was black throughout the entire task during the no luminance condition. For the imagery luminance condition the background ramped up to yellow (a mix of the green and red colours used for the rivalry patterns, with luminance at 4.41 cdm^2), during the six-second imagery period. During this period the background luminance was smoothly ramped up and down to avoid visual transients, which may result in attention being directed away from the task.

Mock rivalry displays were included on 12.5% of trials to assess any effects of decisional bias in the imagery task. One half of the mock rivalry stimuli was a red Gabor patch, with the other half being a green Gabor patch (a spatial mix) and they shared the same parameters as the green and red Gabor patches mentioned in the previous paragraph. The mock rivalry stimuli were spatially split with blurred edges and the exact division-path differed on each catch trial (random walk zig–zag edge) to resemble actual piecemeal rivalry. The aphantasic participants mock priming was not significantly different to 50% ($t(14) = 1.08$, $p = .30$), indicating a lack of decisional priming.

1.3. *Experimental procedure*

All aphantasic participants came to the University of New South Wales to participate in approximately 3 h of testing. They were reimbursed $15 AUD per hour for their participation in the study. At the beginning of the experimental session they were briefed verbally about the study (they were told they were going to fill-in some questionnaires, see some visual illusions, do some memory tests and imagine some pictures) and written informed consent was obtained. The participants then completed the following questionnaires and binocular rivalry task (lasting for about 1–1.5 h) as well as completing some other memory and imagery tasks for a different study, not reported on here.

1.4. *Questionnaires*

All participants completed the vividness of visual imagery questionnaire (VVIQ2) (Marks, 1973), spontaneous use of imagery scale (SUIS) (Reisberg, Culver, Heuer, & Fischman, 1986), and the object and spatial imagery questionnaire (OSIQ) (Blajenkova, Kozhevnikov, & Motes, 2006). The VVIQ asks participants to imagine several scenes and then rate how vivid their imagery is for each item on a scale of 1–5; with 1 = 'No image at all, you only "know" that you are thinking of the object' and 5 = 'Perfectly clear and vivid as normal vision'. Both the SUIS and the OSIQ give participants statements and they have to rate how much they agree with the statement from 1 to 5, with 1 = 'totally disagree' and 5 = 'totally agree'. An example question from the SUIS is: 'When I hear a radio announcer or DJ I've never actually seen, I usually find myself picturing what they might look like'.

1.5. *Binocular rivalry task*

Before completing the binocular rivalry imagery task each participant's eye dominance was assessed (for a more in depth explanation see Pearson et al. (2008)) to ensure rivalry dominance was not being driven by pre-existing eye dominance, as this would prevent imagery affecting rivalry dominance.

Following the eye dominance task participants completed either 2 or 3 blocks of 40 trials depending on time constraints and number of mixed percepts. Mixed percept trials were not analysed here, so for this reason we attempted to have at least 60 analysable trials per participant, however due to time constraints and mixes, 4 participants only completed 32, 34, 35, and 45 trials. There was however no correlation between the number of trials completed and rivalry priming ($r_s = .04$, $p = .90$, Spearman's correction for non-normality), hence these participants' data are included in the analysis. Participants also completed 2 or 3 blocks of 40 trials of the binocular rivalry task with a luminous background during the imagery period.

Binocular rivalry imagery paradigm: Fig. 1B shows the timeline of the binocular rivalry imagery experiment. At the beginning of each trial participants were presented with either an 'R' or a 'G' which cued them to imagine either a red-horizontal Gabor patch ('R') or a green-vertical Gabor patch ('G'). Following this, participants were presented with an imagery period of 6 sec. In the no luminance condition the background remained black during this imagery period, in the luminance condition the background ramped up and down to yellow over the first and last second of the 6 sec imagery period to avoid visual transients. After this 6 sec period participants were asked to rate how 'vivid' the image they imagined was on a scale of 1–4 (using their left hand on the numbers on the top of the keyboard) with '1' = 'No image at all, you only "know" that you are thinking of the object' and '4' = 'Perfectly vivid'. After this they were presented with a binocular rivalry display comprising the red-horizontal and green-vertical Gabor patches and asked to indicate which image they saw most, of using their right hand on the key pad: '1' = green-vertical, '2' = perfectly mixed, '3' = red-horizontal.

2. Results

Table 1 and Fig. 2A–C show participants' scores on the visual imagery questionnaires. The data supports Zeman et al. (2015) findings that aphantasic participants rate their imagery as very poor or non-existent on the VVIQ. These data also show that participants also rate their spontaneous use of visual imagery as very low on both the SUIS and Object component of the OSIQ. Interestingly, the aphantasic participants' spatial component of the OSIQ was almost double that of their object score. To further assess this finding 15 non-age matched participants also completed the OSIQ. There was a significant

Table 1 – Average scores on visual imagery questionnaires for the aphantasic participants.

	Object OSIQ/75	Spatial OSIQ/75	VVIQ/80	SUIS/60
Total score mean	21.53	41.80	19.00	17.20
Standard deviation	3.46	10.33	6.78	1.65

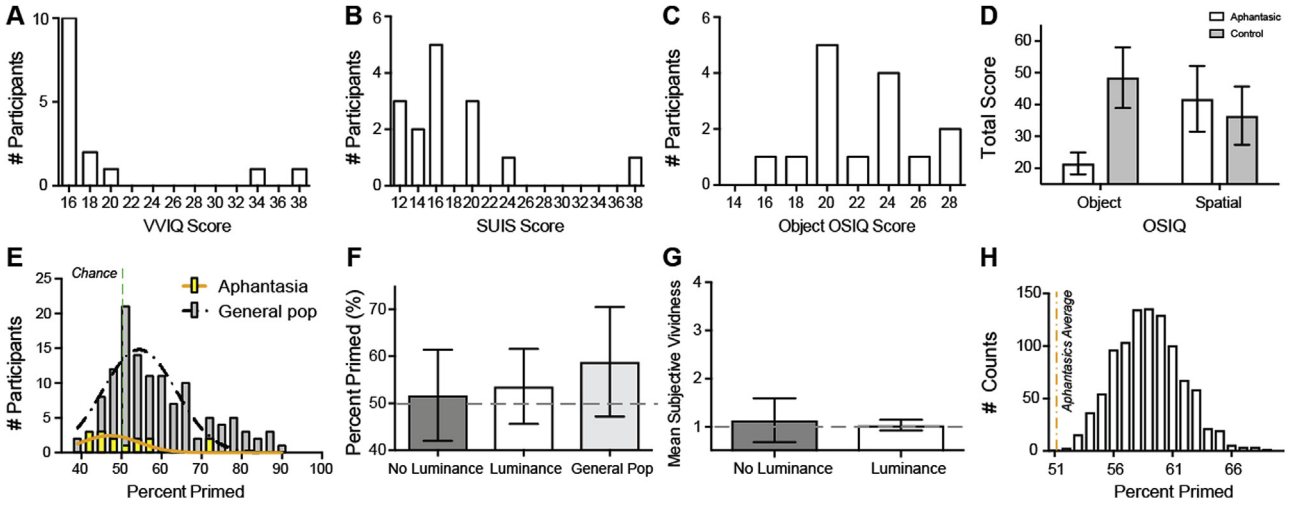

Fig. 2 – Frequency Histograms for aphantasic participants scores on the VVIQ (Bins = 2) (A), SUIS (Bins = 2) (B) and Object components of the OSIQ (Bins = 2) (C). D. Object and spatial scores on the OSIQ for aphantasic (white bars) and control participants (grey bars). E. Frequency histogram for imagery priming scores for aphantasic participants (yellow bars and orange line) and general population (grey bars and black dashed line), (Bins = 5). The green dashed line shows chance performance (50% priming). F. Average priming scores for aphantasic participants in the no background luminance condition (dark grey bar), aphantasic participants in the background luminance condition (white bar) and general population with no background luminance (light grey bar). G. Mean 'online' trial-by-trial vividness ratings for aphantasic participants in the no background luminance (grey bars) and luminous background condition (white bar). H. Frequency histogram of Bootstrapping from the general population data (Bins = 1). 15 subjects were randomly chosen, averaged, then returned to the main pool of subjects. Data shows the distribution of the mean of N = 15 for 1000 iterations. The aphantasic mean is shown on the far left (orange dotted line), with a P = .001 chance of pulling such a mean from the general population. All error bars show ±SD's

interaction between the spatial and object components of the OSIQ and the participant group (aphantasic/control), Mixed repeated measures ANOVA: $F(1, 28) = 45.25$, $p < .001$ (see Fig. 2D). Post hoc analysis of the simple effects demonstrated that as expected the aphantasic participants rated their use of spontaneous object imagery as significantly lower than the controls ($p < .001$). The aphantasics self-rated spontaneous use of spatial imagery was not significantly higher than the controls ($p = .15$), mean scores: Aphantasic = 41.80 and control = 36.53.

Next the binocular rivalry imagery priming scores were examined. As can be seen in Fig. 2E and F, aphantasics had significantly lower priming on average than our general sample of participants (Mann–Whitney $U = 914$, $p < .01$, 2-tailed). In fact, the aphantasic group's priming scores were not significantly different from chance (50%) (Fig. 1E grey filled bar, one sample t-test: $t(14) = .68$, $p = .51$), unlike the general population whose mean is significantly different to chance (one sample t-test: $t(208) = 10.96$, $p < .001$). There were also no correlations between visual imagery priming for the aphantasic participants and any of the questionnaire measures, likely due to a restriction of range (all p's >. 37). Additionally, when aphantasic participants completed the task with a luminous background during the imagery period, their priming was no different to priming in the no luminance condition (paired sample t-test: $t(14) = 1.10$ $p = .29$) and was again not significantly different from chance (one sample t-test: $t(14) = 1.75$, $p = .10$). These results suggest that the aphantasic participant's imagery has little effect on subsequent binocular rivalry. Aphantasic participants' mean 'online' trial-by-trial vividness ratings were also very low, with the average ratings not significantly different from the lowest rating of 1 (one sample t-tests: no luminance condition: $t(14) = 1.18$, $p = .36$, luminance condition: 1.37, $p = .19$, see Fig. 2G). The vividness ratings were not different between the no luminance and luminance conditions (paired sample t-test: $t(14) = 1.10$, $p = .29$).

One possible explanation for the observed differences between aphantasics and the general population may be that the eye dominance test simply did not adequately work for the aphantasic group, thus preventing any imagery priming. If a participant naturally has one eye that dominates over the other, this will result in them only seeing the one image that is presented to that dominant eye – which will result in chance

levels of priming. At the beginning of the imagery experiment all participants complete an eye dominance task to assess which eye is dominant. The contrast of the red and green Gabor patches are then adjusted in accordance with the participant's eye dominance, e.g., if the participant sees more green/has a stronger left eye, the contrast of the green Gabor patch will be decreased, while the red Gabor patch is increased. This results in each participant having different eye dominance values. To assess whether eye dominance differences might be driving our effect, or lack of effect, we compared eye dominance values (red and green contrasts) used for the aphantasic participants with 15 other participants randomly drawn from the general population pool. We found that there was no significant difference in the eye dominance values for the aphantasic and control participants, with no interaction between the contrast values (red/green/green factor) or group (aphantasic/general population) mixed repeated measures ANOVA: $F(2,56) = .55$, $p = .58$. This suggests that it is unlikely that the aphantasic participants have different eye dominance compared to the general population, and it is not driving our observed null effect.

One possible confounding factor is that there may have been slight variations in stimuli parameters used across groups due to the general population data being collected across multiple years on several different computers. To assess this we looked at a subset of the participants ($N = 47$) whose data was collected on the same computer in the same testing room as the aphantasic group. When this was done we found the same results as when using all 209 participants, that the aphantasic group priming scores are significantly lower than the sub-sample from the same room in the general population: (Mann–Whitney $U = 200$, $p = .01$).

Our aphantasic group sample size was very small compared to our general population sample (15 *vs* 209). Hence, we wanted to ensure our results were not spurious, due to the small sample size. To further assess this we ran a bootstrapping resampling analysis to ascertain the probability of getting the aphantasic mean priming score by randomly sampling from the general population. To do this we pulled a random fifteen participants out of our general pool of participants and recorded the group mean priming score, this was done 1000 times, the results of this resampling can be seen in Fig. 2H. We found that of the 1000 iterations only one had an average score equal to or less that the mean priming score of the aphantasic participants, or a probability of $p = .001$. These results suggest that it is highly unlikely (1 out of a 1000) that our result is a spurious one due to random chance or our small sample size.

3. Discussion

Our combined findings from the imagery questionnaires and psychophysical imagery task support the theory that congenital aphantasia is characterised by a lack of low-level sensory visual imagery, and is not due to a lack of metacognition or an inability to introspect. So why is it that some people appear to be born without visual imagery?

An interesting finding from our results is that while the aphantasic participants were impaired on all measures of visual object imagery (lower VVIQ, SUIS, Object OSIQ and imagery priming scores), they were not impaired on their spontaneous use of *spatial* imagery, in fact on average they rated their spontaneous use of spatial imagery higher than a control group (although this effect was not significant). This measure of spatial imagery has been shown to correlate with performance on mental rotation tasks (Blajenkova et al., 2006). Interestingly, a case study by Zeman et al. (2010) found that their patient who developed aphantasia after surgery was still able to perform perfectly on a mental rotation task. The 'what' and 'where' pathways of the visual processing stream may help explain these findings. The dorsal (early visual cortex to parietal lobes), or 'where' stream contains information about the location of objects in space, while the ventral (early visual cortex to temporal lobe) or 'what' stream contains information about an object's identity, which becomes more and more complex as it moves up the hierarchy (Goodale & Milner, 1992). Neuroimaging and brain stimulation work has demonstrated that mental rotation activates the where pathway (specifically the parietal cortex) (Harris & Miniussi, 2003; Jordan, Heinze, Lutz, Kanowski, & Jancke, 2001; Parsons, 2003; Zacks, 2008), in addition to the motor areas such as the supplementary motor areas and primary motor cortex (Cona, Marino, & Semenza, 2016; Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998). In contrast to this, when participants imagine static images the visual cortex tends to show increased activity (Cui, Jeter, Yang, Montague, & Eagleman, 2007; Kosslyn & Thompson, 2003; Kosslyn, Alpert, & Thompson, 1997), although this is not always the case (D'Esposito et al., 1997; Ishai, Ungerleider, & Haxby, 2000; Mellet et al., 2000), and when individuals imagine simple Gabor patches the content of the image can be decoded from early visual cortex (Albers et al., 2013; Koenig-Robert & Pearson, 2016). Another study has shown that the level of BOLD response in the visual cortex during an imagery task correlates with the subjective vividness of an individual's visual imagery (Cui et al., 2007). These results suggest a separation in the neural networks used in static object imagery and mental rotation or spatial imagery; as such it may be the case that aphantasics may have a severe deficiency with the ventral or 'what' pathway, or components of the pathway such as early visual or temporal cortex, but not the where pathway.

Research has indicated that when people imagine visual scenes or objects not just the visual cortex is activated, but also a large network extending to the parietal and frontal areas (see Pearson et al. (2015)). It is thought that frontal engagement is driving feedback connections that activate the sensory representations in the visual cortex. It may be possible that aphantasics have a deficit with these feedback connections from frontal cortex, and are unable to activate the visual cortex in such a way as to create a visual image in mind. Recent work from our lab indicates that cortical excitability of both the visual and pre-frontal cortex plays an important role in governing imagery strength (Keogh, Bergmann, & Pearson, 2016), hence it may be that aphantasics have abnormal activity levels in either the visual, frontal or both areas.

Some researchers have suggested that it might be the case that aphantasic individuals choose not to imagine, as opposed

to simply not being able to, possibly due to psychogenic causes (de Vito & Bartolomeo, 2016), or due to a strong belief that they cannot imagine, so they do not try. Although the exact nature of such causes is very difficult to test, we think this is unlikely for a number of reasons. Firstly, we did not see any priming or suppression for the included mock-rivalry trials in the study, which assess possible demand characteristics. Secondly, participants still reported having spatial imagery in the OSIQ, which one would not expect if participants were merely saying they cannot imagine anything. In the OSIQ they could just respond with 1's for all of the responses, however the low scores were only specific to object imagery questions. Additionally, many of our participants report that they would like to be able to imagine visually, and that they have made attempts to imagine in the past, without success, indicating a willingness to try to imagine. Some preliminary results from our lab also indicate that these participants perform above chance on a mental rotation task, which should not be the case if these individuals are just refusing to imagine during any tasks that should involve a visual imagery component. Future behavioural and neuroimaging results will likely help to answer this possibility.

Further research should investigate exactly what other behavioural and cognitive functions are impaired or even boosted in aphantasics. Additionally, functional neuroimaging research will be important for identifying possible differences in regional cortical activity during imagery based tasks as well as the large scale neuronal networks that may differ in aphantasics compared to the general population. This research will not only help to improve our understanding of the mechanisms of visual imagery, but will help us to understand the neurological differences that give rise to our vastly different abilities and experiences of our internal worlds.

Funding

This work was supported by Australian NHMRC grants GNT1046198 and GNT1085404 and ARC discovery projects DP140101560 and DP160103299. JP was supported by an NHMRC Career Development Fellowship GNT1049596.

Acknowledgements

We would like to thank first of all of our aphantasic participants who participated in the research. We would also like to give a special thanks to Adam Zeman for his generous time and putting us in touch with many of the participants in this study.

REFERENCES

Albers, A. M., Kok, P., Toni, I., Dijkerman, H. C., & de Lange, F. P. (2013). Shared representations for working memory and mental imagery in early visual cortex. *Current Biology: CB, 23*(15), 1427–1431. https://doi.org/10.1016/j.cub.2013.05.065.

Amit, E., & Greene, J. D. (2012). You see, the ends don't justify the means: Visual imagery and moral judgment. *Psychological Science, 23*(8), 861–868. https://doi.org/10.1177/0956797611434965.

Arntz, A., Tiesema, M., & Kindt, M. (2007). Treatment of PTSD: A comparison of imaginal exposure with and without imagery rescripting. *Journal of Behavior Therapy and Experimental Psychiatry, 38*(4), 345–370. https://doi.org/10.1016/j.jbtep.2007.10.006.

Bergen, B. K., Lindsay, S., Matlock, T., & Narayanan, S. (2007). Spatial and linguistic aspects of visual imagery in sentence comprehension. *Cognitive Science, 31*(5), 733–764. https://doi.org/10.1080/03640210701530748.

Bergmann, J., Genç, E., Kohler, A., Singer, W., & Pearson, J. (2015). Smaller primary visual cortex is associated with stronger, but less precise mental imagery. *Cerebral Cortex*. https://doi.org/10.1093/cercor/bhv186.

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: New self-report imagery questionnaire. *Applied Cognitive Psychology, 20*(2), 239–263. https://doi.org/10.1002/acp.1182.

Brascamp, J. W., Knapen, T. H., Kanai, R., van Ee, R., & van den Berg, A. V. (2007). Flash suppression and flash facilitation in binocular rivalry. *Journal of Vision, 7*(12), 12.11–12.12. https://doi.org/10.1167/7.12.12.

Chang, S., Lewis, D. E., & Pearson, J. (2013). The functional effects of color perception and color imagery. *Journal of Vision, 13*(10). https://doi.org/10.1167/13.10.4.

Cona, G., Marino, G., & Semenza, C. (2016). TMS of supplementary motor area (SMA) facilitates mental rotation performance: Evidence for sequence processing in SMA. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2016.10.032.

Cui, X., Jeter, C. B., Yang, D., Montague, P. R., & Eagleman, D. M. (2007). Vividness of mental imagery: Individual variability can be measured objectively. *Vision Research, 47*(4), 474–478. https://doi.org/10.1016/j.visres.2006.11.013. S0042-6989(06)00556-6 [pii].

D'Esposito, M., Detre, J. A., Aguirre, G. K., Stallcup, M., Alsop, D. C., Tippet, L. J., et al. (1997). A functional MRI study of mental image generation. *Neuropsychologia, 35*(5), 725–730. S0028-3932(96)00121-2 [pii].

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review, 95*(3), 307–317.

Gaesser, B., & Schacter, D. L. (2014). Episodic simulation and episodic memory can increase intentions to help others. *Proceedings of the National Academy of Sciences of the United States of America, 111*(12), 4415–4420. https://doi.org/10.1073/pnas.1402461111.

Galton, F. (1883). *Inquiries into human faculty and its development*. Macmillan.

Ganis, G., Keenan, J. P., Kosslyn, S. M., & Pascual-Leone, A. (2000). Transcranial magnetic stimulation of primary motor cortex affects mental rotation. *Cerebral Cortex, 10*(2), 175–180.

Ghaem, O., Mellet, E., Crivello, F., Tzourio, N., Mazoyer, B., Berthoz, A., et al. (1997). Mental navigation along memorized routes activates the hippocampus, precuneus, and insula. *NeuroReport, 8*(3), 739–744.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*(1), 20–25.

Harris, I. M., & Miniussi, C. (2003). Parietal lobe contribution to mental rotation demonstrated with rTMS. *Journal of Cognitive Neuroscience, 15*(3), 315–323. https://doi.org/10.1162/089892903321593054.

Holmes, E. A., Arntz, A., & Smucker, M. R. (2007). Imagery rescripting in cognitive behaviour therapy: Images, treatment techniques and outcomes. *Journal of Behavior Therapy and Experimental Psychiatry, 38*(4), 297–305. https://doi.org/10.1016/j.jbtep.2007.10.007.

Horikawa, T., & Kamitani, Y. (2017). Generic decoding of seen and imagined objects using hierarchical visual features. *Nature*

Communications, 8, 15037. https://doi.org/10.1038/ncomms15037.
Ishai, A., & Sagi, D. (1995). Common mechanisms of visual imagery and perception. *Science, 268*(5218), 1772–1774.
Ishai, A., Ungerleider, L. G., & Haxby, J. V. (2000). Distributed neural systems for the generation of visual images. *Neuron, 28*(3), 979–990.
Jordan, K., Heinze, H. J., Lutz, K., Kanowski, M., & Jancke, L. (2001). Cortical activations during the mental rotation of different visual objects. *NeuroImage, 13*(1), 143–152. https://doi.org/10.1006/nimg.2000.0677.
Keogh, R., Bergmann, J., & Pearson, J. (2016). Cortical excitability controls the strength of mental imagery. *bioRxiv*. , 093690. https://doi.org/10.1101/093690.
Keogh, R., & Pearson, J. (2011). Mental imagery and visual working memory. *PLoS One, 6*(12), e29221. https://doi.org/10.1371/journal.pone.0029221.
Keogh, R., & Pearson, J. (2014). The sensory strength of voluntary visual imagery predicts visual working memory capacity. *Journal of Vision, 14*(12). https://doi.org/10.1167/14.12.7.
Keogh, R., & Pearson, J. (2017). The perceptual and phenomenal capacity of mental imagery. *Cognition, 162*, 124–132. https://doi.org/10.1016/j.cognition.2017.02.004.
Koenig-Robert, R., & Pearson, J. (2016). Decoding the nonconscious dynamics of thought generation. *bioRxiv*. , 090712. https://doi.org/10.1101/090712.
Kosslyn, S. M. (2005). Mental images and the brain. *Cognitive Neuropsychology, 22*(3), 333–347. https://doi.org/10.1080/02643290442000130, 769488928 [pii].
Kosslyn, S. M., Alpert, N. M., & Thompson, W. L. (1997). Neural systems that underlie visual imagery and visual perception: A PET study. *Journal of Nuclear Medicine, 38*(5), 1205–1205.
Kosslyn, S. M., DiGirolamo, G. J., Thompson, W. L., & Alpert, N. M. (1998). Mental rotation of objects versus hands: Neural mechanisms revealed by positron emission tomography. *Psychophysiology, 35*(2), 151–161.
Kosslyn, S. M., & Thompson, W. L. (2003). When is early visual cortex activated during visual mental imagery? *Psychological Bulletin, 129*(5), 723–746. https://doi.org/10.1037/0033-2909.129.5.723.
Marks, D. F. (1973). Visual imagery differences in the recall of pictures. *British Journal of Psychology, 64*(1), 17–24.
Matthews, N. L., Collins, K. P., Thakkar, K. N., & Park, S. (2014). Visuospatial imagery and working memory in schizophrenia. *Cognitive Neuropsychiatry, 19*(1), 17–35. https://doi.org/10.1080/13546805.2013.779577.
Mellet, E., Tzourio-Mazoyer, N., Bricogne, S., Mazoyer, B., Kosslyn, S. M., & Denis, M. (2000). Functional anatomy of high-resolution visual mental imagery. *Journal of Cognitive Neuroscience, 12*(1), 98–109.
Naselaris, T., Olman, C. A., Stansbury, D. E., Ugurbil, K., & Gallant, J. L. (2015). A voxel-wise encoding model for early visual areas decodes mental images of remembered scenes. *NeuroImage, 105*, 215–228. https://doi.org/10.1016/j.neuroimage.2014.10.018.
Parsons, L. M. (2003). Superior parietal cortices and varieties of mental rotation. *Trends in Cognitive Sciences, 7*(12), 515–517.
Pearson, J. (2014). New directions in mental-imagery research: The binocular-rivalry technique and decoding fMRI patterns. *Current Directions in Psychological Science, 23*(3), 178–183. https://doi.org/10.1177/0963721414532287.
Pearson, J., Clifford, C. W. G., & Tong, F. (2008). The functional impact of mental imagery on conscious perception. *Current Biology, 18*(13), 982–986. https://doi.org/10.1016/J.Cub.2008.05.048.
Pearson, J., & Kosslyn, S. M. (2015). The heterogeneity of mental representation: Ending the imagery debate. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1504933112.
Pearson, J., Naselaris, T., Holmes, E. A., & Kosslyn, S. M. (2015). Mental imagery: Functional mechanisms and clinical applications. *Trends in Cognitive Sciences, 19*(10), 590–602. https://doi.org/10.1016/j.tics.2015.08.003.
Pylyshyn, Z. (2003). Return of the mental image: Are there really pictures in the brain? *Trends in Cognitive Sciences, 7*(3), 113–118.
Rademaker, R. L., & Pearson, J. (2012). Training visual imagery: Improvements of metacognition, but not imagery strength. *Frontiers in Psychology, 3*, 224. https://doi.org/10.3389/fpsyg.2012.00224.
Reisberg, D., Culver, L. C., Heuer, F., & Fischman, D. (1986). Visual memory: When imagery vividness makes a difference. *Journal of Mental Imagery, 10*(4), 51–74.
Reisberg, D., Pearson, D. G., & Kosslyn, S. M. (2003). Intuitions and introspections about imagery: The role of imagery experience in shaping an investigator's theoretical views. *Applied Cognitive Psychology, 17*(2), 147–160.
Sack, A. T., van de Ven, V. G., Etschenberg, S., Schatz, D., & Linden, D. E. (2005). Enhanced vividness of mental imagery as a trait marker of schizophrenia? *Schizophrenia Bulletin, 31*(1), 97–104. https://doi.org/10.1093/schbul/sbi011.
Sherwood, R., & Pearson, J. (2010). Closing the mind's eye: Incoming luminance signals disrupt visual imagery. *PLoS One, 5*(12), e15217. https://doi.org/10.1371/journal.pone.0015217.
Shine, J. M., Keogh, R., O'Callaghan, C., Muller, A. J., Lewis, S. J., & Pearson, J. (2015). Imagine that: Elevated sensory strength of mental imagery in individuals with Parkinson's disease and visual hallucinations. *Proceedings. Biological Sciences, 282*(1798), 20142047. https://doi.org/10.1098/rspb.2014.2047.
de Vito, S., & Bartolomeo, P. (2016). Refusing to imagine? On the possibility of psychogenic aphantasia. A commentary on Zeman et al. (2015). *Cortex, 74*, 334–335. https://doi.org/10.1016/j.cortex.2015.06.013.
Winawer, J., Huk, A. C., & Boroditsky, L. (2010). A motion aftereffect from visual imagery of motion. *Cognition, 114*(2), 276–284. https://doi.org/10.1016/j.cognition.2009.09.010.
Zacks, J. M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of Cognitive Neuroscience, 20*(1), 1–19. https://doi.org/10.1162/jocn.2008.20013.
Zamuner, E., Oxner, M., & Hayward, W. G. (2017). Visual perception and visual mental imagery of emotional faces generate similar expression aftereffects. *Consciousness and Cognition, 48*, 171–179. https://doi.org/10.1016/j.concog.2016.11.010.
Zeman, A., Dewar, M., & Della Sala, S. (2015). Lives without imagery - congenital aphantasia. *Cortex, 73*, 378–380. https://doi.org/10.1016/j.cortex.2015.05.019.
Zeman, A. Z., Della Sala, S., Torrens, L. A., Gountouna, V. E., McGonigle, D. J., & Logie, R. H. (2010). Loss of imagery phenomenology with intact visuo-spatial task performance: A case of 'blind imagination'. *Neuropsychologia, 48*(1), 145–155. https://doi.org/10.1016/j.neuropsychologia.2009.08.024.
Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language comprehenders mentally represent the shapes of objects. *Psychological Science, 13*(2), 168–171.