Cognition

Are there unconscious visual images in aphantasia? Development of an implicit priming paradigm

--Manuscript Draft--

Manuscript Number:	COGNIT-D-24-00197R1
Article Type:	Full Length Article
Section/Category:	Felipe De Brigard - Memory, Imagination, Counterfactual Thinking, Moral Psychology, Neuroscience
Keywords:	Aphantasia, Visual imagery, Sensory priming
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Are there unconscious visual images in aphantasia? Development of an implicit priming paradigm

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Abstract

For some people the experience of visual imagery is lacking, a condition recently referred to as aphantasia. So far, most of the studies on aphantasia rely on subjective reports, leaving the question of whether mental images can exist without reaching consciousness unresolved. In the present study, the formation of mental images was estimated in individuals with aphantasia without explicitly asking them to generate mental images. 151 Participants performed an implicit priming task where a probe is assumed to automatically reactivate a mental image. An explicit priming task, where participants were explicitly required to form a mental image after a probe, served as a control task. While control participants showed a priming effect in both the implicit and explicit tasks, aphantasics did not show any priming effects. These results suggest that aphantasia relies on a genuine inability to generate mental images rather than on a deficit in accessing these images consciously. Our priming paradigm might be a promising tool for characterizing mental images without relying on participant introspection.

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Keywords: Aphantasia, visual imagery, sensory priming

Response to reviewers

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Dear Dr. De Brigard,

We are pleased to submit a revised version of our manuscript entitled "*Are there unconscious visual images in aphantasia? Development of an implicit priming paradigm*" for consideration for publication in *Cognition*. We have addressed all the points raised by the reviewers and made the necessary changes to the manuscript. Below, we provide a point-by-point response to each of the reviewers' comments. We have mentioned the page and line number associated with each change based on the anonymised Word version of the manuscript.

We would like to thank the reviewers for their insightful comments and suggestions. We believe that their feedback has significantly improved the quality and clarity of our manuscript. We hope that the revised version of the manuscript meets the standards of *Cognition* and is suitable for publication.

Finally, we would like to request a change in the authorship order. Dr. Eddy Cavalli has moved to the position of co-last author along with Dr. Gaën Plancher in the revised manuscript. We added the request at the end of this letter.

Sincerely,

The Authors

Reviewer 1

In this interesting and well written paper, the authors explore to what extent unconscious priming effects are preserved in individuals with aphantasia. Previous research has shown impaired effects of explicit imagination on perceptual readouts in individuals with aphantasia. I think the authors here rightfully argue that these effects might be tainted by demand characteristics, so the goal to test whether these effects might be preserved when imagination is induced automatically is a worthwhile endeavour. I have some suggestions and questions that I think will improve the paper if addressed.

First, I do not think that the present paper needs to rely on the concept of unconscious imagination. As the authors mention in the discussion as well, the extent to which the concept of unconscious imagination differentiates itself from mechanisms like working memory and prediction is somewhat controversial. The concept of unconscious imagination seems to have emerged from the aphantasia field by Nanay (2020), to describe cognitive processes that also involve top-down mechanisms in perception, but do not necessarily involve a subjective experience, and argue that these mechanisms might still be preserved in aphantasia, and thus unconscious imagination exists. I think the move to categorise these processes as unconscious imagination is only interesting to the extent to which this concept is coherent. In other words, it is only interesting to the extent we can make the claim that individuals with aphantasia are still "imagining" things, but they might just not be conscious of it. In contrast, if these mechanisms are not forms of imagination - and I think a strong case could be made that these aren't forms of imagination - finding preserved working memory and priming in aphantasia would be of much less significant empirical and theoretical value.

Please note that I do not think this would be hindrance to the present study. After all the present study finds that individuals with aphantasia are in fact impaired in an implicit priming task. I ask the authors to consider this as evidence that there might be a more broad deficit in the way the brain uses top-down information processing in perceptual inference, rather than a deficit that is specific to (unconscious) imagination. I realise that the authors mention the work on sensorimotor simulation as a possible overlapping mechanism. However, many have argued that the brains ability to form predictive signals on the basis of priors is a fundamental principle of cognitive function, and a deficit in such mechanisms have been theorised to underlie various sensory and cognitive aberrances, as seen in psychosis and autism. Since individuals with aphantasia seem to have a disturbance in these mechanisms thought to be fundamental to cognitive function, perhaps it would be useful if the authors connected to this line of work in their discussion a little bit more to discuss what the implications might be.

We thank the reviewer for this comment. We agree on the idea that "unconscious imagination" or "unconscious mental imagery" might not be a relevant concept. Our results and their implications are in line with a recent discussion by Krempel & Monzel (2024) in favour of a true absence of visual imagery in aphantasia and against the elusive notion of an "unconscious" form of it. However, the hypothesis and concept of unconscious visual images in aphantasia is still prevalent in the literature (e.g., Liu & Bartolomeo, 2023, *inter alia*) and there is a need for empirical evidence to support the theoretical arguments against the very notion, especially considering that aphantasia is still largely identified using subjective reports. Consequently, we believe that maintaining the use of "unconscious mental imagery" is necessary, at least as an "anchor" concept that is being argued against.

We thank the reviewer for the suggestion to discuss the hypothesis of perceptual inference and predictive signals deficits. However, we would argue that this hypothesis might be too strong: we think that showing that aphantasics do not process visual images for perceptual inference do not necessarily imply that they have a "*deficit in the way the brain uses* top-down information", but rather an *absence of the very information* to be processed, that is, visual images. Thus, they would not have a "general" deficit in the ability to form predictive signals, but an inability to form them from certain specific modalities. This would explain slower response times in certain very fast visual tasks similar to ours, but a typical functioning in more integrated tasks (working memory, etc.) by using other modalities to represent information. This point is discussed in Section 4.2, p.30.

As a minor comment, perhaps make it very clear that Jacobs 2018 is a N=1 study, and that these results (although widely cited), really requires further replication.

We thank the reviewer for this suggestion. This precision was added on p.2: "Although on a N = 1 case study, this result may still suggest the existence of this unconscious form of imagery in aphantasia."

I was curious how strongly the effects in the implicit and explicit condition are correlated. It wouldn't undermine the findings in the present study, but it might be useful to know for the reader to what extent the implicit and explicit effects are separable.

We thank the reviewer for this interesting interrogation. We computed a correlation between the two effects, and it is not significant ($\rho = 0.05$, 95% CI [-0.11, 0.21], $p = 0.57$). Thus, the two effects indeed appear to be separable to some extent. We added this analysis in the Methods on p.17, and the Results on p.26-27.

Minor suggestions for the figures: Could the authors include some transitional probabilities in figure 2, so it is immediately clear which stimuli follow with which probabilities. The figure now seems to suggest that there is no preceding cue in the black gabor conditions, which I know is not the case from reading the methods.

Further, I think the data figures would be improved if they included individuals data points (violin or raincloud plots perhaps). Also, the plotted effect is a within subject effect, so within standard errors of the mean would be a more intuitive presentation of the results, rather than standard errors of the mean.

We thank the reviewer for these suggestions. Figure 2 has been adjusted on p.11. For the response times Figures 5 and 6, the choice of representing the marginal means for the groups only was based on the important gap between individual mean response times (approximately ranging from 500 to 1000ms) and the effect size of interest (~30ms). We added global figures with individual data points and "zoomed" versions to highlight the effect of interest for each task. This resulted in Figures 5 on p.20, 6 on p.22, 8 on p.24 and 9 on p.26.

When conducting Pearson correlations across groups, you need to control for group as in the presence of large mean differences in groups, a correlation can be driven by group differences, rather than a true linear relationship between the variables. In line with this, the claim about a continuum in the discussion should be softened.

We thank the reviewer for spotting this oversight. We also later realised that the linearity assumption was not justified in our problem, especially considering the ordinal nature of the data and the underlying group structure mentioned. To relax this linearity assumption, we instead conducted Spearman correlations (i.e., on ranked data). Correlations with the OSIQ-O and SUIS remained significant, the correlation with the VVIQ became significant by a slight margin, and the conclusions were nuanced appropriately. Ranked correlations indeed allowed us to discuss the *monotonicity* (preservation of order) of the link, but not the linearity along a continuum, as has been pointed out here. The analytic process was corrected in the Methods on p.17, the Results have been modified on pp.26-27, and the discussion of these results has been adjusted on p.29-30.

Since a claim is being made about the existence of a null-effects in the aphantasia groups, it might be useful to report bayes factors in favour of the null-hypothesis.

We thank the reviewer for suggesting Bayesian analyses. We fitted Bayesian models independently for aphantasic and control groups to assess the evidence in favour or against the existence of a congruence effect in these "sub-models". They confirmed strong evidence in favour of a null congruence effect in the aphantasia group in the implicit task ($BF_{01} = 14.12$) and explicit task ($BF_{01} = 12.09$), and extreme evidence in favour of a congruence effect in the control group in the implicit task ($BF_{01} < .001$) and explicit task ($BF_{01} < .001$). The description of the Bayesian modelling procedure can be found on p.16, and the results are mixed with the reports of model contrasts (and highlighted) throughout the Results.

Could the authors please discuss the limitations of their response mapping procedure. The responses aren't randomized (horizontal is always H and vice versa), which means participants could in theory learn the relationship between a cue and a button-press, rather than the effect of a cue on visual processing speed. How could this change the interpretation of the findings?

Indeed, H was consistently Horizontal and V was Vertical. However, we would like to emphasize that there were as many congruent trials as incongruent ones, which, in our view, implies that participants could not reliably predict the correct response based on the cue alone. If they had responded solely based on the key they associated with the cue, only 50% of the responses would have been correct, which likely would have prevented the observation of a congruence effect. In light of this observation, we do not believe that learning the response key associated with the cue was a relevant or adopted strategy by the participants. Rather, we argue that the effect we measured was indeed related to the influence of a cue on visual processing speed, in line with our interpretation. This methodological consideration was added in the procedure details on p.11.

Were there any differences in accuracy? Even if not, it might still be useful to report.

We thank the reviewer for this suggestion. We initially removed errors as there were very few and they are usually not analysed in RT tasks, however we agree that this precision could be of interest for the reader to have a comprehensive picture of the results. Consequently, we analysed accuracy using logistic regression models to assess potential differences between the groups, before subsequently removing errors for RT analyses. Details of the analytic methods have been added on p.14-15 to describe the models, and results have been added on pp.19. There were no accuracy differences between the groups.

Reviewer 2

In this manuscript, the authors report on an experiment where they have developed a new implicit priming paradigm to test the hypothesis that aphantasics have unconscious mental imagery. Their results support that aphantasics do not have unconscious mental imagery, as they do not demonstrate a priming effect on the task. This is an interesting and well-designed paradigm which gets at a phenomenon which is not often tested in aphantasia research, and as such I think the manuscript would make an important contribution to the literature. However, I believe there are points which warrant substantial revisions in both the analysis conducted and the presentation of the work, and for this reason I would recommend acceptance following major revisions to the manuscript. Below I list points for the authors to address divided into major and minor issues, and I look forward to hearing the authors' responses to the concerns I raise.

"They found no differences in accuracy between the groups, but slower RTs and lower confidence in the aphantasics' answers and argued that this result was consistent with aphantasics having the visual images required to complete the task, albeit without conscious access to them." (p2) The authors here claim that visual images are required to complete the task, but it is not clear that this is in fact the case as alternative hypotheses aren't ruled out. It would be possible to encode information in a different format (e.g. linguistically) and still perform this task. Further, it is unclear why slower RT from aphantasic participants would imply that they still have visual images. Could the authors please clarify the connection between slower RT and lack of mental imagery.

> We thank the reviewer for this comment on the study of Liu & Bartolomeo (2023). We acknowledge that any interpretation remains delicate and should be approached with caution when a task can be completed by encoding information in an alternative format (e.g., linguistically). It is particularly important to be mindful of this possibility in the tasks being proposed. In our own study, we made a concerted effort to account for this possibility by including a condition in which the Gabors had no color, thus preventing participants from employing the linguistic strategy of learning that all red Gabors had a specific orientation and responding solely based on their color. As for the slower reaction times (RTs) observed in

aphantasic individuals, this also remains difficult to interpret, and caution is warranted. Rather than attributing the slower RTs to the use of mental imagery, it is possible that alternative strategies, which take more time to implement, could explain the slower RTs. Liu and Bartolomeo themselves link slower RTs to lower confidence levels and suggest that this link reflects an inability to analyze their own mental processes, or in other words, to "know how they did it." However, we agree that this interpretation should be approached with caution.

We reformulated to try and make this more explicit on p.2: "They found no differences in accuracy between the groups, but slower RTs and lower confidence in the aphantasics' answers, and argued that this result was consistent with aphantasics having the visual images required to succeed at the task, albeit without the knowledge of"how they did it"."

The authors use involuntary/unconscious somewhat interchangeably throughout the manuscript which makes it unclear what hypothesis they are actually intent on testing (p4). Note that involuntary and unconscious are not interchangeable as not all involuntary imagery is unconscious. For example, flashbacks (e.g., as in PTSD) and night-time dreams are cases of involuntary imagery, but these are still conscious. I urge the authors to not confuse involuntary for unconscious, and to be clearer about which cases they are interested in.

We thank the reviewer for this key suggestion. Indeed, all unconscious imagery (if it exists) should be involuntary, but the reverse is not true. Our study focuses on providing evidence to test the idea of "unconscious mental images." We believe that showing no unconscious perceptual priming in aphantasia could help rule out the possibility of unconscious perceptual processing without the actual stimulus, which refers to "unconscious mental images" as described by Nanay (2020). We replaced all imprecise wording throughout the manuscript.

"Consequently, the binocular rivalry paradigm developed by (Keogh & Pearson, 2018; like other objective measures based on explicit instructions to use mental imagery, e.g., Kay et al., 2022; Milton et al., 2021) cannot exclude the possible existence of involuntary and unconscious mental images in aphantasia. We aimed to fill this gap by designing an implicit priming task that would allow us to study unconscious mental images in aphantasia."

(p4) This again seems to assume that involuntary and unconscious go hand in hand, but they actually dissociate (see the point just above). Are authors interested in testing 1) unconscious, or 2) involuntary, or 3) unconscious and involuntary imagery, in aphantasia? Please clarify throughout the manuscript.

> In line with the above comment, the correct concept at the heart of the hypotheses tested here is "unconscious". All imprecise wording has been replaced.

Figure 5 indicates that the response time for participants with aphantasia is consistently just below 680ms in the implicit task, but consistently around 800ms in the explicit task (p19). Is this a significant result? If so, why would it be the case that aphantasics are slower in the explicit task? If aphantasics have neither conscious nor unconscious imagery, should they not show more similar RTs on the implicit and explicit tasks?

> This result also puzzled us at first. It is important to first note that this slowing is observed in both populations, making it systematic rather than exclusive to individuals with aphantasia. Upon reflection, we thought that it might simply be a consequence of the experimental design. The implicit task is fast-paced, with a 500ms fixation, a 150ms cue and an immediate response. In contrast, the explicit task has a 500ms fixation, 1500ms letter cue, 3000ms imagery phase, another 500ms fixation followed finally by the response. That is, each answer was preceded by 5.5 seconds *and* participants were instructed to perform a conscious action (imagery), which might make it harder to find a "rhythm" and react quickly to the stimuli. This is one interpretation among many, but it could explain why the same effects appear at two different time scales (~120ms later) *for both groups*: the same processes (i.e., hypothesised unconscious imagery for controls and absence thereof for aphantasics) are responsible for the priming effect, but its consequences are somehow slightly delayed by the events leading up to the response.

"Extremal VVIQ groups" should be "Extreme VVIQ groups" (p20). However, characterising the contrast as two extremes is misleading, as the control group consisted of participants who score was 42 or above on the VVIQ, which includes participants with a non-extreme score. An extreme (hyperphantasic) score is normally taken to be VVIQ $\geq$ 75 or VVIQ $$80 (see e.g., Zeman (2024)). I would amend this here so that it does not imply that a score above 42 is extreme. I also recommend changing the introduction accordingly where the authors say they will discuss extreme scores, as they do in fact contrast aphantasics with average to extreme scores (and number of hyperphantasics are not reported). Also amend this in the caption of Figure 6, where 'groups at extreme ends of VVIQ' are mentioned. I would also suggest that the authors amend the discussion on p.6 in the Introduction, where they say that their results will shed light on a frequently asked questions in aphantasia research, namely whether there is a difference between aphantasics with VVIQ $\leq$ 16 (no imagery) and VVIQ between 17-32 (vague and dim). As far as I can see in the Results, the authors do not actually contrast these two groups. They seem to instead contrast the group VVIQ $\leq$ 16 with the group VVIQ between 42-80, but this does not get at the question which other authors have posed on p.6. as it only contrast VVIQ $$16 with controls, but not VVIQ between 17-32 with controls. This point raises two major issues of revision. Firstly, as the authors are contrasting their aphantasia sample with controls from 42-80, this raises the possibility that their results could be skewed by hyperphantasics being included in the control group. I suggest the authors carry out analysis comparing aphantasics to the normal range of imagery (VVIQ between 55-60 is reported in Zeman et al (2020), McKelvie (1995), and Dance et al (2022)). Secondly, I suggest that the authors carry out analysis comparing total aphantasics (VVIQ $\leq$ 16) to moderate aphantasia (VVIQ between 17-32) in order to answer the question posed on p.6 and raised by many other researchers as noted.

We thank the reviewer for this thorough recommendation and for spotting this oversight. The intuition here was correct: our sample comprises "total" aphantasics (VVIQ = 16, N = 50), "hypophantasics" (terminology of Reeder & Pounder, 2024, VVIQ between 17 and 32, N = 39), and "controls" (VVIQ between 32 and 74) but only two hyperphantasics (VVIQ $\geq$ 75).

Thus, we conducted a new analysis that could answer several questions raised here, by comparing these "finer-grained" groups of total aphantasics, hypophantasics, and controls, leaving out the two hyperphantasics. These analyses resulted in an interesting trend specific to the hypophantasic group, with a trend implicit effect but no explicit effect. We amended the introduction on p.6, the

Methods on p.17, the Results on pp.23-26, and these new pattern are discussed on p.29. The conclusion on p.34 has also been modified accordingly.

"We argue that this novel paradigm provides a strong base to develop implicit objective behavioural assessments of visual imagery, thereby opening promising avenues for a better objective characterization of aphantasia." (p25) What do authors mean by "better" here? Do they mean that it's better than binocular rivalry, galvanic skin response, automatic pupil dilation? If so, why? Is it more reliable? Please elaborate on what makes it better, and what it makes it better relative to.

Studies using binocular rivalry, galvanic skin response, and automatic pupil dilation have greatly inspired us and made valuable contributions to the objective characterization of aphantasia. With our study, we aimed to provide an additional and original contribution, which, alongside the work of other teams, would contribute toward a better objective characterization of aphantasia. However, we wish to highlight the strengths and unique features of our paradigm, namely that it relies on implicit rather than explicit mental imagery, is easy to implement (requiring no expensive or complex equipment, just a computer), and can be conducted online, allowing for the recruitment of a wider sample. In our view, these strengths make our paradigm a significant contribution.

The sentence has been modified to better reflect our thought on p.29: "We propose that this novel online paradigm provides a foundation to develop implicit, objective behavioural assessments of visual imagery using a minimal setup, thereby opening new avenues for a large-scale, objective characterization of aphantasia."

It is not clear why including the non-coloured condition makes it unlikely that a propositional (rather than imagery based) strategy could have been used by participants with aphantasia (p28). Please clarify the reasoning here.

Our phrasing likely led to the assumption that the non-colored condition made the use of a propositional strategy unlikely, and it requires clarification. Our point is rather that this strategy would only be advantageous in the colored condition: as soon as the color of the target appears, participants using this strategy respond with the key corresponding to the orientation associated with the color of the Gabor, an association they have memorized verbally (e.g., “red means horizontal”). However, when the non-colored target appears, participants can no longer rely on the color of the target to use the propositional strategy and are thus forced to process the orientation of the lines. Since the colored and non-colored trials were presented randomly, sticking to the propositional strategy could be hard, thus our hypothesis that it encouraged participants to abandon it. The misleading wording in our sentence was likely to be “our tasks had the advantage of *preventing* the use of these type of strategies”, as our tasks do not strictly “prevent” anything. We nuanced it on p.32: “our tasks have the advantage of making the use of this type of strategies more difficult to adhere to, thanks to a condition in which the targets are not coloured.”

“Curiously, the analysis of questionnaire data yielded a significant difference between aphantasics and controls in reported spatial imagery, assessed by the spatial scale of the OSIQ, contrasting with previous studies on aphantasia that used this questionnaire and found no between-group differences (Bainbridge et al., 2021; Dawes et al., 2020; Keogh & Pearson, 2018).” (p29) The authors should take into account alternative explanations. For example, it could be explained by the different uses of cut-off points in aphantasia. The differing results here could potentially be explained by differences in how aphantasia groups are demarcated in different articles. The authors used VVIQ ≤ 16 to denote aphantasia, whereas the other studies use other cut-off points (see Blomkvist and Marks, 2023 and Blomkvist 2022 for discussions).

We thank the reviewer for this relevant point. As suggested, we have now separated our sample in hypophantasics and aphantasics. This had led to new results showing that hypophantasic did not significantly differ to controls in the OSIQ-spatial, but scored higher to aphantasic, although aphantasics and controls still significantly differed. This is coherent with the suggestion of the reviewer that the choice of cut-off is crucial in aphantasia. Accordingly, we added some sentence in the discussion p.32: “Large differences in spatial imagery ability also existed within the aphantasic group, as shown by the difference between the hypophantasic and aphantasic groups on the OSIQ-Spatial. This finding could be specifically tied to the choice of cut-offs used in aphantasia studies".

"In stark contrast, it is often implied that the absence of fast automatic predictive processing and simulation of sensory representations in aphantasia could be a major functional disadvantage (Blomkvist & Marks, 2023; see for instance Monzel et al., 2022), therefore framing the condition as mostly characterized by deficits and drawbacks." (p29) It is not clear that the authors cited here should be read in this way as they both caution against interpreting aphantasia as having an overly negative impact on a person's life. Moreover, it is unclear how the results of the current study would speak to this point. Please clarify. In general, the discussion in this final section strikes me as unnuanced as it fails to capture the points that other authors make in a fair light. I would suggest rewriting this section to better reflect the points made by other author rather than setting it out in an antagonistic way.

"This could shed new light on this condition and help to define aphantasia as a balanced state rather than a disorder." (p29) This paints other authors in the light of trying to show that it is a disorder, but this is exactly what they are denying. This discussion does not correctly represent the views stated by authors in articles cited, and mischaracterises them in important ways which I believe is unfortunate for the field of aphantasia research as a whole as many authors are particularly calling for aphantasia not to be pathologised. As suggested above, I would rewrite this discussion with more sensitivity to the issue of whether aphantasia is a disorder, a condition, or an individual difference.

We thank the reviewer for these comments. Indeed, we acknowledge that this part of the discussion was not nuanced enough and we understated the "antagonistic" tone of certain paragraphs, this was a mistake on our end. This is especially true given recent occurrences of expressions on the subject by the authors cited, such as the discussion of Monzel (2023) or Blomkvist (2023), which we do not ignore, and we realise that several sentences could appear as oversimplifying the views of some authors. Section 4.4 on p.33 has been rewritten in an attempt to be more in line with the current views in the field of aphantasia research and remove superfluous antagonistic formulations. Our point originally came from the observation of very similar accuracy between groups and across the imagery spectrum on our task, which we felt echoed the debate about benefits and drawbacks of aphantasia.

"[…] received renewed attention only nine years ago, when Zeman et al. (2015), in a study that has since become very popular" (p1) Strange word choice of 'popular'. Maybe instead refer to the fact that it's often cited?

The wording was indeed inaccurate and has been replaced by "a study that has since been highly cited, coining the term"*aphantasia*" to refer to "reduced or absent voluntary imagery" on p.1.

Zeman et al. (2015) suggest that "We propose the use of the term 'aphantasia' to refer to a condition of reduced or absent voluntary imagery." (p1) The authors only mention an inability to generate mental images when citing this. Please amend.

The definition has been corrected on p.1, same quote as above.

The authors keep referring the aphantasia as a 'condition' whilst recognising the heterogeneity of it. I would recommend looking at Blomkvist and Mark's (2023) discussion of whether aphantasia should even be classified as a condition given what we currently know, and to incorporate this into the present article.

We thank the reviewer for this comment. The characterisation of aphantasia as a disorder, a condition, or an individual difference is indeed of primary importance, and our choice of words needs to reflect our view and be consistent throughout the article. We added a discussion of Blomkvist and Marks (2023) in Section 4.4, p.33, and chose to harmonise the wording throughout the article by simply using the term "aphantasia" when referring to it.

The author discusses Nanay's hypothesis that some people with aphantasia could have intact unconscious imagery based on a study from Jacobs et al. (2018), but does not mention Blomkvist's (2022) argument against this interpretation of the data (p2). I would suggest that authors incorporate this into their discussion for a more nuanced discussion. I would also suggest that the authors actually define here what they mean by 'unconscious mental imagery' as this is not clear.

We thank the reviewer for this suggestion. We added a mention of Blomkvist's (2022) views to this paragraph on p.3, "On the other hand, several studies that sought to develop objective measures assessing visual imagery found consistent behavioural and physiological differences between aphantasics and controls on imagery tasks, thus challenging Nanay's (2020) hypothesis of unconscious mental imagery in aphantasia (see also Blomkvist, 2022). Aphantasics have been shown to have a reduced skin conductance response […]"

As mentioned earlier, the terms used throughout the article will be harmonised and the unconscious mental imagery at stake here was better defined on p.2.

The author cites the Jacobs et al. (2018) study as potential evidence for unconscious imagery in aphantasia, but ignore the results from Keogh and Pearson (2019) which speak against this (p2). This is moreover both discussed in Nanay (2020) and Blomkvist (2023) and would be relevant to mention here.

The results speaking against this interpretation of Jacobs' experiment and the idea of unconscious imagery (Keogh & Pearson, 2018, cited also by Blomkvist, 2022) are detailed in the next paragraph. The structure we chose was to expose arguments brought forward by teams supporting the "unconscious imagery" hypothesis, then the opposite view. We apologize if this structure was unclear at the time of reading. We added additional details on the counter-arguments in the subsequent paragraph to makes this more clear on p.3.

"This possibility, often raised in discussions about the condition, prevents from firmly concluding from these results that unconscious mental images exist in aphantasia." (p3) Citations missing for these discussions.

Citations of Jacobs et al. (2018), Knight et al. (2022), Liu & Bartolomeo (2023) and Monzel et al. (2021) have been added on p.3.

"On the other hand, several studies that sought to develop objective measures assessing visual imagery found behavioural and physiological differences between aphantasics and controls, such as aphantasics having no skin conductance response to frightening scenarios (Wicken et al., 2021), no automatic pupil dilatation in reaction to imagined bright stimuli (Kay et al., 2022), or no priming by visual imagery (Keogh & Pearson, 2018), suggesting that aphantasics are truly unable to produce mental images." (p3) Results are reported in a misleading way here. Neither of these studies found no skin conductance response/pupil dilation/priming, but rather found that these effects were reduced. Please rewrite to clearly clarify the findings from the respective studies.

We clarified this aspect on p.3, all mentions of "no effect" were replaced by "reduced effect".

Add recent study by Krempel and Monzel to discussion about involuntary imagery (p4). The study can be found here: https://pubmed.ncbi.nlm.nih.gov/38564857/

This recent review by Krempel and Monzel is indeed very relevant for the subject of our study. We added their views on p.30.

The discussion of Muraki et al (2023) is confusing, as the authors talk about how self-diagnosed participants were asked to form voluntary images, and this could have skewed results as they were asked to do something they believe they couldn't (p4). However, Muraki et al. (2023) is not a study, it is a review article without any new empirical work. Which study are authors referring to here?

This refers to the theoretical discussion of Muraki et al. (2023) of the concept of unconscious mental imagery, its implications, and the challenges it poses both to confirm or refute its existence. This mention in the introduction was superfluous and added nothing to the point, so it has been removed.

"If aphantasia relies only on a difficulty to access mental images, a priming effect should be observed for both groups in the implicit task, but not in the explicit one. If aphantasia relies on a genuine difficulty in creating mental images, no priming effect should be observed for the aphantasia group neither in the implicit nor in the explicit task, as opposed to the control group." (p6) This section talks about aphantasia as a problem of accessing mental images. However, the sections in the introduction focus on discussing involuntary imagery and unconscious imagery. It would be helpful for the reader if the hypotheses were put in that language here too, to make a clearer link between the cases. If I understand correctly, the authors are suggesting a contrast between a voluntary and an involuntary task, and hypothesising that if aphantasics retain unconscious imagery, then no priming effect should be observed for aphantasics in either the involuntary or voluntary task (whereas priming effect should be observed for controls).

We adjusted the wording for consistency and clarity. The new sentence is: "If aphantasics have only difficulties with conscious mental imagery, a priming effect should be observed for both groups in the implicit task, but not in the explicit one. If aphantasics have difficulties with both conscious and unconscious mental imagery, no priming effect should be observed for the aphantasia group neither in the implicit nor in the explicit task, as opposed to the control group." (on p.6)

"("Perfectly clear and vivid as if it were a normal vision")." (p8) Typo, remove "a".

The typo was corrected on p.8.

Final scoring is reported for the SUIS but not the VVIQ (p8). Amend for consistency.

The VVIQ score range (16-80) was added on p.8.

"This result was also present when adopting a more conservative definition of aphantasia by analysing groups restricted to aphantasics scoring at floor VVIQ and controls with high VVIQ scores." (p24) It is misleading to say that a VVIQ of 42 is high. Most scores above 42 will be in the average range.

This discussion was amended on p.29, to reflect the results of the new analyses on finer-grained VVIQ groups mentioned earlier that replaced this.

"This result supports the hypothesis that aphantasia may be associated with a reduction or absence of mental image generation, even unconscious, as opposed to a lack of conscious access to mental images."(p24) "may be associated with" is too vague. Be clearer about the relationship.

This sentence has been rephrased on p.28: "This result supports the hypothesis that aphantasics have difficulty generating both conscious and unconscious mental images, rather than only conscious ones."

“The explicit task with instructions to produce mental imagery was inspired by the binocular rivalry paradigm developed by Keogh & Pearson (2018) and managed to replicate their pattern of results showing an absence of priming in aphantasia, thus validating the effectiveness of priming tasks to evidence conscious mental imagery differences.” (p24) It would be relevant here to point out that the priming effect from Keogh and Pearson (2018) is not the same as the priming effect in the current study, as the current study was not in fact assessing binocular rivalry by presenting different stimuli to the two eyes at the same time.

We thank the reviewer for spotting this oversight. This precision was added on p.29: “The explicit task with instructions to produce mental imagery was inspired by the binocular rivalry paradigm developed by Keogh (2018) and produced a similar pattern of results showing an absence of priming in aphantasia with a different task, thus validating the effectiveness of priming tasks to evidence conscious mental imagery differences.”

“It is interesting to observe that our paradigm correlates with rather ecological forms of visual imagery.” (p25) Do the authors mean to imply that the VVIQ items are not ecological? Most of them seem to be, comprising e.g., of imagining a person you know well or a shopfront. Please elaborate on this claim to clarify whether the VVIQ contains non-ecological items and why these should be taken to be non-ecological.

Our wording was also inaccurate here. By “ecological”, we meant to designate the broader scope of the SUIS and OSIQ, which also probe the use of different forms of imagery in daily life, whereas the VVIQ is focused on the immediate experience upon filling the questionnaire.

However, based on a suggestion by another reviewer, we corrected our method for the correlational analyses and conducted Spearman (i.e., ranked) correlations instead of Pearson correlations to account for the ordinal nature of questionnaire responses and the inability to make the claim of a linear relationship between continuous questionnaires scores and congruence effects. The results of these new analyses showed that the correlations with the VVIQ were in the same range as those of the OSIQ and SUIS, but that they might be driven by group differences. As such, this argument about the nature of the VVIQ was not relevant anymore. The entire correlation results part has been corrected accordingly and this discussion paragraph changed entirely on p.29.

“However, this raises the question of whether our study assessed”mental imagery”, as it is commonly defined as a conscious and voluntary experience.” (p26) Please provide citations for this claim. In fact, many definitions do not have a take on whether this has to be voluntary and conscious and instead claim the opposite (see for example, Pearson (2019), Nanay (2020)).

We thank the reviewer for this comment. The sentence here was indeed inaccurate, as the problem we eventually discuss is whether the concept of “unconscious imagery” is relevant. This introductory sentence was revised on p.30.

The authors start section 4.2 by discussing whether their study is really targeting unconscious mental imagery and then go on to discuss claims made by Muraki et al. regarding sensorimotor stimulation (pp26-27). I’m not sure this is the most relevant material to draw on. Nanay’s conception of unconscious mental imagery seems more appropriate. The final sentence in this section is also somewhat difficult to parse, please consider rephrasing.

We thank the reviewer for this suggestion. Indeed, Nanay’s (2020) views were very important in the field of aphantasia to define the concept of unconscious mental imagery which is at the heart of the present study. We added a discussion of these views in the same paragraph on p.30.

“This type of strategy could even have been detrimental, which could explain slower response times in the uncoloured condition than in the coloured condition.” (p28) What do authors mean by “detrimental” here, it seems like a strange choice of word? Consider rewording.

The wording is indeed inaccurate here. We used the word in the meaning of “counter-productive”, and replaced it accordingly on p.32.

“Large differences in spatial imagery ability also existed within the aphantasic group, hinting that this finding could be specifically tied to our sample and, more generally, that there could exist various sub-types in aphantasia characterized by their variable reliance on different forms of mental representations (e.g., spatial, verbal, kinaesthetic).” (p29) This seems like a rather odd suggestion. It is commonplace to suggest that there are different kinds of aphantasia based on different sensory modalities (auditory, visual, olfactory, gustatory, tactile), as well as other systems (affective, motor). But something like “verbal aphantasia” seems like a contradiction in terms as aphantasia explicitly has to do with mental imagery (a form of mental representation) and a verbal representations are per definition not imagistic.

> We thank the reviewer for this comment. The word “verbal” was replaced by “auditory” on p.33, which is more relevant as a form of aphantasia.

“Furthermore, it has not yet been proven that aphantasia is a pathological disorder Blomkvist & Marks (2023).” (p29) This point could be put a bit more delicately, as it seems to imply that researchers are trying to prove this and that we should expect that it will be proven. It would also be relevant to cite Monzel et al. (2023) here as this is the study which investigates the question, which Blomkvist and Marks then discuss.

> As we acknowledged in response to a previous comment, our tone was too rough in some places and lacked nuance. This was adjusted throughout the discussion, and indeed here on p.33: ” Furthermore, it has been shown that aphantasia does not meet the criteria of a pathological disorder (Monzel et al., 2023; Blomkvist & Marks, 2023).”

“In sum, our findings provided evidence suggesting that aphantasia does not only result from lacking metacognition but might reflect an actual alteration (whether a reduction or an absence) of both conscious and unconscious mental imagery.” (p29) This conclusion is too broad as authors only tested VVIQ $\leq$ 16, and the parenthesis mention reduction in mental imagery (which I take to imply 17-32) but the authors only investigated a sample of participants with VVIQ $\leq$ 16.

> In line with previous comments, this final sentence on p.34 was adjusted to better reflect the results and nuance the findings: “In sum, our findings provide evidence suggesting that”total” aphantasia (defined by a VVIQ score of 16) may not solely result from impaired metacognition but could indicate an underlying reduction in both conscious and unconscious mental imagery. Additionally, a trend

in the results indicated that hypophantasia (i.e., reduced imagery, VVIQ scores between 17 and 32) may involve the presence of unconscious imagery, albeit without the capacity for voluntary imagery generation."

References

Krempel, R., & Monzel, M. (2024). Aphantasia and involuntary imagery. *Consciousness and Cognition, 120,* 103679. https://doi.org/10.1016/j.concog.2024.103679

Liu, J., & Bartolomeo, P. (2023). Probing the unimaginable: The impact of aphantasia on distinct domains of visual mental imagery and visual perception. *Cortex*, *166*, 338–347. https://doi.org/10.1016/j.cortex.2023.06.003

Nanay, B. (2020). Unconscious mental imagery. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1817), 20190689. https://doi.org/10.1098/rstb.2019.0689

Reeder, R., & Pounder, Z. (2024). *Non-visual spatial strategies are efficient for maintaining precise information in visual working memor*. https://doi.org/10.31234/osf.io/gx2dv

Subject: Request for a change in the authorship order

Dear Pr. De Brigard,

We would like to request a change in the authorship order regarding the revised manuscript number COGNIT-D-24-00197 entitled "*Are there unconscious visual images in aphantasia? Development of an implicit priming paradigm*". The co-first author Mr. Maël Delem, is currently PhD candidate under the co-supervision of Dr. Gaën Plancher and Dr. Eddy Cavalli. In line with the progression of their respective academic careers, and should this revised manuscript be accepted for publication in Cognition, both supervisors would benefit from an equal contribution as co-last authors.

With the consent of all the co-authors of the manuscript (see table below)—including the two co-first authors Mr. Rudy Purkart and Mr. Maël Delem, Pr. Rémy Versace, Mrs. Virginie Ranson and Mrs. Charlotte Andrey who were both Master's students at the time of the first submission—Dr. Eddy Cavalli has moved to the position of co-last author along with Dr. Gaën Plancher in the revised manuscript.

Author name	Written approval of the rearrangement
Rudy Purkart	I agree to the proposed new authorship
Maël Delem	I agree to the proposed new authorship
Virginie Ranson	I agree to the proposed new authorship
Charlotte Andrey	I agree to the proposed new authorship
Rémy Versace	I agree to the proposed new authorship
Eddy Cavalli	I agree to the proposed new authorship
Gaën Plancher	I agree to the proposed new authorship

We appreciate your time and consideration, and we sincerely hope that our request will meet with your approval.

Yours sincerely,

Dr. Gaën Plancher, corresponding author.

1. Introduction

Close your eyes and try to mentally visualize your breakfast table as you sat down to it this morning. Most people would report having a clear image of the scene in their "*mind's eye*": this experience is referred to as visual imagery, commonly defined as the experience of visual sensory information without a direct external stimulus (Pearson, 2019). Nonetheless, there are great differences between individuals concerning the vividness of these images, some people even declaring that they have no visual mental images at all. This extreme phenomenon, although already observed in the 19^{th} century (Galton, 1880) and noted in various studies since then (e.g., Farah et al., 1988; Faw, 2009; Marks, 1973a; McKelvie, 1995; Paivio & Ernest, 1971; Sheehan, 1987; Slatter, 1960), received renewed attention only nine years ago, when Zeman et al. (2015) published a study that has since been highly cited, coining the term "*aphantasia*" to refer to "reduced or absent voluntary imagery".

Early estimates suggest that aphantasia could concern 3-4% of the global population (see for instance Dance et al., 2022; Dawes et al., 2020; Palermo et al., 2022). However, many people with aphantasia may be unaware of it, suggesting a potential underestimation of the phenomenon (Faw, 2009; Zeman et al., 2020). Aphantasics often report reduced or absent sensory imagery in various modalities, fewer and less rich dreams (Dawes et al., 2020), reduced episodic and autobiographical memory (Dawes et al., 2020; Zeman et al., 2020), yet with intact spatial imagery (Bainbridge et al., 2021; Dawes et al., 2020; Keogh & Pearson, 2018; Zeman et al., 2015). Although self-reports by aphantasics are very consistent across studies, many authors stress the need to cross subjective reports with more objective tasks assessing visual imagery. This need is highlighted by the heterogeneity and complexity of aphantasia: for example, some aphantasics report visual mental imagery when dreaming, some have preserved mental imagery in other sensory modalities, while others report a complete absence of conscious mental imagery, both voluntary and involuntary (Dawes et al., 2020; Zeman et al., 2020). In light of this, a reliable measurement of visual imagery would be a valuable tool to better define aphantasia. Yet a crucial question for this assessment is still being debated: is aphantasia a genuine absence of mental images, or do aphantasics have them but are simply unable to access them *consciously*?

Some researchers doubt that mental imagery could be completely absent, and have hypothesized that aphantasics who report having no conscious imagery at all might still have *unconscious* mental imagery (Nanay, 2020). As this phenomenon is difficult to identify, little is known about unconscious mental imagery in aphantasia. A recent study by Liu & Bartolomeo (2023) used a behavioural task to assess visual imagery in various domains (the French Perception-Imagination Battery) in aphantasics and controls. The task consisted of mentally comparing pairs of items based on various features (e.g. "beaver" - "fox": which is the *longest*?). They found no differences in accuracy between the groups, but slower RTs and lower confidence in the aphantasics' answers, and argued that this result was consistent with aphantasics having the visual images required to succeed at the task, albeit without the knowledge of "how they did it". Similarly, in a task that supposedly required visual imagery to verify whether a target dot was inside the boundaries of a previously presented geometric shape, Jacobs et al. (2018) found no difference in accuracy between an aphantasic participant and controls. As proposed by Nanay (2020), this result could be interpreted as reflecting an unconscious comparison of a visual image with the stimuli perceived by the aphantasic participant. Although on a N = 1 case study, this result may still suggest the existence of this unconscious form of imagery in aphantasia. However, due to the potential conscious processes at play in these behavioural tasks (with or without sensory imagery), neither study could completely rule out the hypothesis of aphantasics using strategies other than visual imagery (e.g. semantic processing, spatial imagery) to solve the tasks. This possibility, often raised in discussions about aphantasia (e.g., Jacobs et al., 2018; Knight et al., 2022; Liu & Bartolomeo, 2023; Monzel et al., 2021), prevents from firmly concluding from these results regarding the existence of unconscious mental images.

On the other hand, several studies that sought to develop objective measures assessing visual imagery found consistent behavioural and physiological differences between aphantasics and controls on imagery tasks, thus challenging Nanay's (2020) hypothesis of unconscious mental imagery in aphantasia (see also Blomkvist, 2022). Aphantasics have been shown to have a reduced skin conductance response to frightening scenarios (Wicken et al., 2021), a reduced automatic pupil dilatation in reaction to imagined bright stimuli (Kay et al., 2022), or a reduced priming by visual imagery (Keogh & Pearson, 2018), suggesting that aphantasics are truly unable to produce mental images. The latter priming paradigm developed by (Keogh & Pearson, 2018) is particularly often cited as a promising and relatively undemanding task for objectively identifying aphantasia, and has already been used for this purpose in several subsequent studies (Chang, Zhang, et al., 2023; e.g., Keogh & Pearson, 2020). In their initial study, they investigated visual imagery in aphantasics and controls using a binocular rivalry paradigm: in this task, participants were cued either with the letter "R" (for red) or the letter "G" (for green) and had to imagine one of two images, respectively a red-horizontal Gabor or a green-vertical Gabor. After rating the vividness of their mental image, they were presented with both Gabors simultaneously, one in the left eye, the other in the right, and asked to say which colour they had seen first. Their results showed that the mental visualization of the Gabors influenced the colour seen in the binocular rivalry task for control participants, but not for aphantasics. The authors interpreted this absence of priming in aphantasia as a real inability to generate mental images, and not just as a lack of metacognition skills.

While these conclusions are convincing about conscious imagery, they cannot yet rule out the hypothesis of unconscious mental imagery. A first caveat in this study is that self-diagnosed aphantasics were explicitly asked to *voluntarily* form mental images and rate their vividness during the task. This aspect of their paradigm may have skewed the results from the start, as aphantasics were asked to do something they knew (or believed) they could not do in the first place. It is possible, then, that participants did not fully engage with the task - or did not perform it correctly - because they firmly believed that they would fail to comply with the instructions, due to the awareness of their aphantasia (see Cabbai et al., 2023 for evidence on demand biases in aphantasia). Secondly, by using explicit priming, their study could not account for potential unconscious mental imagery, which is typically investigated with implicit priming tasks. Consequently, the binocular rivalry paradigm developed by (Keogh & Pearson, 2018; like other objective measures based on explicit instructions to use mental imagery, e.g., Kay et al., 2022; Milton et al., 2021) cannot exclude the possible existence of unconscious mental images in aphantasia. We aimed to fill this gap by designing an implicit priming task that would allow us to study unconscious mental images in aphantasia.

The present study

The objective of this study was to develop a new task inspired by the binocular rivalry used by Keogh & Pearson (2018), including a priming task explicitly asking to use mental imagery, along with an implicit priming task specifically targeting unconscious mental imagery. Such a task would provide a novel and unprecedented behavioural method to identify the presence or absence of visual imagery and, by extension, to objectively characterize aphantasia.

To create an implicit task, the paradigm was divided into two parts: a prior association phase, and the implicit task itself. The association phase asked the participants to indicate the colour of a red horizontal Gabor or a blue vertical Gabor to implicitly memorize the colour-orientation association. In the subsequent implicit task, a red or blue coloured circle was presented as a prime before a target, which was a Gabor either congruent or incongruent with the colour seen (see Figure 1 and Figure 2 in the Procedure section). As previous works of our team have shown (e.g., Brunel et al., 2013; Rey et al., 2015; Rey et al., 2018), the prime is assumed to reactivate an unconscious mental image of the associated Gabor automatically. Participants were then asked to indicate the orientation of the target. An explicit task was added for control and comparison where participants were overtly asked to produce a mental image of the Gabors before the targets. In the explicit task, like in Keogh and Pearson's study, participants were asked to imagine one of the previous Gabors by presenting a letter (R or B) as a cue. A Gabor congruent or incongruent with the colour was then presented as a target, and participants were asked to indicate the orientation of the lines of the target.

Shorter RTs in the congruent trials compared to the incongruent ones would therefore reflect an influence of unconscious mental images, helping participants to respond faster.

Moreover, to ensure that any priming observed would be the consequence of mental imagery (as opposed to semantic priming, for example), in half of the trials the targets were presented in black and white rather in than colour. If aphantasics have only difficulties with conscious mental imagery, a priming effect should be observed for both groups in the implicit task, but not in the explicit one. If aphantasics have difficulties with both conscious and unconscious mental imagery, no priming effect should be observed for the aphantasia group neither in the implicit nor in the explicit task, as opposed to the control group.

In addition, we carried out a second analysis by defining "finer-grained" VVIQ sub-groups, with a subset of our sample composed solely of aphantasics with a minimal VVIQ score of 16, people with low imagery (VVIQ between 17 and 32), hereinafter called "hypophantasics" (using the terminology from Reeder & Pounder, 2024), and controls (our sample included only two participants with VVIQ > 75, so group analyses with hyperphantasics were not possible). This analysis aimed at answering a frequent interrogation in aphantasia literature about subgroups in aphantasia with differing characteristics: several authors pointed out that the fact of reporting *completely absent* imagery could be qualitatively very distinct from having only *vague* images (Blomkvist & Marks, 2023; Dance et al., 2022; Liu & Bartolomeo, 2023; Muraki et al., 2023). The object of our study, unconscious mental images, is a difficult phenomenon to reach, so this additional analysis could be crucial to judge the effects of our paradigm.

Finally, to assess the potential of this paradigm as a predictive tool for visual imagery ability, we performed correlations between the self-report questionnaires and the magnitude of the priming effect. If this effect is related to the generation of mental images, a clear association should arise between a greater priming effect and higher visual imagery ability.

2. Methods

2.1 Participants

We compared a group of self-identified aphantasic individuals with a control group of individuals with self-reported intact visual imagery. Participants were recruited from Facebook online community platforms dedicated to aphantasia in France using a recruitment ad. 151 participants completed the study. All completed an online version of the French Vividness of Visual Imagery Questionnaire (VVIQ-F, Santarpia et al., 2008; adapted from Marks, 1973b): aphantasic participants were identified as the ones with a total VVIQ score below 32, which is the conventional threshold used in most studies on aphantasia (e.g., Dance, Ward, et al., 2021; Dance, Jaquiery, et al., 2021; Dawes et al., 2020; Zeman et al., 2015). 89 participants were in the aphantasic group ($M_{age} = 34.7$, $SD_{age} = 10.6$, $range_{age} = [19; 59]$, $M_{VVIQ} = 19.2$, $SD_{VVIQ} = 4.6$, $range_{VVIQ} = [16; 31.5]$, 65 women) and 62 in the control group ($M_{age} = 33.2$, $SD_{age} = 9.7$, $range = [18; 65]$, $M_{VVIQ} = 54.5$, $SD_{VVIQ} = 12.3$, $range = [32; 78.5]$, 31 women). All participants reported no lesions or acquired neurological or psychiatric disorders and no impaired or uncorrected vision.

The study was carried out following the recommendations of the French Law (Loi Jardé n◦2012- 300) with written informed consent being obtained from all the participants following the Declaration of Helsinki.

2.2 Questionnaires

2.2.1 Vividness of Visual Imagery Questionnaire - French adaptation (VVIQ-F)

The French version of the VVIQ (VVIQ-F, Santarpia et al., 2008; adapted from Marks, 1973b) used in this study was adapted in a Google Form version. It consists of sixteen items, each asking participants to imagine a particular scene and rate the vividness of their mental imagery using a Likert scale ranging from 1 ("No image at all, you only know that you are thinking about the object") to 5 ("Perfectly clear and vivid as if it were normal vision"). The final score is ranging from 16 to 80.

2.2.2 Spontaneous use of imagery scale (SUIS)

The French version of the SUIS (SUIS-F, Ceschi & Pictet, 2018; adapted from Reisberg et al., 1986) used in this study was adapted in a Google Form version. It consists of 12 items, each asking participants to rate the degree to which a spontaneous use of mental imagery in a particular situation is appropriate to them using a Likert scale ranging from 1 ("Never appropriate") to 5 ("Completely appropriate"). The final score is ranging from 12 to 60.

2.2.3 Object and spatial imagery questionnaire (OSIQ)

The French version of the OSIQ (Dutriaux, unpublished, adapted from Blazhenkova et al., 2006) used in this study was adapted in a Google Form version. It consists of 30 items, half of the items (i.e., 15 items) are used to assess participants' ability to imagine an object's shape, texture, and colour (object imagery score), and the other half (i.e., 15 items) are used to assess participants' ability to imagine location, movements, and spatial relationships (spatial imagery score). For each item, participants rate the degree to which they agree with the statement using a Likert scale ranging from 1 (“Totally disagree”) to 5 (“Totally agree”).

2.3 Stimuli

2.3.1 Gabor patterns

Four Gaussian-shaped Gabor patterns were generated: one red Gabor with horizontal lines and one blue Gabor with vertical lines (coloured Gabors); one black Gabor with horizontal lines and one black Gabor with vertical lines (uncoloured Gabors). All Gabor were superposed on a white 160 × 160 pixels background.

2.3.2 Cues

Two cues were generated: a red circle and a blue circle. Both were of the same size as the Gabor patterns and were superposed on a white 160x160 pixels background.

2.4 Software

The tasks were programmed using OpenSesame (Mathôt et al., 2012) and were uploaded on Jatos (Lange et al., 2015), a server used to run experiments online. All the experimental material is openly available on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

2.5 Procedure

Participants were provided with two links, one directing to the experiments, and one directing to the questionnaire. They were instructed to perform the experiments and the questionnaires alone, in a quiet and not distracting environment, and to turn off their phones and other messaging devices. They were also asked to use a computer with a keyboard, as well as a good internet connection. Once participants clicked on the link to the experiments, the first experimental task launched.

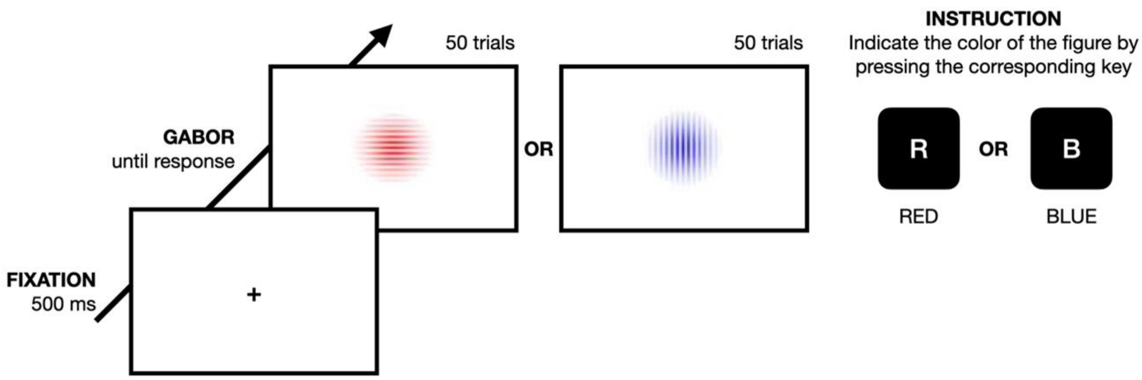

Figure 1: ***Associative task.*** *A fixation cross (500 ms) is followed by one of the two coloured Gabor. Participants had to indicate the colour of the Gabor by pressing the corresponding key (either R for Red or B for Blue), without time constraint. Each Gabor was presented 50 times.*

Participants began with the implicit priming task. This task began with an associative phase (Figure 1) in which a fixation cross (500 ms) was followed by one of the two coloured Gabor, and participants had to indicate the colour of the Gabor by pressing the corresponding key (either R for Red or B for Blue), without time constraint. Each Gabor was presented 50 times. After the association phase, participants started the implicit priming test phase (Figure 2) in which a fixation cross (500 ms) was followed by a cue (150 ms) that was either a red or a blue circle, and then depending on the condition by either one of the two coloured Gabor or by one of the uncoloured Gabor, as a target. Participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand. In the congruent condition, the cue has the same colour as the target Gabor (coloured condition) or primed the Gabor with the same line orientation as the black target Gabor (uncoloured condition), contrary to the non-congruent condition. There were 16 trials per congruence and colour pairs, amounting to 64 trials total for the task. Response mapping was not randomised due to the structure of the task: as there were as many congruent trials as incongruent ones, participants could not reliably predict the correct response based on the cue alone and a cue-response key association. Should they respond solely based on the key they associated with a cue, responses would be close to random, which could be easily spotted in the data. Consequently, learning a response key associated with a cue was not relevant and randomisation was not deemed necessary.

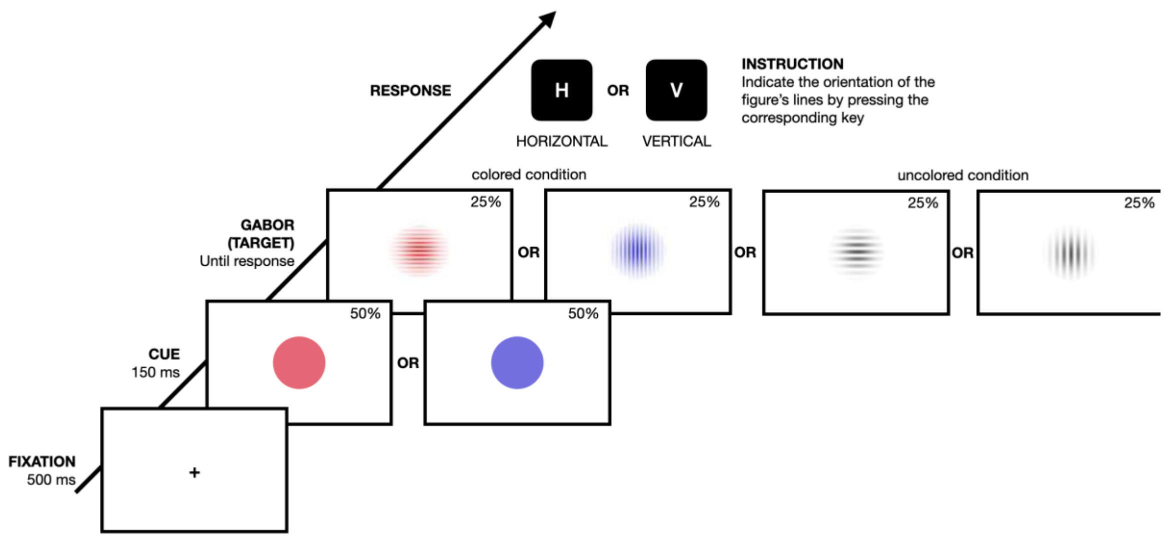

Figure 2: ***Implicit priming task.*** *A fixation cross (500 ms) is followed by a cue (150 ms) that was either a red or a blue circle, and then by one of the two coloured Gabor, or by one of the uncoloured Gabor, as a target. Participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand.*

After the implicit priming task and a short break, participants transitioned to the explicit task (Figure 3) in which a fixation cross (500 ms) was followed by a letter as a cue (1500 ms) that was either the letter R (for red) or B (for blue). In response to the cue, participants were asked to form a mental imagery of the corresponding Gabor (a red with horizontal lines or a blue with vertical lines) and to keep that image in mind during 3000 ms while fixing the centre of a blank screen. Then, a fixation cross (500 ms) was presented followed by one of the two coloured Gabor, or by one of the uncoloured Gabor, and participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand. In the congruent condition, the cue designated the same colour as the target Gabor (coloured condition) or primed the Gabor with the same line orientation as the black target Gabor (uncoloured condition), contrary to the non-congruent condition. Likewise, there were 16 trials per congruence and colour pairs, amounting to 64 trials total for the task. It is worth mentioning that participants had practice trials at the beginning of each task and phase. Moreover, the implicit priming task was divided into two blocks, each beginning with the association phase, and ending with the implicit priming phase, to preserve the association between the colour of the Gabor and the orientation of its lines.

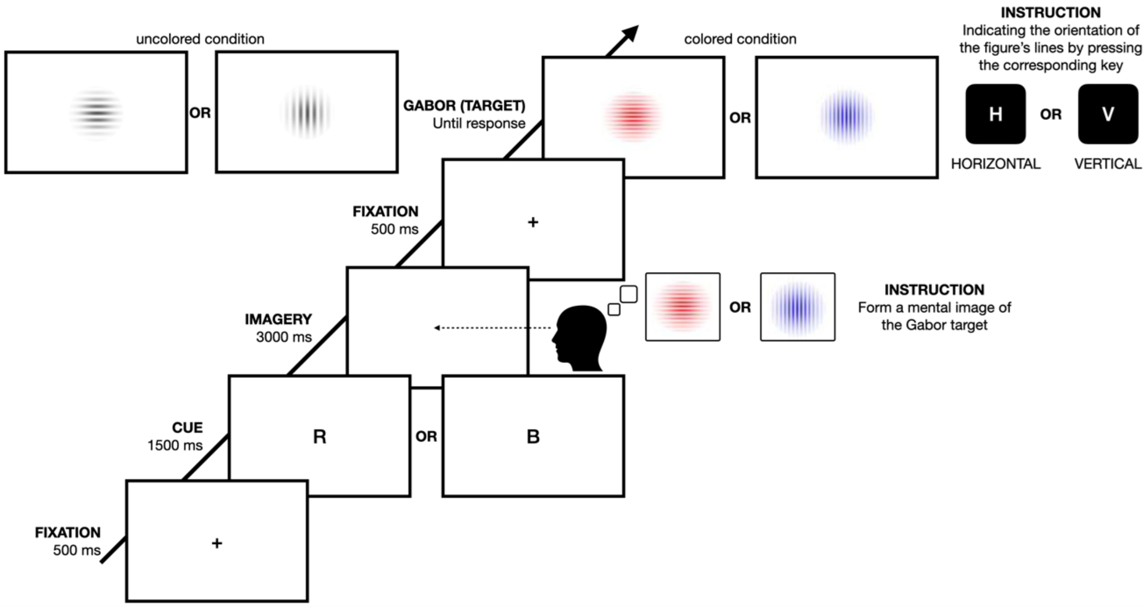

Figure 3: ***Explicit priming task.*** *A fixation cross (500 ms) was followed by a letter as a cue (1500 ms) that was either the letter R (for red) or B (for blue). In response to the cue, participants were asked to form a mental imagery of the corresponding Gabor (a red with horizontal lines or a blue with vertical lines) and to keep that imagery in mind during 3000 ms while fixing the centre of a blank screen. Then, a fixation cross (500 ms) was presented followed by one of the two coloured Gabor, or by one of the uncoloured Gabor, and participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand.*

2.6 Analyses

The data analysis was programmed in R language (version 4.2.0, R Core Team, 2022) on RStudio (Posit team, 2023). The raw data, code, and analysis outputs are available on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

2.6.1 Self-report questionnaires

The scores of the four questionnaires were modelled with linear models on ranked scores to accommodate the ordinal nature of the questionnaire data and to control for the influence of age on the group differences. The models included the *Group* as a categorical predictor and the *Age* as a continuous co-variate. For group differences, we report estimated means, their standard errors, and two-tailed *p*-values of marginal contrasts between means, computed using a Wald *t*-distribution approximation.

2.6.2 Outlier detection procedure

We excluded data from five participants that exceeded 43% of errors (therefore with too few trials to analyze). Trials with RTs abnormally fast or slow ($<$ 250ms or $>$ 3s, 1% and .7% respectively) that could represent false alarms (especially given the internet-based nature of the task) were removed. Participants with an aberrant RT average exceeding the median $\pm 3 \times$ MAD were excluded for each task (MAD proved to be more robust than standard deviations for outlier detection, see Leys et al., 2013). The remaining data comprised N = 9082 trials for the implicit task and N = 8824 trials for the explicit task. For the analysis of reaction times (RTs), incorrect responses were also removed (2.7% and 3.6% of trials in the implicit/explicit task respectively). The remaining RT data comprised N = 8777 trials for the implicit and N = 8603 trials for the explicit task.

2.6.3 Accuracy

Before removing incorrect responses for the analysis of response times, we first checked for any differences in accuracy between the groups. To this end, we fitted Generalized Logistic Mixed Models to predict accuracy with the *Group* (aphantasic, control), *Congruence* condition (congruent or incongruent), and *Colour* condition (colour or uncoloured) along with all their two and three-way interactions as fixed categorical predictors, while *participants* have been included as grouping factors (i.e. “random effects”).

The models were implemented in the *lme4* R package (Bates et al., 2014). Overall fixed effects were assessed with Type II Wald χ^2 tests using the *car* R package (Fox et al., 2023).

2.6.4 Response times

Power analysis

As the experiment was conducted online, the sample size was mostly limited by the time resources of the project. Likewise, the number of trials per condition and the total amount of trials were balanced in order not to overload the Internet experiment. From these two constraints, we estimated the statistical power conferred by the sample size eventually reached and the experimental design *a priori*, i.e. based on effect sizes reported in the literature and our hypotheses. We used the *simr* package (Green & MacLeod, 2016) to simulate datasets reflecting the experimental design, featuring expected patterns of means and variance, and fitting generalized linear mixed models on them.

Common effect sizes reported in the literature and intra-individual trial-to-trial variability in RTs in perceptual discrimination tasks have been used to simulate data and estimate the statistical power to detect effects tied to experimental conditions (for a similar procedure, see Fucci et al., 2023). The main effect of interest chosen was the interaction between Group and Congruence, where we hypothesized a reduction in RTs for the control group in the congruent condition that would not be present in aphantasics. Simulations have shown that the statistical power reached 80% even with little effect sizes nearing 24ms, and exceeded 90% when the effect size went up and above 30ms. Details of the procedure can be found in an extended analysis report on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

Generalized Linear Mixed Models

To account for the non-normal, positively skewed distributions of the RTs, we fitted Generalized Linear Mixed Models (GLMMs) with inverse Gaussian distributions, as recommended by Lo & Andrews (2015). The models included the *Group* (aphantasic, control), *Congruence* condition (congruent or incongruent), and *Colour* condition (colour or uncoloured) along with all their two and three-way interactions as fixed categorical predictors, while *participants* have been included as grouping factors (i.e. "random effects"). Overall fixed effects were assessed with Type II Wald χ^2 tests.

Due to the way that variance is partitioned in linear mixed models (Rights & Sterba, 2019), there does not exist an agreed-upon way to calculate standard effect sizes for individual terms such as main effects or interactions in these models. Thus, in line with general recommendations on how to report effect sizes (e.g., Pek & Flora, 2018), we report and analyse unstandardised effect sizes for post-hoc tests in the form of estimated marginal contrasts in milliseconds (i.e. differences in model-estimated marginal means, hereinafter denoted Δ) where appropriate.

Bayesian Modelling

To complement the frequentist approach, Bayesian hypothesis testing was also used to quantify the evidence in favour or against a congruence effect for each group. To this end, we fitted Bayesian multilevel models (analogous to the frequentist GLMMs presented above) separately for each group to predict RTs with the *Congruence* condition (congruent or incongruent), *Colour* condition (colour or uncoloured) and their two-way interaction as fixed categorical predictors, along with *participants* as grouping factors. Models were implemented in the *brms* R package (Bürkner, 2017). The evidence ratio of interest was then computed as the Bayes Factor between the hypothesis of a congruence effect against the null hypothesis. We report the BF_{01} in favour of the null hypothesis of an absence of congruence effect for a given group alongside the contrasts in the *Group* × *Congruence* interaction. The proposed interpretations of the strength of the evidence from Bayes Factor values were based on Jeffrey's scale thresholds (see e.g., Kass & Raftery, 1995).

2.6.5 Finer-grained VVIQ groups

Additional analyses were conducted with more refined groups: the aphantasic group was restricted to participants scoring at the lowest point on the VVIQ (VVIQ = 16, N = 46), an "hypophantasic" group was created with participants scoring between 17 and 32 (N = 37), and the control group was restricted to participants scoring between 33 and 74 (N = 54). Our sample included only two "hyperphantasics" (VVIQ ≥ 75). These two participants were therefore removed from the analyses, as it was shown that hyperphantasics constitute a group with significant differences from typical imagers (see e.g., Milton et al., 2021; Zeman et al., 2020), but there were not enough of them in the present study to create such a group. Similar analyses to those carried out for the two initial groups were performed.

2.6.6 Correlation analyses

Spearman correlation coefficients were computed to assess the monotonic relationship between each questionnaire score and the *congruence effects* in both tasks. The congruence effect was computed for each participant as the difference between the mean RT in the incongruent condition minus the mean RT in the congruent condition, first averaging across colour conditions to account for this factor. Spearman correlations were chosen to relax the assumption of linearity of Pearson correlations, particularly given that the questionnaire variables are ordinal and that the data have an underlying group structure.

Correlations were also computed between the effects in both tasks. A False Discovery Rate (FDR) correction (Benjamini & Hochberg, 1995) was applied to the p-values to control for multiple comparisons.

3. Results

3.1 Self-report questionnaires

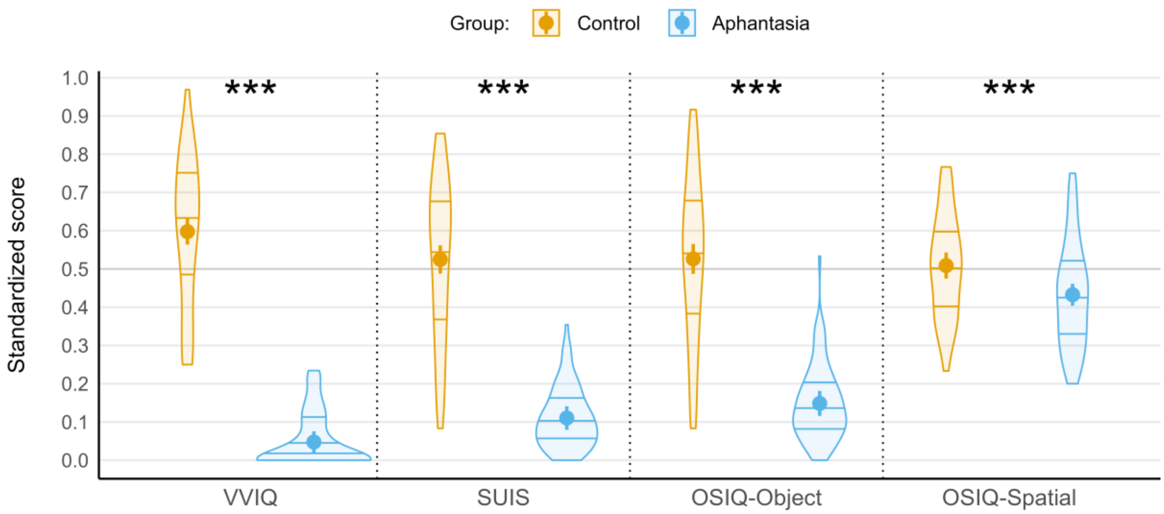

Figure 4: Visualization of self-report questionnaires results for aphantasics and controls. Violin plots depict the distributions and quantiles of the scores in each group, median-centred on each scale. Coloured dots depict standardized means of the scores to the questionnaires, while the solid lines represent their standard errors. On the vertical axis, 0.0 is the normalized lowest possible score, 0.5 is the median score, and 1 is the maximum possible score for each questionnaire. Stars denote p-values inferior to .001 for each pairwise contrast between groups.

As expected, aphantasic participants reported significantly less visual imagery across questionnaires (see Figure 4), scoring below controls on the VVIQ ($M_{Aph.} = 19.20 \pm .47$; $M_{Controls} = 54.39 \pm 1.61$; $t(147) = 24.23$, $p < .001$), the SUIS ($M_{Aph.} = 17.31 \pm .44$;

$M_{Controls}$ = 37.07 ± 1.13; $t(147) = 18.35$, $p < .001$) and the object scale of the OSIQ ($M_{Aph.}$ = 23.90 ± .65; $M_{Controls}$ = 46.50 ± 1.52; $t(147) = 15.19$, $p < .001$). Surprisingly, aphantasics scored significantly lower than controls on the spatial scale of the OSIQ ($M_{Aph.}$ = 40.98 ± .83; $M_{Controls}$ = 45.59 ± 1.10; $t(147) = 3.41$, $p < .001$), a result contrasting with previous studies having found no between-group differences on this scale (e.g., Dawes et al., 2020; Keogh & Pearson, 2018). Nevertheless, this difference is much less pronounced than in other questionnaires, and there are large variations on this scale in the aphantasic group (e.g., the lowest observed score is 27/75, while the highest is 61/75).

3.2 Accuracy

The models did not reveal any difference in accuracy between the two groups, neither in the implicit task (Wald χ^2 = 1.17, p = 0.28) nor in the explicit task (Wald χ^2 = 1.57, p = 0.21). The only significant effect concerned the Colour condition, both in the implicit task (Wald χ^2 = 6.37, p = 0.01) and in the explicit task (Wald χ^2 = 18.96, p = 0.21). In both cases, participants were more likely to answer correctly in the coloured condition rather than in the uncoloured ones (implicit task uncoloured/coloured odds ratio = 0.73, 95% CI [0.58, 0.92], z = -2.63, p = .009; explicit task uncoloured/coloured odds ratio = 0.52, 95% CI [0.39, 0.69], z = -4.49, $p < .001$). Elsewhere, in both tasks, the model did not reveal any main effects of Congruence (implicit: p = 0.59; explicit: p = 0.6), no Group × Congruence interaction (implicit: p = 0.58; explicit: p = 0.89), no Group × Colour interaction (implicit: p = 0.9; explicit: p = 0.43) and no Congruence × Colour interaction (implicit: p = 0.9; explicit: p = 0.29).

3.3 Response times

3.3.1 Implicit task

The model for the RTs in the implicit task yielded a significant main effect of Congruence (Wald χ^2 = 8.6, p = 0.003) and a significant interaction between Group and Congruence (Figure 5; Wald χ^2 = 8.58, p = 0.003). Post-hoc contrasts of marginal means showed that controls responded faster in the congruent condition (*Δ*(controls RT congruent - incongruent) = -30ms, SE = 6ms, 95% CI [-40, -10], $p < .001$), with extreme evidence in favour of a congruence effect for the control group ($BF_{01} < .001$). The contrast analysis also shows that the faster response of controls was driving the main effect of Congruence, as aphantasics did not respond faster in the congruent condition (*Δ*(aphantasics RT congruent - incongruent) = -2ms, SE = 5ms, 95% CI [-10, 10], p = .73), with strong evidence against a congruence effect for the aphantasia group ($BF_{01} = 14.12$). The model did not show any main effect of Group (p = .43) or colour (p = .51), no interaction between Group and colour (p = 0.96) or Congruence and colour (p = 0.14), and no three-way interaction (p = 0.23).

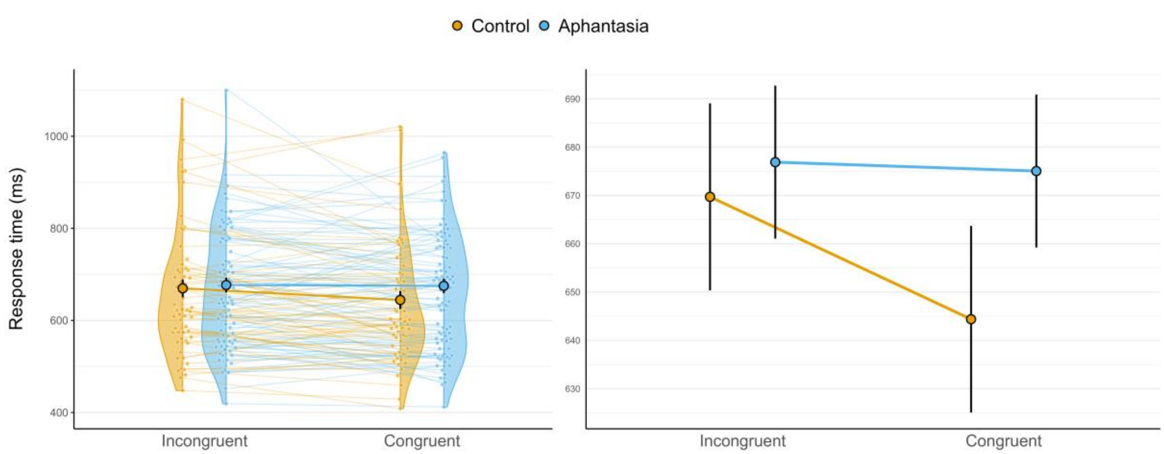

Figure 5: Visualizations of the interactions between Group and Congruence in the implicit task. The left plot shows the full range of mean response times; the right plot is a

zoomed version on the marginal means to see the details of the effect sizes. The central coloured dots in both plots indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates. On the left plot, the mean response times of each participant in the two conditions are represented as smaller coloured dots connected by a line to illustrate the individual congruence effects.

3.3.2 Explicit task

The model for the RTs in the explicit task yielded a significant main effect of Congruence (Wald χ^2 = 14.5, $p < .001$) and Colour (Wald χ^2 = 47.6, $p < .001$). The model also revealed a significant interaction between Group and Congruence (Figure 6; Wald χ^2 = 10.7, p = 0.001). Post-hoc contrasts of marginal means showed that, once again, controls responded faster in the congruent condition (Δ(controls RT congruent - incongruent) = -30ms, SE = 6ms, 95% CI [-40, -20], $p < .001$), with extreme evidence in favour of a congruence effect for the control group ($BF_{01} = .003$). Likewise, the faster response of controls was driving the main effect of Congruence, as aphantasics did not respond faster in the congruent condition either (Δ(aphantasics RT congruent - incongruent) = -5ms, SE = 5ms, 95% CI [-20, 10], p = .39), with strong evidence against a congruence effect in the aphantasia group ($BF_{01} = 12.09$). The main effect of Colour reflects the fact that participants responded faster overall in the coloured condition (Δ(RT coloured - uncoloured) = -30ms, SE = 4ms, 95% CI [-40, -20], $p < .001$), although this factor did not interact with the two others. The model did not show any main effect of Group (p = .78), no interaction between Group and Colour (p = 0.37) or Congruence and Colour (p = 0.64), and no three-way interaction (p = 0.40).

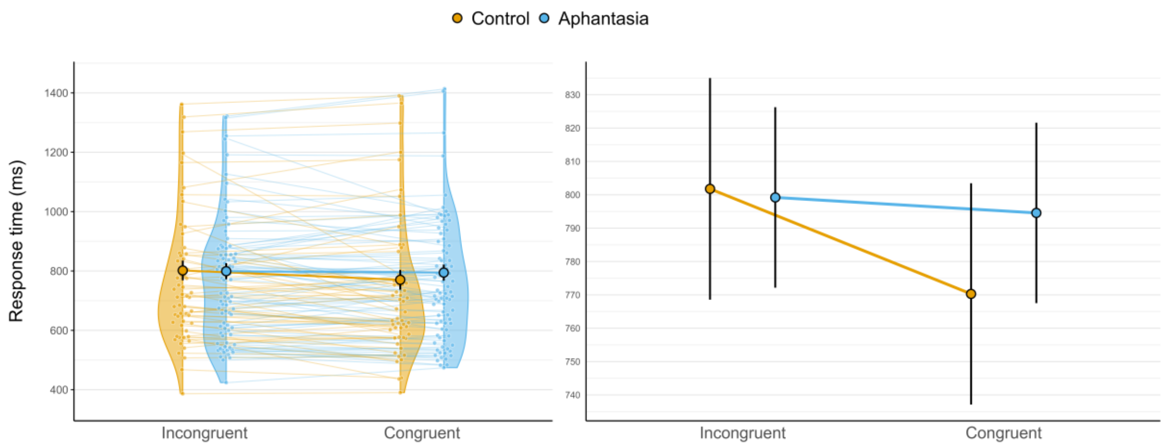

Figure 6: Visualizations of the interactions between Group and Congruence in the explicit task. The left plot shows the full range of mean response times; the right plot is a zoomed version on the marginal means to see the details of the effect sizes. The central coloured dots in both plots indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates. On the left plot, the mean response times of each participant in the two conditions are represented as smaller coloured dots connected by a line to illustrate the individual congruence effects.

3.4 Finer-grained VVIQ groups

3.4.1 Self-report questionnaires

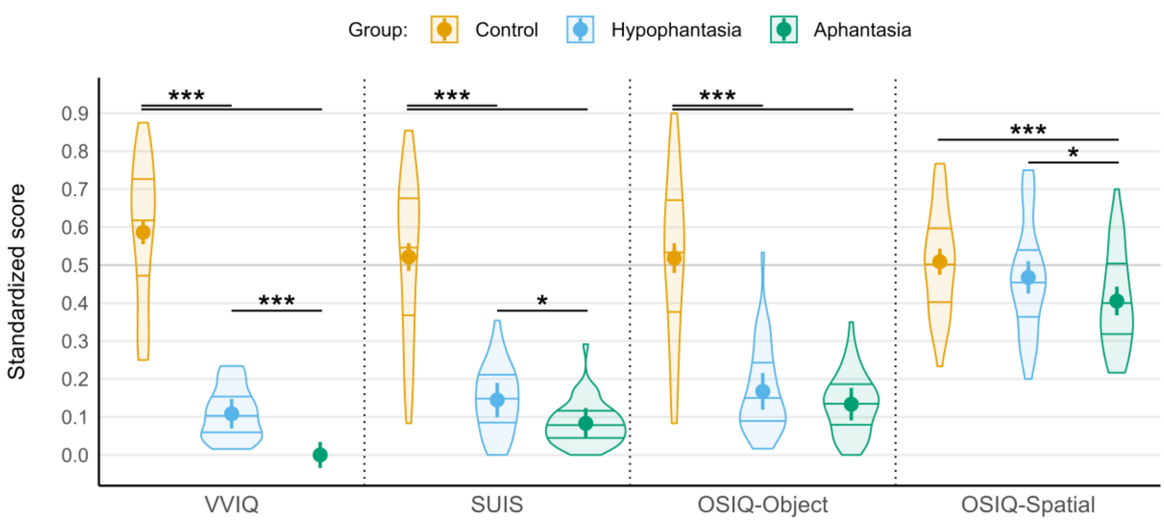

*Figure 7: Visualization of self-report questionnaires results for aphantasics, hypophantasics and controls. Violin plots depict the distributions and quantiles of the scores in each group, median-centred on each scale. Coloured dots depict standardized means of the scores to the questionnaires, while the solid lines represent their 95% CI. On the vertical axis, 0.0 is the normalized lowest possible score, 0.5 is the median score, and 1 is the maximum possible score for each questionnaire. *: $p < .05$; *: $p* < .01$; ***: $p < .001$.*

The newly created hypophantasic group scored higher than the aphantasic group and lower than the control group on the VVIQ (see Figure 7; $M_{Aph.}$ = 16; $M_{Hypo.}$ = 22.9 $\pm$ 1.1; $M_{Controls}$ = 53.49 $\pm$ 1; Δ (Control-Hypo.) = 30.57, 95%CI [27.37, 33.75], $p < .001$, Δ(Hypo.-Aph.) = 6.87, 95%CI [3.54, 10.21], $p < .001$) and SUIS ($M_{Aph.}$ = 16.1 $\pm$ 0.99; $M_{Hypo.}$ = 18.89 $\pm$ 1.1; $M_{Controls}$ = 36.98 $\pm$ 0.89; Δ(Control-Hypo.) = 18.09, 95%CI [15.28, 20.89], $p < .001$, Δ(Hypo.-Aph.) = 2.79, 95%CI [-0.14, 5.72], $p < .001$). The control group scored higher than the other two on the OSIQ-Object, however the hypophantasic group did not score higher than the aphantasic group ($M_{Aph.}$ = 23.04 $\pm$ 1.31; $M_{Hypo.}$ = 25.04 $\pm$ 1.48; $M_{Controls}$ = 46.09 $\pm$ 1.19; Δ(Hypo.-Aph.) = 2, 95%CI [-1.91, 5.91], p = 0.31). On the OSIQ-Spatial, the control and hypophantasic group scored higher than the aphantasic group, but the control group did not score higher than the hypophantasic group ($M_{Aph.}$ = 39.46 $\pm$ 1.15; $M_{Hypo.}$ = 42.98 $\pm$ 1.3; $M_{Controls}$ = 45.47 $\pm$ 1.05; -Δ(Control-Aph.) = 6.01, 95%CI [2.93, 9.09], $p < .001$; Δ(Control.-Hypo.) = 2.49, 95%CI [-0.80, 5.77], p = 0.14; Δ(Hypo.-Aph.) = 3.52, 95%CI [0.09, 6.95], p = 0.04).

3.4.2 Implicit task

The new model for the implicit task showed a significant main effect of Congruence (Wald χ^2 = 8.7, p = 0.003) and a significant interaction between Group and Congruence (Figure 8; Wald χ^2 = 13.23, p = .001). Once again, the contrast analyses revealed that the effect of Congruence was driven by controls responding faster in the congruent condition (Δ(controls RT congruent - incongruent) = -30ms, SE = 7ms, 95% CI [-40, -10], $p <$ .001, BF_{01} = .004, extreme evidence in favour of a congruence effect), as opposed to aphantasics (Δ(aphantasics RT congruent - incongruent) = -5ms, SE = 7ms, 95% CI [-20, 10], p = 0.46, BF_{01} = 12.59, strong evidence against a congruence effect). Interestingly, the hypophantasic group fitted in between, with a trend effect of Congruence (Δ(RT congruent - incongruent) = -10ms, SE = 8ms, 95% CI [-30, 0], p = 0.07) and inconclusive evidence for or against a congruence effect (BF_{01} = 2.41). There were no main effects of Group (p = 0.49), Colour (p = .46), no interaction between Group and Colour (p = .54) or Congruence and Colour (p = .17), and no triple interaction (p = .42).

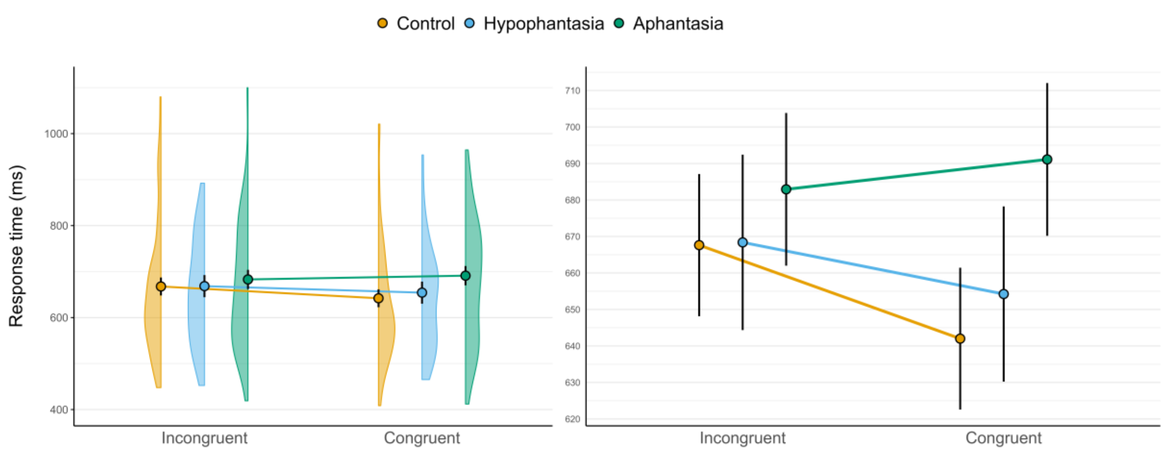

Figure 8: Visualizations of the interactions between Group and Congruence in the implicit task with redefined groups. The coloured dots the indicate the marginal means of

the groups in each condition whereas the black bars represent the standard error of these estimates.

3.4.3 Explicit task

The new model for the explicit task showed a significant main effect of Congruence (Wald χ^2 = 11.43, p < .001) and Colour (Wald χ^2 = 44.05, p < .001), along with a significant interaction between Group and Congruence (Figure 9; Wald χ^2 = 8.18, p = 0.017). The contrast analyses again showed that the effect of Congruence was driven by controls responding faster in the congruent condition (Δ (controls RT congruent - incongruent) = -30ms, SE = 7ms, 95% CI [-40, -20], $p < .001$, BF_{01} < .001, extreme evidence in favour of a congruence effect), while aphantasics did not (Δ(aphantasics RT congruent - incongruent) = 5ms, SE = 7ms, 95% CI [-10, 20], p = 0.46, BF_{01} = 11.78, strong evidence against a congruence effect). This time, however, hypophantasics were aligned with the aphantasic group and showed no congruence effect (Δ(RT congruent - incongruent) = 4ms, SE = 8ms, 95% CI [-20, 10], p = 0.65, BF_{01} = 9.81, substantial evidence against a congruence effect). Contrast analysis on the main effect of Colour showed that participants responded faster overall in the coloured condition (Δ(RT coloured - uncoloured) = -30ms, SE = 5ms, 95% CI [-40, -20], $p < .001$), although this factor did not interact with the two others. There were no main effects of Group (p = 0.98), no interaction between Group and Colour (p = 0.79) or Congruence and Colour (p = 0.62), and no triple interaction (p = 0.32).

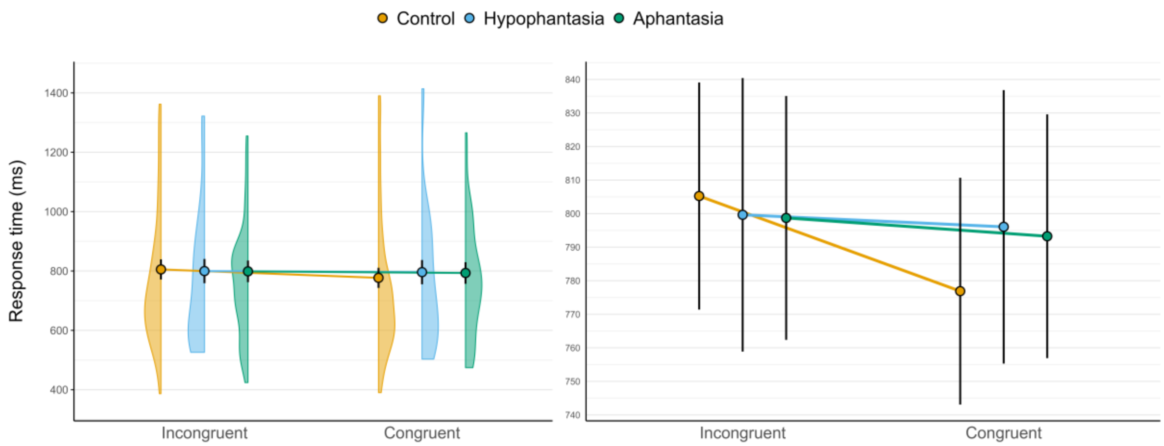

Figure 9: Visualizations of the interactions between Group and Congruence in the explicit task with redefined groups. The coloured dots the indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates.

3.5 Correlations with the subjective questionnaires

	VVIQ	OSIQ-Object	OSIQ-Spatial	SUIS
Implicit task congruence effect	ρ = **0.21**	ρ **= 0.26**	r = 0.05	***r* = .27**
	p = 0.02*	***p*** **=** 0.003**	p = .57	***p*** **=** 0.002**
Explicit task congruence effect	ρ = 0.08	ρ = 0.12	ρ = -0.02	ρ = 0.16
	p = 0.43	p = 0.19	p = 0.83	p = 0.08

Table 1: Matrix of the pairwise Spearman correlation coefficients ρ between each questionnaire score and the congruence effect in both tasks.

Finally, Spearman correlations were computed to assess the monotonic relationship between the questionnaire scores and the *congruence effects* in both tasks. In the explicit task, the congruence effect was not correlated with the VVIQ (p = 0.43), the OSIQ-Object (p = 0.19), the OSIQ-Spatial (p = 0.43), or the SUIS (p = 0.43). Interestingly, the congruence effect in the explicit task also did not correlate with the effect observed in the implicit task (p = 0.57). In the implicit task however, the congruence effect correlated with the VVIQ (ρ = 0.21, 95% CI [0.05, 0.37], p = 0.02), the OSIQ-Object (ρ = 0.26, 95% CI [0.10, 0.40], p = 0.003) and the SUIS (ρ = 0.27, 95% CI [0.11, 0.41], p = 0.002), but no correlation with the OSIQ-Spatial (ρ = 0.05, 95% CI [-0.11, 0.21], p = 0.57). All the pairwise correlations between the scores and the congruence effects in both tasks are presented in Table 1. The three significant correlations of the implicit task congruence effects with the VVIQ, OSIQ-Object and SUIS are represented in Figure 10.

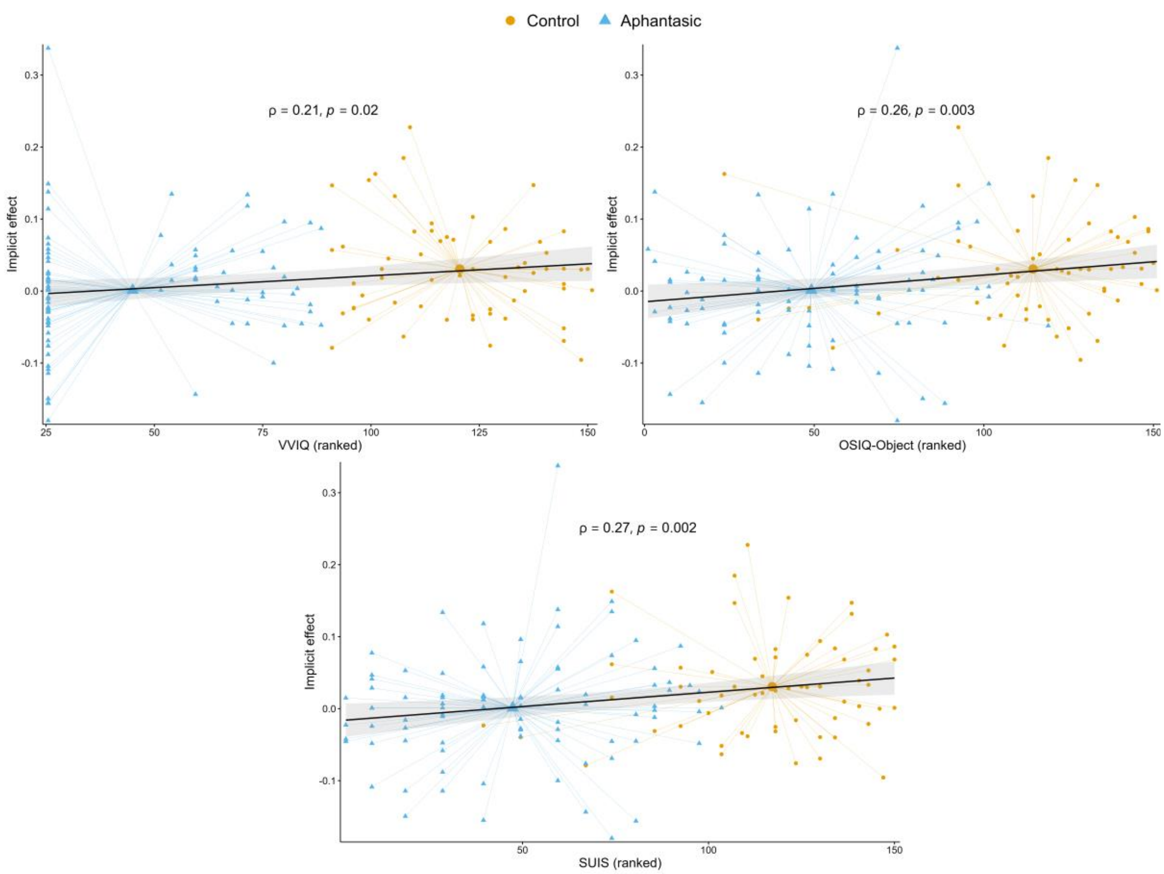

Figure 10: Visualizations of the correlation between the congruence effect (i.e. the mean difference between incongruent and congruent RTs) in the implicit task and the VVIQ, OSIQ-Object and SUIS ranked scores. Aphantasics are represented with blue triangles,

and controls with orange dots. All the observations are connected with a thin line to their group mean, represented as a bigger symbol. The black regression line denotes the Spearman correlation between the scores and the effect, independently of groups, along with its confidence interval.

4. Discussion

The objective of the present study was to examine whether aphantasics could form mental images but could not access them consciously, or whether they presented a genuine deficit in the generation of mental images. To this end, we built and tested implicit and explicit priming paradigms on aphantasic and control participants. Analyses revealed striking evidence that the control group showed a consistent congruence effect in both tasks, whereas the aphantasic group did not. The intensive study of Gabors in a preliminary association should have facilitated the decision for Gabors congruent with the prime, as demonstrated in the control group, an effect that can be interpreted as the influence of an unconscious mental image of the studied Gabors. However, this effect was not observed in the aphantasic group. This result was also present when adopting a more conservative definition of aphantasia by analysing groups restricted to aphantasics scoring at floor VVIQ. This result supports the hypothesis that aphantasics have difficulty generating both conscious and unconscious mental images, rather than only conscious ones.

4.1 Towards an implicit objective assessment of aphantasia

The priming task developed in the present study proved to be efficient to discriminate between groups of visual imagery ability, both when implemented with explicit instructions to use imagery and when implemented with implicit priming. The explicit task with instructions to produce mental imagery was inspired by the binocular rivalry paradigm developed by Keogh & Pearson (2018) and produced a similar pattern of results showing an absence of priming in aphantasia with a different task, thus validating the effectiveness of priming tasks to evidence conscious mental imagery differences. However, the main aim of our study was to go one step further and develop a task that could evidence mental imagery differences *without* relying on instructions to produce it. Thus, the implicit priming task developed here was designed to target specifically unconscious mental imagery without giving participants instructions. The results of this task consistently followed the same pattern as the explicit task, lending credence to the hypothesis that the implicit task involved an unconscious form of mental imagery. Moreover, an in-depth analysis of finer-grained groups dissociating “complete aphantasia” (VVIQ = 16) from “hypophantasia” (17 < VVIQ < 32) revealed striking differences that characterized the two sub-groups. While the complete aphantasia group showed no priming effect in either the implicit and explicit tasks, the hypophantasia group showed a mixed pattern, with traces of a priming effect in the implicit task but not in the explicit one. We propose to interpret this pattern of results as suggesting that aphantasics may differ fundamentally from hypophantasics in that they would have neither conscious nor unconscious imagery, while hypophantasics might retain some unconscious imagery, but without the ability to voluntarily generate conscious mental images (i.e., what was asked of them in the explicit task). In light of these results, we propose that this novel online paradigm provides a foundation to develop implicit, objective behavioural assessments of visual imagery using a minimal setup, thereby opening new avenues for a large-scale, objective characterization of aphantasia.

The correlations of the congruence effect in the implicit task with the VVIQ, OSIQ-Object scale and the SUIS corroborate the potential of our paradigm to assess individual differences in visual imagery. This relationship supports that implicit tasks may prove to be stable relative to various assessments of visual imagery, and encourages further investigation of such implicit effects on a real continuum to depart from group comparisons. Future work investigating implicit behavioural effects which are correlated with visual imagery and observed at a *by-participant* level will be crucial to further ascertain results on aphantasia and individual differences in mental imagery. Considering this result, we also argue that a wider diversity of psychometric questionnaires needs to be used along with efficient behavioural tasks when studying aphantasia, to better understand the complex construct that is mental imagery.

4.2 Unconscious mental imagery and sensorimotor simulation

A main novelty of our paradigm is that participants were not instructed to produce any specific mental content in the implicit task, thus avoiding demand bias. This design therefore relies on the assumption that the task would trigger an unconscious form of imagery for those capable of it. However, this raises the question of whether the concept of "unconscious" mental images is relevant. The concept was introduced in the field of research on aphantasia research by Nanay (2020), but its ability to explain behavioural findings on aphantasia has been debated debated since (see e.g., Blomkvist, 2022; Krempel & Monzel, 2024). These hypothetical unconscious mental images could neither be voluntarily produced by the participant nor consciously experienced, and are therefore by definition very hard to objectify. Muraki et al. (2023) suggest that the idea of "unconscious mental images" could be likened to the concept of "sensorimotor simulation" developed in the field of embodied cognition research. A sensorimotor simulation is the re-creation of the states in which the individual's perceptual and motor systems were in a previous experience, as well as their emotional and introspective states (e.g., Barsalou, 2008, 2009; Dijkstra & Post, 2015; Mille et al., 2021; Versace et al., 2009; Versace et al., 2014; Versace et al., 2018). From this re-creation emerges a representation that can reach consciousness in the form of a mental image of an object, if the neurons in the perceptual and motor systems that were activated during confrontations with this object are reactivated in the current situation. In support of this hypothesis, Petilli et al. (2021) have shown using implicit priming tasks that verbal cues affected subsequent processing of target words with related visual properties, even when visual processing was neither requested nor required. Various cross-modal priming studies have shown that such cues could also influence behavioural responses based on other modalities (e.g., verbal cues influencing decision tasks on images or sounds, see Brunel et al., 2010; Rey et al., 2015; Rey et al., 2017; Vallet et al., 2010). Similarly, Amit et al. (2017) have provided evidence that feature representations are generated in visual cortices during verbal cues, even in decision tasks based on verbal processing. This evidence supports the idea that multi-modal sensory representations emerge in priming tasks and influence behaviour. Consequently, following the association drawn by Muraki et al. (2023) between sensorimotor simulation and unconscious mental images, our results provide evidence that the simulation of the visual properties of incoming information could be reduced or absent in aphantasia.

4.3 Alternative strategies and forms of imagery

A recurrent challenge when studying aphantasia is that many tasks that are often considered to require visual imagery could also be solved by other non-visual strategies, such as the use of internal or covert verbalization Monzel et al. (2022). In that vein, it could be argued that our tasks could be completed using a verbal or propositional strategy based on the colour of the stimuli. For instance, in the association phase, participants may have used the propositional strategy of forming the abstract or semantic representation of an association between colour and line orientation of the Gabors (e.g., by internally repeating that "blue patches have vertical lines"). During the tasks, participants could then have used such a representation when a prime was presented, which may have facilitated their response when the target's colour was congruent with the colour of the prime. However, our tasks have the advantage of making the use of this type of strategies more difficult to adhere to, thanks to a condition in which the targets are not coloured. As no semantic representations had been previously associated with uncoloured targets, a colour-based strategy was inappropriate for these stimuli. This type of strategy could even have been counter-productive, which could explain slower response times in the uncoloured condition than in the coloured condition. Thus, the persistence of the interaction between group and congruence independently of the colour conditions supports the idea that our results can not be explained purely by the reliance on propositional strategies.

Curiously, the analysis of questionnaire data yielded a significant difference between aphantasics and controls in reported spatial imagery, assessed by the spatial scale of the OSIQ, contrasting with previous studies on aphantasia that used this questionnaire and found no between-group differences (Bainbridge et al., 2021; Dawes et al., 2020; Keogh & Pearson, 2018). While this difference is hard to interpret on its own, it is worth noting that although significant, the difference in spatial imagery between the groups is much less pronounced than the difference observed on visual imagery scales. Large differences in spatial imagery ability also existed within the aphantasic group, as shown by the difference between the hypophantasic and aphantasic groups on the OSIQ-Spatial. This finding could be specifically tied to the choice of cut-offs used in aphantasia studies. In addition, there could exist various sub-types in aphantasia in our sample characterized by their variable reliance on different forms of mental representations (e.g., spatial, auditory, kinaesthetic). Nevertheless, it should be mentioned that our paradigm relied partially on spatial judgements (namely, orientation properties of items) that might be impacted by spatial imagery abilities. This hypothesis may also apply to a growing number of studies on aphantasia that used paradigms consisting in the detection of orientation changes of Gabor patches, thought to assess visual imagery or visual working memory (e.g., Chang, Wang, et al., 2023; Keogh et al., 2021; Keogh & Pearson, 2018, 2020; Knight et al., 2022; Slinn et al., 2023 inter alia). While our results did exhibit differing patterns between groups, future studies should still pay particular attention to this spatial imagery factor. On the one hand, this would require a more systematic investigation of spatial imagery, which has proved to have distinct characteristics from visual imagery in aphantasia (see Blazhenkova & Pechenkova, 2019; Palermo et al., 2022). On the other hand, this entails that care should be taken to design tasks that target visual imagery as specifically as possible, manipulating item properties such as colour or shape while accounting for semantic and spatial properties of items (see e.g., Liu & Bartolomeo, 2023).

4.4 Consequences on aphantasia

Finally, the functional implications of the differences in information processing found in aphantasia also need to be evaluated in the context of their "real-world" consequences. Aphantasics have demonstrated to live typical lives, most eloquently echoed by the fact that aphantasia often goes unnoticed for years (Zeman et al., 2015, 2020). Furthermore, it has been shown that aphantasia does not meet the criteria of a pathological disorder (see Blomkvist & Marks, 2023; Monzel et al., 2023 for a discussion). Thus, the finding of reduced unconscious mental imagery (or sensorimotor simulation) in aphantasia may be best interpreted as showing that these processes might not play a crucial role as previously thought, for instance on conceptual processing (see e.g., Meteyard et al., 2012; Pecher & Zeelenberg, 2018). Several recent studies even suggest that this attenuation of internal sensory representations in aphantasia could have positive consequences: Wicken et al. (2021) showed that aphantasics exhibited dimmed electrophysiological responses to frightening scenarios; Keogh et al. (2023) used a laboratory model of PTSD and noted that aphantasics reported fewer intrusive memories when confronted with traumatic films; Königsmark et al. (2021) demonstrated, using a rhythmic flicker paradigm to induce pseudo-hallucinations, that aphantasics experienced less anomalous percepts. In the present study we have brought evidence suggesting that aphantasics may simulate less sensory elements in their unconscious representations. The potential positive consequences of this reduction in sensory simulation in aphantasia is an interesting topic that deserves further research.

4.5 Conclusion

In sum, our findings provide evidence suggesting that "total" aphantasia (defined by a VVIQ score of 16) may not solely result from impaired metacognition but could indicate an underlying reduction in both conscious and unconscious mental imagery. Additionally, a trend in the results indicated that hypophantasia (i.e., reduced imagery, VVIQ scores between 17 and 32) may involve the presence of unconscious imagery, albeit without the capacity for voluntary imagery generation. The consistency of the congruence effect patterns obtained in both our implicit and explicit tasks for the control and aphantasic groups suggests that this priming paradigm provides a promising and reliable foundation for developing future behavioral tasks that objectively and implicitly characterize unconscious mental imagery, without depending on participant introspection.

Data and code availability

All the materials and implementations of the questionnaires and tasks, the anonymised data, the analysis scripts, and in-depth analysis notebooks are all freely available on the Open Science Framework (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

Author contributions

Conceptualization: RP, EC, VR, CA, RV, GP. **Data curation**: RP, MD, VR. **Formal analysis**: MD. **Funding acquisition**: GP, EC. **Investigation**: VR, CA. **Methodology**: RP, EC, VR, CA, RV, GP. **Project administration**: GP, EC. **Resources**: VR, CA, GP. **Software**: MD. **Supervision**: GP, EC. **Visualization**: MD. **Writing - Original Draft Preparation**: RP, MD, EC, VR, GP. **Writing - Review & Editing**: All authors.

Declaration of interest

None.

References

Amit, E., Hoeflin, C., Hamzah, N., & Fedorenko, E. (2017). An asymmetrical relationship between verbal and visual thinking: Converging evidence from behavior and fMRI. *NeuroImage*, *152*, 619–627. https://doi.org/10.1016/j.neuroimage.2017.03.029

Bainbridge, W. A., Pounder, Z., Eardley, A. F., & Baker, C. I. (2021). Quantifying aphantasia through drawing: Those without visual imagery show deficits in object but not spatial memory. *Cortex*, *135*, 159–172. https://doi.org/10.1016/j.cortex.2020.11.014

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Barsalou, L. W. (2009). Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1521), 1281–1289. https://doi.org/10.1098/rstb.2008.0319

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv Preprint arXiv:1406.5823*.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

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

Blazhenkova, O., & Pechenkova, E. (2019). The two eyes of the blind mind: Object vs. Spatial aphantasia? *Russian Journal of Cognitive Science*, *6*(4), 51–65.

Blomkvist, A. (2022). Aphantasia: In search of a theory. *Mind & Language*, *n/a*(n/a). https://doi.org/10.1111/mila.12432

Blomkvist, A., & Marks, D. F. (2023). Defining and “diagnosing” aphantasia: Condition or individual difference? *Cortex*. https://doi.org/10.1016/j.cortex.2023.09.004

Brunel, L., Goldstone, R. L., Vallet, G., Riou, B., & Versace, R. (2013). When Seeing a Dog Activates the Bark. *Experimental Psychology*, *60*(2), 100–112. https://doi.org/10.1027/1618-3169/a000176

Brunel, L., Lesourd, M., Labeye, E., & Versace, R. (2010). The sensory nature of knowledge: Sensory priming effects in semantic categorization [10.1080/17470210903134369]. *Quarterly Journal of Experimental Psychology*, *63*(5), 955–964.

Bürkner, P.-C. (2017). Brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*, 1–28. https://doi.org/10.18637/jss.v080.i01

Cabbai, G., Dance, C., Dienes, Z., Simner, J., Forster, S., & Lush, P. (2023). Investigating relationships between trait visual imagery and phenomenological control: The role of context effects. *Unpublished*.

Ceschi, G., & Pictet, A. (2018). *Imagerie mentale et psychothérapie: Un ouvrage sur la psychopathologie cognitive*. Mardaga.

Chang, S., Wang, J., & Meng, M. (2023). The behavioral performance and cortical structural properties of aphantasia. *Journal of Vision*, *23*(9), 5985. https://doi.org/10.1167/jov.23.9.5985

Chang, S., Zhang, X., Pearson, J., & Meng, M. (2023). *Imageless imagery in aphantasia: Decoding non-sensory imagery in aphantasia*. https://www.researchsquare.com. https://doi.org/10.21203/rs.3.rs-3162223/v1

Dance, C. J., Ipser, A., & Simner, J. (2022). The prevalence of aphantasia (imagery weakness) in the general population. *Consciousness and Cognition*, *97*, 103243. https://doi.org/10.1016/j.concog.2021.103243

Dance, C. J., Jaquiery, M., Eagleman, D. M., Porteous, D., Zeman, A., & Simner, J. (2021). What is the relationship between aphantasia, synaesthesia and autism? *Consciousness and Cognition*, *89*, a103087 1–18. https://doi.org/10.1016/j.concog.2021.103087

Dance, C. J., Ward, J., & Simner, J. (2021). What is the Link Between Mental Imagery and Sensory Sensitivity? Insights from Aphantasia. *Perception*, *50*(9), 757–782. https://doi.org/10.1177/03010066211042186

Dawes, A., Keogh, R., Andrillon, T., & Pearson, J. (2020). A cognitive profile of multi-sensory imagery, memory and dreaming in aphantasia. *Scientific Reports*, *10*(1), 10022. https://doi.org/10.1038/s41598-020-65705-7

Dijkstra, K., & Post, L. (2015). Mechanisms of embodiment. *Frontiers in Psychology*, *6*.

Farah, M. J., Levine, D. N., & Calvanio, R. (1988). A case study of mental imagery deficit. *Brain and Cognition*, *8*(2), 147–164. https://doi.org/10.1016/0278-2626(88)90046-2

Faw, B. (2009). Conflicting Intuitions May Be Based On Differing Abilities. *Journal of Consciousness Studies*, 25.

Fox, J., Weisberg, S., & Price, B. (2023). *Car: Companion to applied regression*. https://r-forge.r-project.org/projects/car/

Fucci, E., Abdoun, O., Baquedano, C., & Lutz, A. (2023). Ready to help, no matter what you did: Responsibility attribution does not influence compassion in expert Buddhist practitioners. *Preprint*. https://doi.org/10.31234/osf.io/d6y4w

Galton, F. (1880). Statistics of mental imagery. *Mind*, *os-V*(19), 301–318. https://doi.org/10.1093/mind/os-V.19.301

Green, P., & MacLeod, C. J. (2016). SIMR : An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution*, *7*(4), 493–498. https://doi.org/10.1111/2041-210X.12504

Jacobs, C., Schwarzkopf, D. S., & Silvanto, J. (2018). Visual working memory performance in aphantasia. *Cortex*, *105*, 61–73. https://doi.org/10.1016/j.cortex.2017.10.014

Kass, R. E., & Raftery, A. E. (1995). Bayes Factors. *Journal of the American Statistical Association*, *90*(430), 773–795. https://doi.org/10.1080/01621459.1995.10476572

Kay, L., Keogh, R., Andrillon, T., & Pearson, J. (2022). The pupillary light response as a physiological index of aphantasia, sensory and phenomenological imagery strength. *eLife*, *11*, e72484. https://doi.org/10.7554/eLife.72484

Keogh, R., & Pearson, J. (2018). The blind mind: No sensory visual imagery in aphantasia. *Cortex*, *105*, 53–60. https://doi.org/10.1016/j.cortex.2017.10.012

Keogh, R., & Pearson, J. (2020). Attention driven phantom vision: Measuring the sensory strength of attentional templates and their relation to visual mental imagery and aphantasia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1817), 20190688. https://doi.org/10.1098/rstb.2019.0688

Keogh, R., Wicken, M., & Pearson, J. (2021). Visual working memory in aphantasia: Retained accuracy and capacity with a different strategy. *Cortex*, *143*, 237–253. https://doi.org/10.1016/j.cortex.2021.07.012

Keogh, R., Wicken, M., & Pearson, J. (2023). Fewer intrusive memories in aphantasia: Using the trauma film paradigm as a laboratory model of PTSD. *In Review*.

Knight, K. F., Milton, F. N., & Zeman, A. (2022). Memory without Imagery: No Evidence of Visual Working Memory Impairment in People with Aphantasia. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *44*, 8.

Königsmark, V. T., Bergmann, J., & Reeder, R. R. (2021). The Ganzflicker experience: High probability of seeing vivid and complex pseudo-hallucinations with imagery but not aphantasia. *Cortex*, *141*, 522–534. https://doi.org/10.1016/j.cortex.2021.05.007

Krempel, R., & Monzel, M. (2024). Aphantasia and involuntary imagery. *Consciousness and Cognition*, *120*, 103679. https://doi.org/10.1016/j.concog.2024.103679

Lange, K., Kühn, S., & Filevich, E. (2015). "Just Another Tool for Online Studies” (JATOS): An Easy Solution for Setup and Management of Web Servers Supporting Online Studies. *PLOS ONE*, *10*(6), e0130834. https://doi.org/10.1371/journal.pone.0130834

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology*, *49*(4), 764–766. https://doi.org/10.1016/j.jesp.2013.03.013

Liu, J., & Bartolomeo, P. (2023). Probing the unimaginable: The impact of aphantasia on distinct domains of visual mental imagery and visual perception. *Cortex*, *166*, 338–347. https://doi.org/10.1016/j.cortex.2023.06.003

Lo, S., & Andrews, S. (2015). To transform or not to transform: Using generalized linear mixed models to analyse reaction time data. *Frontiers in Psychology*, *6*.

Marks, D. F. (1973a). Visual Imagery Differences in the Recall of Pictures. *British Journal of Psychology*, *64*(1), 17–24. https://doi.org/10.1111/j.2044-8295.1973.tb01322.x

Marks, D. F. (1973b). Vividness of visual imagery Questionnaire. *Journal of Mental Imagery*.

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McKelvie, S. J. (1995). The VVIQ as a psychometric test of individual differences in visual imagery vividness: A critical quantitative review and plea for direction. *Journal of Mental Imagery*, *19*(3-4), 1–106.

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, *48*(7), 788–804. https://doi.org/10.1016/j.cortex.2010.11.002

Mille, J., Magnon, V., Versace, R., & Vallet, G. (2021). Les "Sens” de la mémoire. *Intellectica. Revue de l’Association Pour La Recherche Cognitive*, *74*(1), 185–209. https://doi.org/10.3406/intel.2021.1990

Milton, F., Fulford, J., Dance, C., Gaddum, J., Heuerman-Williamson, B., Jones, K., Knight, K. F., MacKisack, M., Winlove, C., & Zeman, A. (2021). Behavioral and Neural Signatures of Visual Imagery Vividness Extremes: Aphantasia versus Hyperphantasia. *Cerebral Cortex Communications*, *2*(2), tgab035. https://doi.org/10.1093/texcom/tgab035

Monzel, M., Keidel, K., & Reuter, M. (2021). Imagine, and you will find Lack of attentional guidance through visual imagery in aphantasics. *Attention, Perception, & Psychophysics*, *83*(6), 2486–2497. https://doi.org/10.3758/s13414-021-02307-z

Monzel, M., Vetterlein, A., & Reuter, M. (2022). Memory deficits in aphantasics are not restricted to autobiographical memory Perspectives from the Dual Coding Approach. *Journal of Neuropsychology*, *16*(2), 444–461. https://doi.org/10.1111/jnp.12265

Monzel, M., Vetterlein, A., & Reuter, M. (2023). No general pathological significance of aphantasia: An evaluation based on criteria for mental disorders. *Scandinavian Journal of Psychology*, *64*(3), 314–324. https://doi.org/10.1111/sjop.12887

Muraki, E. J., Speed, L. J., & Pexman, P. M. (2023). Insights into embodied cognition and mental imagery from aphantasia. *Nature Reviews Psychology*. https://doi.org/10.1038/s44159-023-00221-9

Nanay, B. (2020). Unconscious mental imagery. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1817), 20190689. https://doi.org/10.1098/rstb.2019.0689

Paivio, A., & Ernest, C. H. (1971). Imagery ability and visual perception of verbal and nonverbal stimuli. *Perception & Psychophysics*, *10*(6), 429–432. https://doi.org/10.3758/BF03210327

Palermo, L., Boccia, M., Piccardi, L., & Nori, R. (2022). Congenital lack and extraordinary ability in object and spatial imagery: An investigation on sub-types of aphantasia and hyperphantasia. *Consciousness and Cognition*, *103*, 103360. https://doi.org/10.1016/j.concog.2022.103360

Pearson, J. (2019). The human imagination: The cognitive neuroscience of visual mental imagery. *Nature Reviews Neuroscience*, *20*(10), 624–634. https://doi.org/10.1038/s41583-019-0202-9

Pecher, D., & Zeelenberg, R. (2018). Boundaries to grounding abstract concepts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1752), 20170132. https://doi.org/10.1098/rstb.2017.0132

Pek, J., & Flora, D. B. (2018). Reporting effect sizes in original psychological research: A discussion and tutorial. *Psychological Methods*, *23*(2), 208–225. https://doi.org/10.1037/met0000126

Petilli, M. A., Günther, F., Vergallito, A., Ciapparelli, M., & Marelli, M. (2021). Data-driven computational models reveal perceptual simulation in word processing. *Journal of Memory and Language*, *117*, 104194. https://doi.org/10.1016/j.jml.2020.104194

Posit team. (2023). *RStudio: Integrated development environment for r*. Posit Software, PBC. http://www.posit.co/

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Reeder, R., & Pounder, Z. (2024). *Non-visual spatial strategies are efficient for maintaining precise information in visual working memor*. https://doi.org/10.31234/osf.io/gx2dv

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.

Rey, A. E., Riou, B., Muller, D., Dabic, S., & Versace, R. (2015). “The mask who wasn’t there”: Visual masking effect with the perceptual absence of the mask. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(2), 567–573. https://doi.org/10.1037/xlm0000051

Rey, A. E., Riou, B., Vallet, G. T., & Versace, R. (2017). The automatic visual simulation of words: A memory reactivated mask slows down conceptual access. *Canadian Journal of Experimental Psychology / Revue Canadienne de Psychologie Expérimentale*, *71*(1), 14–22. https://doi.org/10.1037/cep0000100

Rey, A. E., Versace, R., & Plancher, G. (2018). When a reactivated visual mask disrupts serial recall: Evidence that refreshing relies on memory traces reactivation in working memory. *Experimental Psychology*, *65*(5), 263–271. https://doi.org/10.1027/1618-3169/a000414

Rights, J. D., & Sterba, S. K. (2019). Quantifying explained variance in multilevel models: An integrative framework for defining R-squared measures. *Psychological Methods*, *24*(3), 309–338. https://doi.org/10.1037/met0000184

Santarpia, A., Blanchet, A., Poinsot, R., Lambert, J.-F., Mininni, G., & Thizon-Vidal, S. (2008). Évaluer la vivacité des images mentales dans différentes populations françaises. *Pratiques Psychologiques*, *14*(3), 421–441. https://doi.org/10.1016/j.prps.2007.11.001

Sheehan, P. W. (1987). Toward understanding the variability in imagery test performance: Comments on unvividness paradox. *Journal of Mental Imagery*, *11*(1), 9–12.

Slatter, K. H. (1960). Alpha rhythms and mental imagery. *Electroencephalography and Clinical Neurophysiology*, *12*(4), 851–859. https://doi.org/10.1016/0013-4694(60)90133-4

Slinn, C., Nikodemova, Z., Rosinski, A., & Dijkstra, N. (2023). *Vividness of visual imagery predicts performance on a visual working memory task when an imagery strategy is encouraged*. PsyArXiv. https://doi.org/10.31234/osf.io/34wsv

Vallet, G., Brunel, L., & Versace, R. (2010). The Perceptual Nature of the Cross-Modal Priming Effect. *Experimental Psychology*, *57*(5), 376–382. https://doi.org/10.1027/1618-3169/a000045

Versace, R., Brouillet, D., & Vallet, G. (2018). *Cognition incarnée: Une cognition située et projetée*. Mardaga.

Versace, R., Labeye, É., Badard, G., & Rose, M. (2009). The contents of long-term memory and the emergence of knowledge. *European Journal of Cognitive Psychology*, *21*(4), 522–560. https://doi.org/10.1080/09541440801951844

Versace, R., Vallet, G. T., Riou, B., Lesourd, M., Labeye, É., & Brunel, L. (2014). Act-In: An integrated view of memory mechanisms. *Journal of Cognitive Psychology*, *26*(3), 280–306. https://doi.org/10.1080/20445911.2014.892113

Wicken, M., Keogh, R., & Pearson, J. (2021). The critical role of mental imagery in human emotion: Insights from fear-based imagery and aphantasia. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1946), 20210267. https://doi.org/10.1098/rspb.2021.0267

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., Milton, F., Della Sala, S., Dewar, M., Frayling, T., Gaddum, J., Hattersley, A., Heuerman-Williamson, B., Jones, K., MacKisack, M., & Winlove, C. (2020). Phantasia psychological significance of lifelong visual imagery vividness extremes. *Cortex*, *130*, 426–440. https://doi.org/10.1016/j.cortex.2020.04.003

1. Introduction

Close your eyes and try to mentally visualize your breakfast table as you sat down to it this morning. Most people would report having a clear image of the scene in their "*mind's eye*": this experience is referred to as visual imagery, commonly defined as the experience of visual sensory information without a direct external stimulus (Pearson, 2019). Nonetheless, there are great differences between individuals concerning the vividness of these images, some people even declaring that they have no visual mental images at all. This extreme phenomenon, although already observed in the 19^{th} century (Galton, 1880) and noted in various studies since then (e.g., Farah et al., 1988; Faw, 2009; Marks, 1973a; McKelvie, 1995; Paivio & Ernest, 1971; Sheehan, 1987; Slatter, 1960), received renewed attention only nine years ago, when Zeman et al. (2015) published a study that has since been highly cited, coining the term "aphantasia" to refer to "reduced or absent voluntary imagery".

Early estimates suggest that aphantasia could concern 3-4% of the global population (see for instance Dance et al., 2022; Dawes et al., 2020; Palermo et al., 2022). However, many people with aphantasia may be unaware of it, suggesting a potential underestimation of the phenomenon (Faw, 2009; Zeman et al., 2020). Aphantasics often report reduced or absent sensory imagery in various modalities, fewer and less rich dreams (Dawes et al., 2020), reduced episodic and autobiographical memory (Dawes et al., 2020; Zeman et al., 2020), yet with intact spatial imagery (Bainbridge et al., 2021; Dawes et al., 2020; Keogh & Pearson, 2018; Zeman et al., 2015). Although self-reports by aphantasics are very consistent across studies, many authors stress the need to cross subjective reports with more objective tasks assessing visual imagery. This need is highlighted by the heterogeneity and complexity of aphantasia: for example, some aphantasics report visual mental imagery when dreaming, some have preserved mental imagery in other sensory modalities, while others report a complete absence of conscious mental imagery, both voluntary and involuntary (Dawes et al., 2020; Zeman et al., 2020). In light of this, a reliable measurement of visual imagery would be a valuable tool to better define aphantasia. Yet a crucial question for this assessment is still being debated: is aphantasia a genuine absence of mental images, or do aphantasics have them but are simply unable to access them consciously?

Some researchers doubt that mental imagery could be completely absent, and have hypothesized that aphantasics who report having no conscious imagery at all might still have unconscious mental imagery (Nanay, 2020). As this phenomenon is difficult to identify, little is known about unconscious mental imagery in aphantasia. A recent study by Liu & Bartolomeo (2023) used a behavioural task to assess visual imagery in various domains (the French Perception-Imagination Battery) in aphantasics and controls. The task consisted of mentally comparing pairs of items based on various features (e.g. “beaver” - “fox”: which is the longest?). They found no differences in accuracy between the groups, but slower RTs and lower confidence in the aphantasics’ answers, and argued that this result was consistent with aphantasics having the visual images required to succeed at the task, albeit without the knowledge of “how they did it”. Similarly, in a task that supposedly required visual imagery to verify whether a target dot was inside the boundaries of a previously presented geometric shape, Jacobs et al. (2018) found no difference in accuracy between an aphantasic participant and controls. As proposed by Nanay (2020), this result could be interpreted as reflecting an unconscious comparison of a visual image with the stimuli perceived by the aphantasic participant. Although on a N = 1 case study, this result may still suggest the existence of this unconscious form of imagery in aphantasia. However, due to the potential conscious processes at play in these behavioural tasks (with or without sensory imagery), neither study could completely rule out the hypothesis of aphantasics using strategies other than visual imagery (e.g. semantic processing, spatial imagery) to solve the tasks. This possibility, often raised in discussions about aphantasia (e.g., Jacobs et al., 2018; Knight et al., 2022; Liu & Bartolomeo, 2023; Monzel et al., 2021), prevents from firmly concluding from these results regarding the existence of unconscious mental images.

On the other hand, several studies that sought to develop objective measures assessing visual imagery found consistent behavioural and physiological differences between aphantasics and controls on imagery tasks, thus challenging Nanay's (2020) hypothesis of unconscious mental imagery in aphantasia (see also Blomkvist, 2022). Aphantasics have been shown to have a reduced skin conductance response to frightening scenarios (Wicken et al., 2021), a reduced automatic pupil dilatation in reaction to imagined bright stimuli (Kay et al., 2022), or a reduced priming by visual imagery (Keogh & Pearson, 2018), suggesting that aphantasics are truly unable to produce mental images. The latter priming paradigm developed by (Keogh & Pearson, 2018) is particularly often cited as a promising and relatively undemanding task for objectively identifying aphantasia, and has already been used for this purpose in several subsequent studies (Chang, Zhang, et al., 2023; e.g., Keogh & Pearson, 2020). In their initial study, they investigated visual imagery in aphantasics and controls using a binocular rivalry paradigm: in this task, participants were cued either with the letter "R" (for red) or the letter "G" (for green) and had to imagine one of two images, respectively a red-horizontal Gabor or a green-vertical Gabor. After rating the vividness of their mental image, they were presented with both Gabors simultaneously, one in the left eye, the other in the right, and asked to say which colour they had seen first. Their results showed that the mental visualization of the Gabors influenced the colour seen in the binocular rivalry task for control participants, but not for aphantasics. The authors interpreted this absence of priming in aphantasia as a real inability to generate mental images, and not just as a lack of metacognition skills.

While these conclusions are convincing about conscious imagery, they cannot yet rule out the hypothesis of unconscious mental imagery. A first caveat in this study is that self-diagnosed aphantasics were explicitly asked to voluntarily form mental images and rate their vividness during the task. This aspect of their paradigm may have skewed the results from the start, as aphantasics were asked to do something they knew (or believed) they could not do in the first place. It is possible, then, that participants did not fully engage with the task - or did not perform it correctly - because they firmly believed that they would fail to comply with the instructions, due to the awareness of their aphantasia (see Cabbai et al., 2023 for evidence on demand biases in aphantasia). Secondly, by using explicit priming, their study could not account for potential unconscious mental imagery, which is typically investigated with implicit priming tasks. Consequently, the binocular rivalry paradigm developed by (Keogh & Pearson, 2018; like other objective measures based on explicit instructions to use mental imagery, e.g., Kay et al., 2022; Milton et al., 2021) cannot exclude the possible existence of unconscious mental images in aphantasia. We aimed to fill this gap by designing an implicit priming task that would allow us to study unconscious mental images in aphantasia.

The present study

The objective of this study was to develop a new task inspired by the binocular rivalry used by Keogh & Pearson (2018), including a priming task explicitly asking to use mental imagery, along with an implicit priming task specifically targeting unconscious mental imagery. Such a task would provide a novel and unprecedented behavioural method to identify the presence or absence of visual imagery and, by extension, to objectively characterize aphantasia.

To create an implicit task, the paradigm was divided into two parts: a prior association phase, and the implicit task itself. The association phase asked the participants to indicate the colour of a red horizontal Gabor or a blue vertical Gabor to implicitly memorize the colour-orientation association. In the subsequent implicit task, a red or blue coloured circle was presented as a prime before a target, which was a Gabor either congruent or incongruent with the colour seen (see Figure 1 and Figure 2 in the Procedure section). As previous works of our team have shown (e.g., Brunel et al., 2013; Rey et al., 2015; Rey et al., 2018), the prime is assumed to reactivate an unconscious mental image of the associated Gabor automatically. Participants were then asked to indicate the orientation of the target. An explicit task was added for control and comparison where participants were overtly asked to produce a mental image of the Gabors before the targets. In the explicit task, like in Keogh and Pearson's study, participants were asked to imagine one of the previous Gabors by presenting a letter (R or B) as a cue. A Gabor congruent or incongruent with the colour was then presented as a target, and participants were asked to indicate the orientation of the lines of the target.

Shorter RTs in the congruent trials compared to the incongruent ones would therefore reflect an influence of unconscious mental images, helping participants to respond faster.

Moreover, to ensure that any priming observed would be the consequence of mental imagery (as opposed to semantic priming, for example), in half of the trials the targets were presented in black and white rather in than colour. If aphantasics have only difficulties with conscious mental imagery, a priming effect should be observed for both groups in the implicit task, but not in the explicit one. If aphantasics have difficulties with both conscious and unconscious mental imagery, no priming effect should be observed for the aphantasia group neither in the implicit nor in the explicit task, as opposed to the control group.

In addition, we carried out a second analysis by defining "finer-grained" VVIQ sub-groups, with a subset of our sample composed solely of aphantasics with a minimal VVIQ score of 16, people with low imagery (VVIQ between 17 and 32), hereinafter called "hypophantasics" (using the terminology from Reeder & Pounder, 2024), and controls (our sample included only two participants with VVIQ $>$ 75, so group analyses with hyperphantasics were not possible). This analysis aimed at answering a frequent interrogation in aphantasia literature about subgroups in aphantasia with differing characteristics: several authors pointed out that the fact of reporting *completely absent* imagery could be qualitatively very distinct from having only *vague* images (Blomkvist & Marks, 2023; Dance et al., 2022; Liu & Bartolomeo, 2023; Muraki et al., 2023). The object of our study, unconscious mental images, is a difficult phenomenon to reach, so this additional analysis could be crucial to judge the effects of our paradigm.

Finally, to assess the potential of this paradigm as a predictive tool for visual imagery ability, we performed correlations between the self-report questionnaires and the magnitude of the priming effect. If this effect is related to the generation of mental images, a clear association should arise between a greater priming effect and higher visual imagery ability.

2. Methods

2.1 Participants

We compared a group of self-identified aphantasic individuals with a control group of individuals with self-reported intact visual imagery. Participants were recruited from Facebook online community platforms dedicated to aphantasia in France using a recruitment ad. 151 participants completed the study. All completed an online version of the French Vividness of Visual Imagery Questionnaire (VVIQ-F, Santarpia et al., 2008; adapted from Marks, 1973b): aphantasic participants were identified as the ones with a total VVIQ score below 32, which is the conventional threshold used in most studies on aphantasia (e.g., Dance, Ward, et al., 2021; Dance, Jaquiery, et al., 2021; Dawes et al., 2020; Zeman et al., 2015). 89 participants were in the aphantasic group ($M_{age} = 34.7$, $SD_{age} = 10.6$, $range_{age} = [19; 59]$, $M_{VVIQ} = 19.2$, $SD_{VVIQ} = 4.6$, $range_{VVIQ} = [16; 31.5]$, 65 women) and 62 in the control group ($M_{age} = 33.2$, $SD_{age} = 9.7$, $range = [18; 65]$, $M_{VVIQ} = 54.5$, $SD_{VVIQ} = 12.3$, $range = [32; 78.5]$, 31 women). All participants reported no lesions or acquired neurological or psychiatric disorders and no impaired or uncorrected vision.

The study was carried out following the recommendations of the French Law (Loi Jardé n◦2012- 300) with written informed consent being obtained from all the participants following the Declaration of Helsinki.

2.2 Questionnaires

2.2.1 Vividness of Visual Imagery Questionnaire - French adaptation (VVIQ-F)

The French version of the VVIQ (VVIQ-F, Santarpia et al., 2008; adapted from Marks, 1973b) used in this study was adapted in a Google Form version. It consists of sixteen items, each asking participants to imagine a particular scene and rate the vividness of their mental imagery using a Likert scale ranging from 1 ("No image at all, you only know that you are thinking about the object") to 5 ("Perfectly clear and vivid as if it were normal vision"). The final score is ranging from 16 to 80.

2.2.2 Spontaneous use of imagery scale (SUIS)

The French version of the SUIS (SUIS-F, Ceschi & Pictet, 2018; adapted from Reisberg et al., 1986) used in this study was adapted in a Google Form version. It consists of 12 items, each asking participants to rate the degree to which a spontaneous use of mental imagery in a particular situation is appropriate to them using a Likert scale ranging from 1 ("Never appropriate") to 5 ("Completely appropriate"). The final score is ranging from 12 to 60.

2.2.3 Object and spatial imagery questionnaire (OSIQ)

The French version of the OSIQ (Dutriaux, unpublished, adapted from Blazhenkova et al., 2006) used in this study was adapted in a Google Form version. It consists of 30 items, half of the items (i.e., 15 items) are used to assess participants' ability to imagine an object's shape, texture, and colour (object imagery score), and the other half (i.e., 15 items) are used to assess participants' ability to imagine location, movements, and spatial relationships (spatial imagery score). For each item, participants rate the degree to which they agree with the statement using a Likert scale ranging from 1 (“Totally disagree”) to 5 (“Totally agree”).

2.3 Stimuli

2.3.1 Gabor patterns

Four Gaussian-shaped Gabor patterns were generated: one red Gabor with horizontal lines and one blue Gabor with vertical lines (coloured Gabors); one black Gabor with horizontal lines and one black Gabor with vertical lines (uncoloured Gabors). All Gabor were superposed on a white 160 × 160 pixels background.

2.3.2 Cues

Two cues were generated: a red circle and a blue circle. Both were of the same size as the Gabor patterns and were superposed on a white 160x160 pixels background.

2.4 Software

The tasks were programmed using OpenSesame (Mathôt et al., 2012) and were uploaded on Jatos (Lange et al., 2015), a server used to run experiments online. All the experimental material is openly available on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

2.5 Procedure

Participants were provided with two links, one directing to the experiments, and one directing to the questionnaire. They were instructed to perform the experiments and the questionnaires alone, in a quiet and not distracting environment, and to turn off their phones and other messaging devices. They were also asked to use a computer with a keyboard, as well as a good internet connection. Once participants clicked on the link to the experiments, the first experimental task launched.

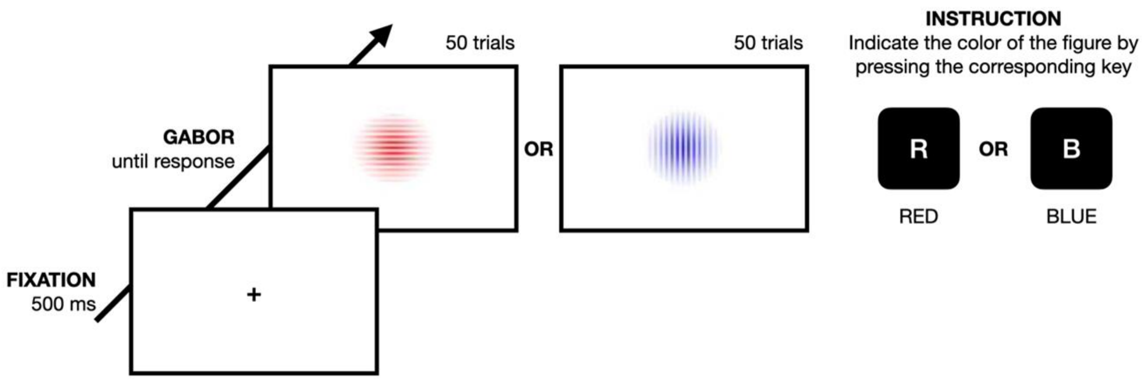

Figure 1: ***Associative task.*** *A fixation cross (500 ms) is followed by one of the two coloured Gabor. Participants had to indicate the colour of the Gabor by pressing the corresponding key (either R for Red or B for Blue), without time constraint. Each Gabor was presented 50 times.*

Participants began with the implicit priming task. This task began with an associative phase (Figure 1) in which a fixation cross (500 ms) was followed by one of the two coloured Gabor, and participants had to indicate the colour of the Gabor by pressing the corresponding key (either R for Red or B for Blue), without time constraint. Each Gabor was presented 50 times. After the association phase, participants started the implicit priming test phase (Figure 2) in which a fixation cross (500 ms) was followed by a cue (150 ms) that was either a red or a blue circle, and then depending on the condition by either one of the two coloured Gabor or by one of the uncoloured Gabor, as a target. Participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand. In the congruent condition, the cue has the same colour as the target Gabor (coloured condition) or primed the Gabor with the same line orientation as the black target Gabor (uncoloured condition), contrary to the non-congruent condition. There were 16 trials per congruence and colour pairs, amounting to 64 trials total for the task. Response mapping was not randomised due to the structure of the task: as there were as many congruent trials as incongruent ones, participants could not reliably predict the correct response based on the cue alone and a cue-response key association. Should they respond solely based on the key they associated with a cue, responses would be close to random, which could be easily spotted in the data. Consequently, learning a response key associated with a cue was not relevant and randomisation was not deemed necessary.

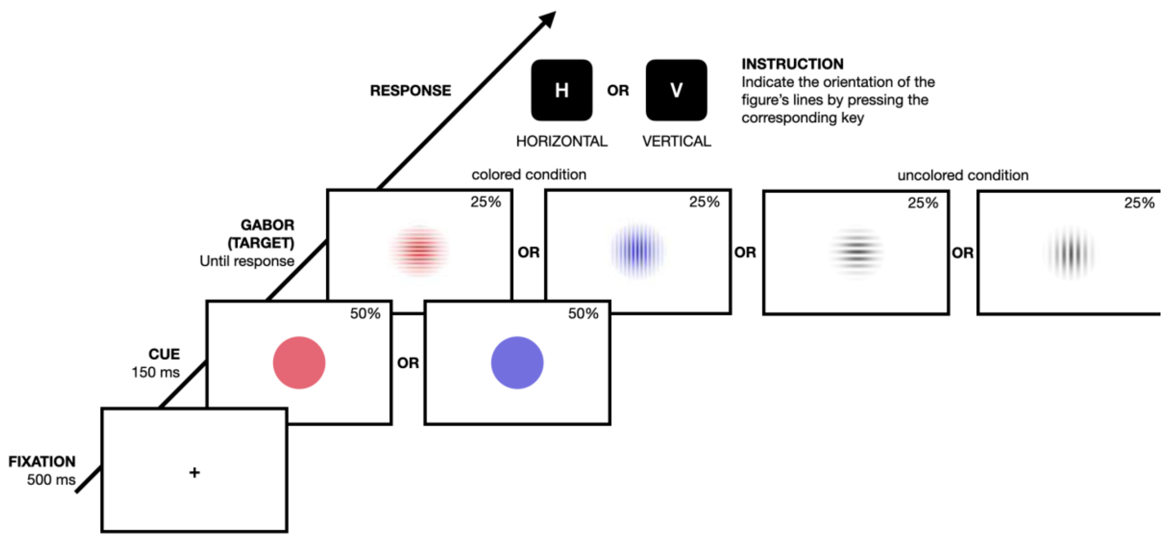

Figure 2: ***Implicit priming task.*** *A fixation cross (500 ms) is followed by a cue (150 ms) that was either a red or a blue circle, and then by one of the two coloured Gabor, or by one of the uncoloured Gabor, as a target. Participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand.*

After the implicit priming task and a short break, participants transitioned to the explicit task (Figure 3) in which a fixation cross (500 ms) was followed by a letter as a cue (1500 ms) that was either the letter R (for red) or B (for blue). In response to the cue, participants were asked to form a mental imagery of the corresponding Gabor (a red with horizontal lines or a blue with vertical lines) and to keep that image in mind during 3000 ms while fixing the centre of a blank screen. Then, a fixation cross (500 ms) was presented followed by one of the two coloured Gabor, or by one of the uncoloured Gabor, and participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand. In the congruent condition, the cue designated the same colour as the target Gabor (coloured condition) or primed the Gabor with the same line orientation as the black target Gabor (uncoloured condition), contrary to the non-congruent condition. Likewise, there were 16 trials per congruence and colour pairs, amounting to 64 trials total for the task. It is worth mentioning that participants had practice trials at the beginning of each task and phase. Moreover, the implicit priming task was divided into two blocks, each beginning with the association phase, and ending with the implicit priming phase, to preserve the association between the colour of the Gabor and the orientation of its lines.

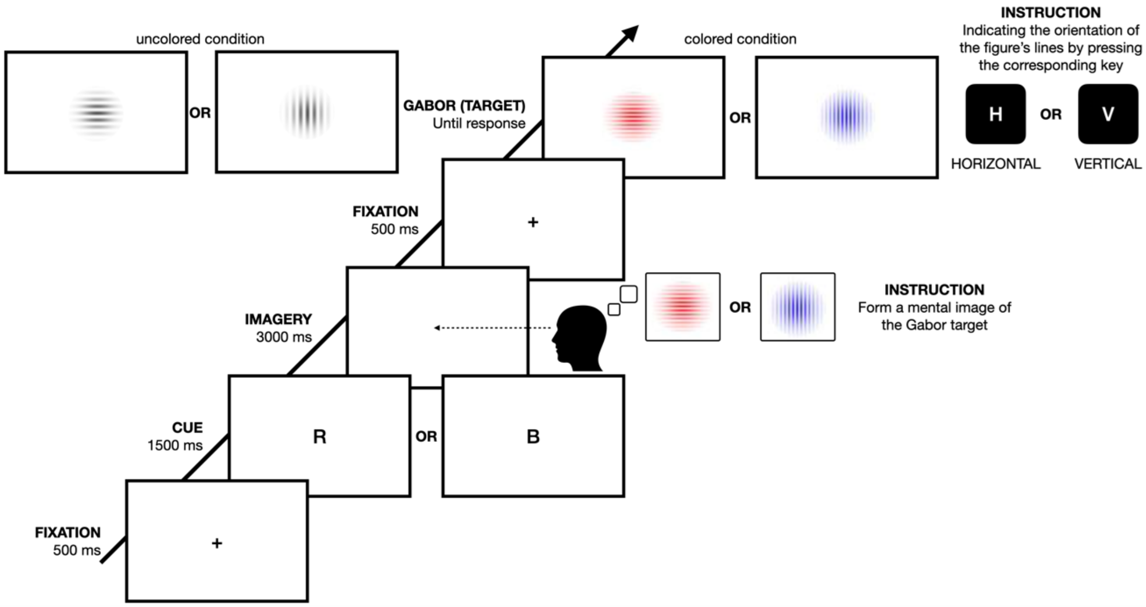

Figure 3: ***Explicit priming task.*** *A fixation cross (500 ms) was followed by a letter as a cue (1500 ms) that was either the letter R (for red) or B (for blue). In response to the cue, participants were asked to form a mental imagery of the corresponding Gabor (a red with horizontal lines or a blue with vertical lines) and to keep that imagery in mind during 3000 ms while fixing the centre of a blank screen. Then, a fixation cross (500 ms) was presented followed by one of the two coloured Gabor, or by one of the uncoloured Gabor, and participants had to indicate the orientation of the Gabor's lines by pressing the corresponding key (either H for horizontal, or V for vertical), using only their dominant hand.*

2.6 Analyses

The data analysis was programmed in R language (version 4.2.0, R Core Team, 2022) on RStudio (Posit team, 2023). The raw data, code, and analysis outputs are available on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

2.6.1 Self-report questionnaires

The scores of the four questionnaires were modelled with linear models on ranked scores to accommodate the ordinal nature of the questionnaire data and to control for the influence of age on the group differences. The models included the *Group* as a categorical predictor and the *Age* as a continuous co-variate. For group differences, we report estimated means, their standard errors, and two-tailed *p*-values of marginal contrasts between means, computed using a Wald *t*-distribution approximation.

2.6.2 Outlier detection procedure

We excluded data from five participants that exceeded 43% of errors (therefore with too few trials to analyze). Trials with RTs abnormally fast or slow ($<$ 250ms or $>$ 3s, 1% and .7% respectively) that could represent false alarms (especially given the internet-based nature of the task) were removed. Participants with an aberrant RT average exceeding the median $\pm 3 \times$ MAD were excluded for each task (MAD proved to be more robust than standard deviations for outlier detection, see Leys et al., 2013). The remaining data comprised N = 9082 trials for the implicit task and N = 8824 trials for the explicit task. For the analysis of reaction times (RTs), incorrect responses were also removed (2.7% and 3.6% of trials in the implicit/explicit task respectively). The remaining RT data comprised N = 8777 trials for the implicit and N = 8603 trials for the explicit task.

2.6.3 Accuracy

Before removing incorrect responses for the analysis of response times, we first checked for any differences in accuracy between the groups. To this end, we fitted Generalized Logistic Mixed Models to predict accuracy with the *Group* (aphantasic, control), *Congruence* condition (congruent or incongruent), and *Colour* condition (colour or uncoloured) along with all their two and three-way interactions as fixed categorical predictors, while *participants* have been included as grouping factors (i.e. “random effects”).

The models were implemented in the *lme4* R package (Bates et al., 2014). Overall fixed effects were assessed with Type II Wald χ^2 tests using the *car* R package (Fox et al., 2023).

2.6.4 Response times

Power analysis

As the experiment was conducted online, the sample size was mostly limited by the time resources of the project. Likewise, the number of trials per condition and the total amount of trials were balanced in order not to overload the Internet experiment. From these two constraints, we estimated the statistical power conferred by the sample size eventually reached and the experimental design *a priori*, i.e. based on effect sizes reported in the literature and our hypotheses. We used the *simr* package (Green & MacLeod, 2016) to simulate datasets reflecting the experimental design, featuring expected patterns of means and variance, and fitting generalized linear mixed models on them.

Common effect sizes reported in the literature and intra-individual trial-to-trial variability in RTs in perceptual discrimination tasks have been used to simulate data and estimate the statistical power to detect effects tied to experimental conditions (for a similar procedure, see Fucci et al., 2023). The main effect of interest chosen was the interaction between Group and Congruence, where we hypothesized a reduction in RTs for the control group in the congruent condition that would not be present in aphantasics. Simulations have shown that the statistical power reached 80% even with little effect sizes nearing 24ms, and exceeded 90% when the effect size went up and above 30ms. Details of the procedure can be found in an extended analysis report on OSF (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

Generalized Linear Mixed Models

To account for the non-normal, positively skewed distributions of the RTs, we fitted Generalized Linear Mixed Models (GLMMs) with inverse Gaussian distributions, as recommended by Lo & Andrews (2015). The models included the *Group* (aphantasic, control), *Congruence* condition (congruent or incongruent), and *Colour* condition (colour or uncoloured) along with all their two and three-way interactions as fixed categorical predictors, while *participants* have been included as grouping factors (i.e. "random effects"). Overall fixed effects were assessed with Type II Wald χ^2 tests.

Due to the way that variance is partitioned in linear mixed models (Rights & Sterba, 2019), there does not exist an agreed-upon way to calculate standard effect sizes for individual terms such as main effects or interactions in these models. Thus, in line with general recommendations on how to report effect sizes (e.g., Pek & Flora, 2018), we report and analyse unstandardised effect sizes for post-hoc tests in the form of estimated marginal contrasts in milliseconds (i.e. differences in model-estimated marginal means, hereinafter denoted Δ) where appropriate.

Bayesian Modelling

To complement the frequentist approach, Bayesian hypothesis testing was also used to quantify the evidence in favour or against a congruence effect for each group. To this end, we fitted Bayesian multilevel models (analogous to the frequentist GLMMs presented above) separately for each group to predict RTs with the *Congruence* condition (congruent or incongruent), *Colour* condition (colour or uncoloured) and their two-way interaction as fixed categorical predictors, along with *participants* as grouping factors. Models were implemented in the *brms* R package (Bürkner, 2017). The evidence ratio of interest was then computed as the Bayes Factor between the hypothesis of a congruence effect against the null hypothesis. We report the BF_{01} in favour of the null hypothesis of an absence of congruence effect for a given group alongside the contrasts in the *Group* × *Congruence* interaction. The proposed interpretations of the strength of the evidence from Bayes Factor values were based on Jeffrey's scale thresholds (see e.g., Kass & Raftery, 1995).

2.6.5 Finer-grained VVIQ groups

Additional analyses were conducted with more refined groups: the aphantasic group was restricted to participants scoring at the lowest point on the VVIQ (VVIQ = 16, N = 46), an "hypophantasic" group was created with participants scoring between 17 and 32 (N = 37), and the control group was restricted to participants scoring between 33 and 74 (N = 54). Our sample included only two "hyperphantasics" (VVIQ ≥ 75). These two participants were therefore removed from the analyses, as it was shown that hyperphantasics constitute a group with significant differences from typical imagers (see e.g., Milton et al., 2021; Zeman et al., 2020), but there were not enough of them in the present study to create such a group. Similar analyses to those carried out for the two initial groups were performed.

2.6.6 Correlation analyses

Spearman correlation coefficients were computed to assess the monotonic relationship between each questionnaire score and the *congruence effects* in both tasks. The congruence effect was computed for each participant as the difference between the mean RT in the incongruent condition minus the mean RT in the congruent condition, first averaging across colour conditions to account for this factor. Spearman correlations were chosen to relax the assumption of linearity of Pearson correlations, particularly given that the questionnaire variables are ordinal and that the data have an underlying group structure.

Correlations were also computed between the effects in both tasks. A False Discovery Rate (FDR) correction (Benjamini & Hochberg, 1995) was applied to the p-values to control for multiple comparisons.

3. Results

3.1 Self-report questionnaires

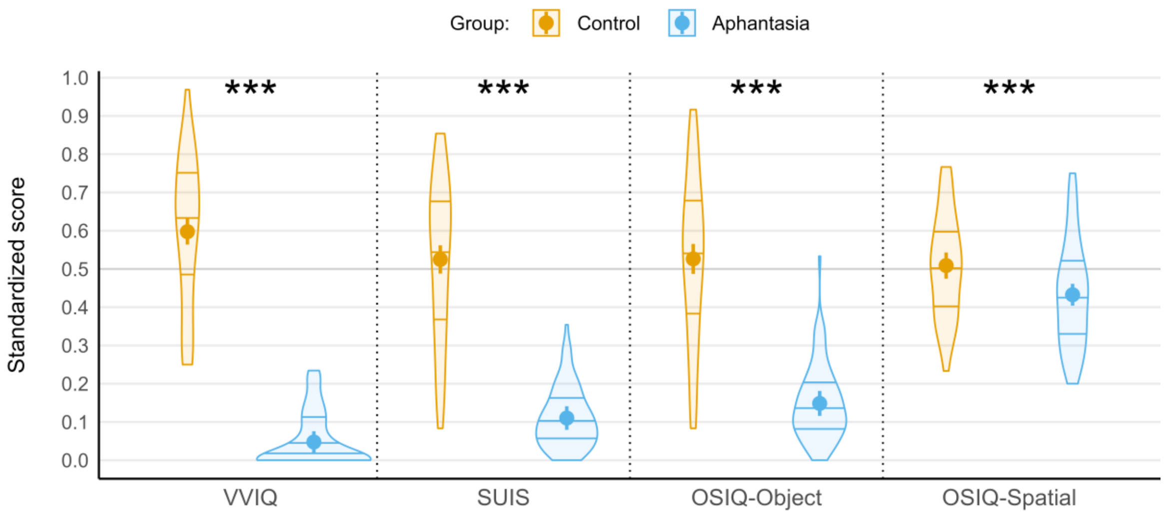

Figure 4: Visualization of self-report questionnaires results for aphantasics and controls. Violin plots depict the distributions and quantiles of the scores in each group, median-centred on each scale. Coloured dots depict standardized means of the scores to the questionnaires, while the solid lines represent their standard errors. On the vertical axis, 0.0 is the normalized lowest possible score, 0.5 is the median score, and 1 is the maximum possible score for each questionnaire. Stars denote p-values inferior to .001 for each pairwise contrast between groups.

As expected, aphantasic participants reported significantly less visual imagery across questionnaires (see Figure 4), scoring below controls on the VVIQ ($M_{Aph.}$ = 19.20 ± .47; $M_{Controls}$ = 54.39 ± 1.61; $t(147)$ = 24.23, $p < .001$), the SUIS ($M_{Aph.}$ = 17.31 ± .44;

$M_{Controls}$ = 37.07 $\pm$ 1.13; t(147) = 18.35, $p < .001$) and the object scale of the OSIQ ($M_{Aph.}$ = 23.90 $\pm$ .65; $M_{Controls}$ = 46.50 $\pm$ 1.52; t(147) = 15.19, $p < .001$). Surprisingly, aphantasics scored significantly lower than controls on the spatial scale of the OSIQ ($M_{Aph.}$ = 40.98 $\pm$ .83; $M_{Controls}$ = 45.59 $\pm$ 1.10; t(147) = 3.41, $p < .001$), a result contrasting with previous studies having found no between-group differences on this scale (e.g., Dawes et al., 2020; Keogh & Pearson, 2018). Nevertheless, this difference is much less pronounced than in other questionnaires, and there are large variations on this scale in the aphantasic group (e.g., the lowest observed score is 27/75, while the highest is 61/75).

3.2 Accuracy

The models did not reveal any difference in accuracy between the two groups, neither in the implicit task (Wald χ^2 = 1.17, p = 0.28) nor in the explicit task (Wald χ^2 = 1.57, p = 0.21). The only significant effect concerned the Colour condition, both in the implicit task (Wald χ^2 = 6.37, p = 0.01) and in the explicit task (Wald χ^2 = 18.96, p = 0.21). In both cases, participants were more likely to answer correctly in the coloured condition rather than in the uncoloured ones (implicit task uncoloured/coloured odds ratio = 0.73, 95% CI [0.58, 0.92], z = -2.63, p = .009; explicit task uncoloured/coloured odds ratio = 0.52, 95% CI [0.39, 0.69], z = -4.49, $p < .001$). Elsewhere, in both tasks, the model did not reveal any main effects of Congruence (implicit: p = 0.59; explicit: p = 0.6), no Group × Congruence interaction (implicit: p = 0.58; explicit: p = 0.89), no Group × Colour interaction (implicit: p = 0.9; explicit: p = 0.43) and no Congruence × Colour interaction (implicit: p = 0.9; explicit: p = 0.29).

3.3 Response times

3.3.1 Implicit task

The model for the RTs in the implicit task yielded a significant main effect of Congruence (Wald χ^2 = 8.6, p = 0.003) and a significant interaction between Group and Congruence (Figure 5; Wald χ^2 = 8.58, p = 0.003). Post-hoc contrasts of marginal means showed that controls responded faster in the congruent condition (Δ(controls RT congruent - incongruent) = -30ms, SE = 6ms, 95% CI [-40, -10], $p < .001$), with extreme evidence in favour of a congruence effect for the control group ($BF_{01} < .001$). The contrast analysis also shows that the faster response of controls was driving the main effect of Congruence, as aphantasics did not respond faster in the congruent condition (Δ(aphantasics RT congruent - incongruent) = -2ms, SE = 5ms, 95% CI [-10, 10], p = .73), with strong evidence against a congruence effect for the aphantasia group ($BF_{01} = 14.12$). The model did not show any main effect of Group (p = .43) or colour (p = .51), no interaction between Group and colour (p = 0.96) or Congruence and colour (p = 0.14), and no three-way interaction (p = 0.23).

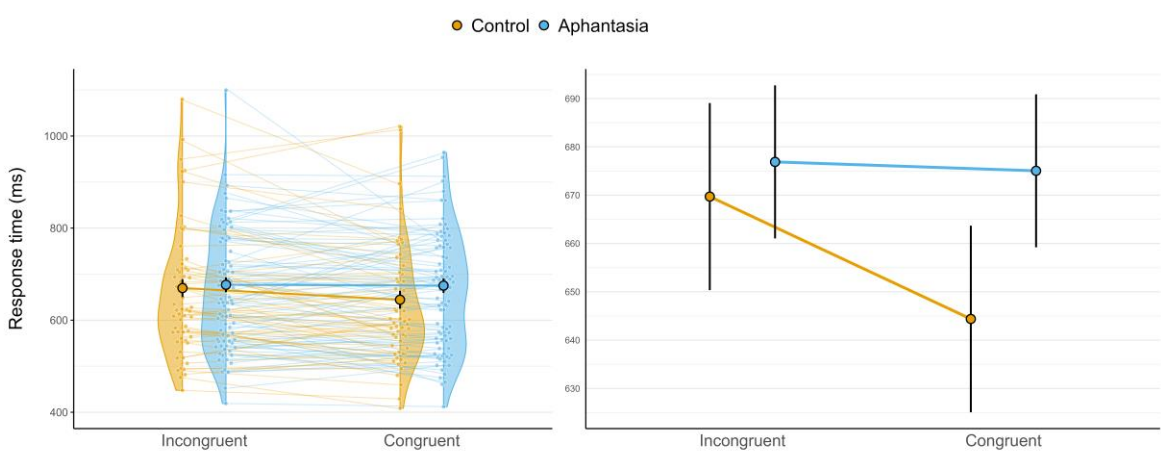

Figure 5: Visualizations of the interactions between Group and Congruence in the implicit task. The left plot shows the full range of mean response times; the right plot is a

zoomed version on the marginal means to see the details of the effect sizes. The central coloured dots in both plots indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates. On the left plot, the mean response times of each participant in the two conditions are represented as smaller coloured dots connected by a line to illustrate the individual congruence effects.

3.3.2 Explicit task

The model for the RTs in the explicit task yielded a significant main effect of Congruence (Wald χ^2 = 14.5, $p < .001$) and Colour (Wald χ^2 = 47.6, $p < .001$). The model also revealed a significant interaction between Group and Congruence (Figure 6; Wald χ^2 = 10.7, p = 0.001). Post-hoc contrasts of marginal means showed that, once again, controls responded faster in the congruent condition (Δ(controls RT congruent - incongruent) = -30ms, SE = 6ms, 95% CI [-40, -20], $p < .001$), with extreme evidence in favour of a congruence effect for the control group ($BF_{01} = .003$). Likewise, the faster response of controls was driving the main effect of Congruence, as aphantasics did not respond faster in the congruent condition either (Δ(aphantasics RT congruent - incongruent) = -5ms, SE = 5ms, 95% CI [-20, 10], p = .39), with strong evidence against a congruence effect in the aphantasia group ($BF_{01} = 12.09$). The main effect of Colour reflects the fact that participants responded faster overall in the coloured condition (Δ(RT coloured - uncoloured) = -30ms, SE = 4ms, 95% CI [-40, -20], $p < .001$), although this factor did not interact with the two others. The model did not show any main effect of Group (p = .78), no interaction between Group and Colour (p = 0.37) or Congruence and Colour (p = 0.64), and no three-way interaction (p = 0.40).

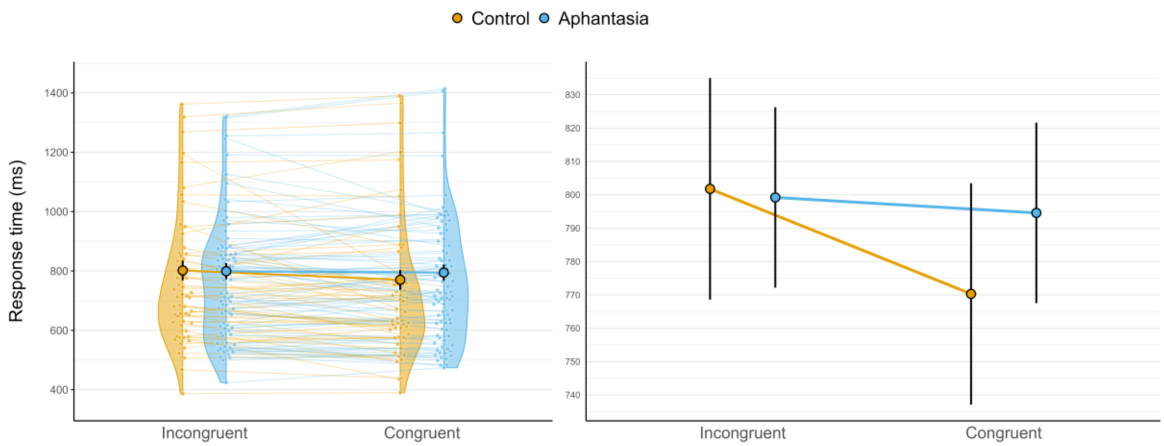

Figure 6: Visualizations of the interactions between Group and Congruence in the explicit task. The left plot shows the full range of mean response times; the right plot is a zoomed version on the marginal means to see the details of the effect sizes. The central coloured dots in both plots indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates. On the left plot, the mean response times of each participant in the two conditions are represented as smaller coloured dots connected by a line to illustrate the individual congruence effects.

3.4 Finer-grained VVIQ groups

3.4.1 Self-report questionnaires

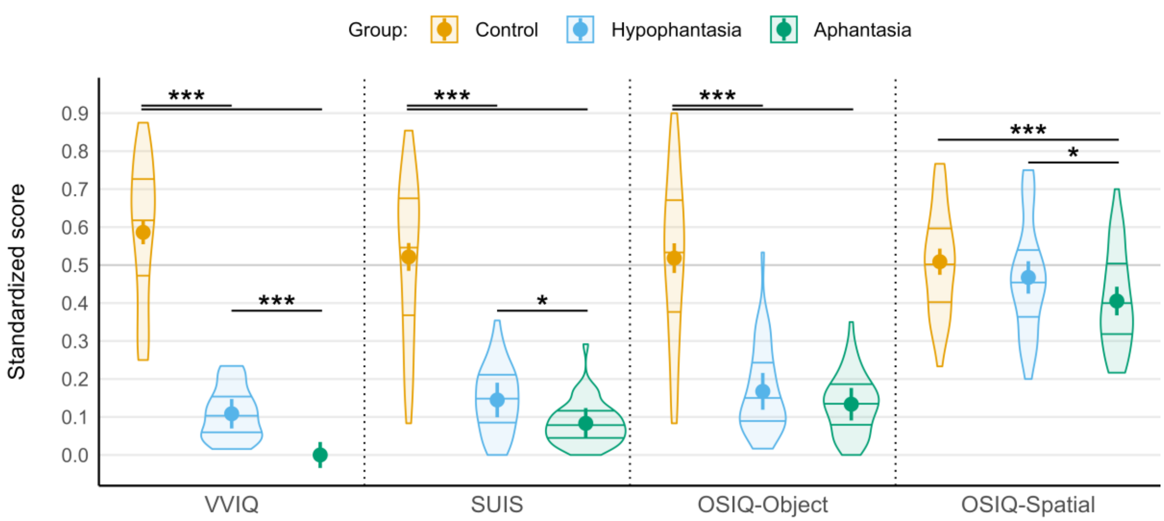

*Figure 7: Visualization of self-report questionnaires results for aphantasics, hypophantasics and controls. Violin plots depict the distributions and quantiles of the scores in each group, median-centred on each scale. Coloured dots depict standardized means of the scores to the questionnaires, while the solid lines represent their 95% CI. On the vertical axis, 0.0 is the normalized lowest possible score, 0.5 is the median score, and 1 is the maximum possible score for each questionnaire. *: $p < .05$; *: $p^* < .01$; ***: $p < .001$.*

The newly created hypophantasic group scored higher than the aphantasic group and lower than the control group on the VVIQ (see Figure 7; $M_{Aph.}$ = 16; $M_{Hypo.}$ = 22.9 $\pm$ 1.1; $M_{Controls}$ = 53.49 $\pm$ 1; Δ(Control-Hypo.) = 30.57, 95%CI [27.37, 33.75], $p < .001$, Δ(Hypo.-Aph.) = 6.87, 95%CI [3.54, 10.21], $p < .001$) and SUIS ($M_{Aph.}$ = 16.1 $\pm$ 0.99; $M_{Hypo.}$ = 18.89 $\pm$ 1.1; $M_{Controls}$ = 36.98 $\pm$ 0.89; Δ(Control-Hypo.) = 18.09, 95%CI [15.28, 20.89], $p < .001$, Δ(Hypo.-Aph.) = 2.79, 95%CI [-0.14, 5.72], $p < .001$). The control group scored higher than the other two on the OSIQ-Object, however the hypophantasic group did not score higher than the aphantasic group ($M_{Aph.}$ = 23.04 $\pm$ 1.31; $M_{Hypo.}$ = 25.04 $\pm$ 1.48; $M_{Controls}$ = 46.09 $\pm$ 1.19; Δ(Hypo.-Aph.) = 2, 95%CI [-1.91, 5.91], p = 0.31). On the OSIQ-Spatial, the control and hypophantasic group scored higher than the aphantasic group, but the control group did not score higher than the hypophantasic group ($M_{Aph.}$ = 39.46 $\pm$ 1.15; $M_{Hypo.}$ = 42.98 $\pm$ 1.3; $M_{Controls}$ = 45.47 $\pm$ 1.05; -Δ(Control-Aph.) = 6.01, 95%CI [2.93, 9.09], $p < .001$; Δ(Control.-Hypo.) = 2.49, 95%CI [-0.80, 5.77], p = 0.14; Δ(Hypo.-Aph.) = 3.52, 95%CI [0.09, 6.95], p = 0.04).

3.4.2 Implicit task

The new model for the implicit task showed a significant main effect of Congruence (Wald χ^2 = 8.7, p = 0.003) and a significant interaction between Group and Congruence (Figure 8; Wald χ^2 = 13.23, p = .001). Once again, the contrast analyses revealed that the effect of Congruence was driven by controls responding faster in the congruent condition (Δ(controls RT congruent - incongruent) = -30ms, SE = 7ms, 95% CI [-40, -10], $p <$ .001, BF_{01} = .004, extreme evidence in favour of a congruence effect), as opposed to aphantasics (Δ(aphantasics RT congruent - incongruent) = -5ms, SE = 7ms, 95% CI [-20, 10], p = 0.46, BF_{01} = 12.59, strong evidence against a congruence effect). Interestingly, the hypophantasic group fitted in between, with a trend effect of Congruence (Δ(RT congruent - incongruent) = -10ms, SE = 8ms, 95% CI [-30, 0], p = 0.07) and inconclusive evidence for or against a congruence effect (BF_{01} = 2.41). There were no main effects of Group (p = 0.49), Colour (p = .46), no interaction between Group and Colour (p = .54) or Congruence and Colour (p = .17), and no triple interaction (p = .42).

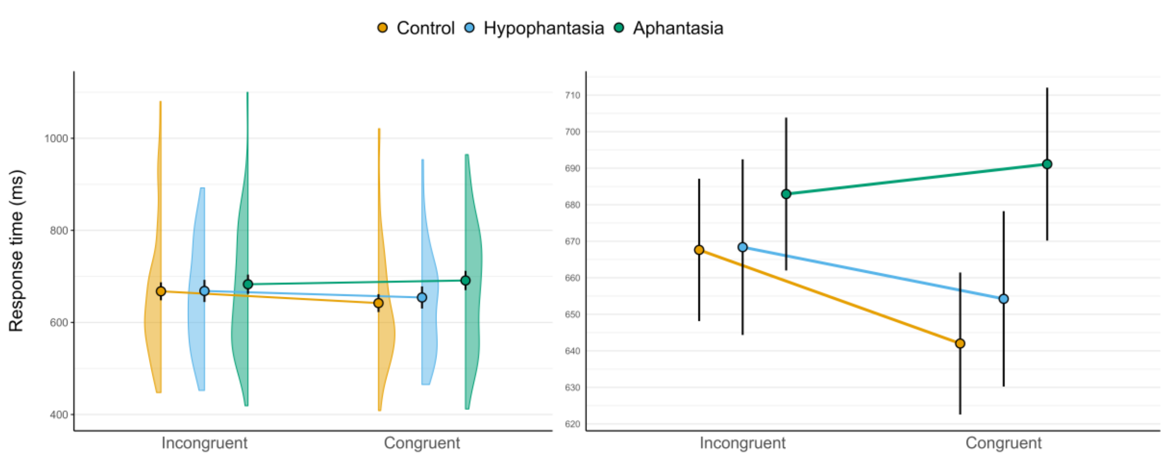

Figure 8: Visualizations of the interactions between Group and Congruence in the implicit task with redefined groups. The coloured dots the indicate the marginal means of

the groups in each condition whereas the black bars represent the standard error of these estimates.

3.4.3 Explicit task

The new model for the explicit task showed a significant main effect of Congruence (Wald χ^2 = 11.43, $p < .001$) and Colour (Wald χ^2 = 44.05, $p < .001$), along with a significant interaction between Group and Congruence (Figure 9; Wald χ^2 = 8.18, p = 0.017). The contrast analyses again showed that the effect of Congruence was driven by controls responding faster in the congruent condition (Δ (controls RT congruent - incongruent) = -30ms, SE = 7ms, 95% CI [-40, -20], p $< .001$, BF_{01} $<$ .001, extreme evidence in favour of a congruence effect), while aphantasics did not (Δ(aphantasics RT congruent - incongruent) = 5ms, SE = 7ms, 95% CI [-10, 20], p = 0.46, BF_{01} = 11.78, strong evidence against a congruence effect). This time, however, hypophantasics were aligned with the aphantasic group and showed no congruence effect (Δ(RT congruent - incongruent) = 4ms, SE = 8ms, 95% CI [-20, 10], p = 0.65, BF_{01} = 9.81, substantial evidence against a congruence effect). Contrast analysis on the main effect of Colour showed that participants responded faster overall in the coloured condition (Δ(RT coloured - uncoloured) = -30ms, SE = 5ms, 95% CI [-40, -20], $p < .001$), although this factor did not interact with the two others. There were no main effects of Group (p = 0.98), no interaction between Group and Colour (p = 0.79) or Congruence and Colour (p = 0.62), and no triple interaction (p = 0.32).

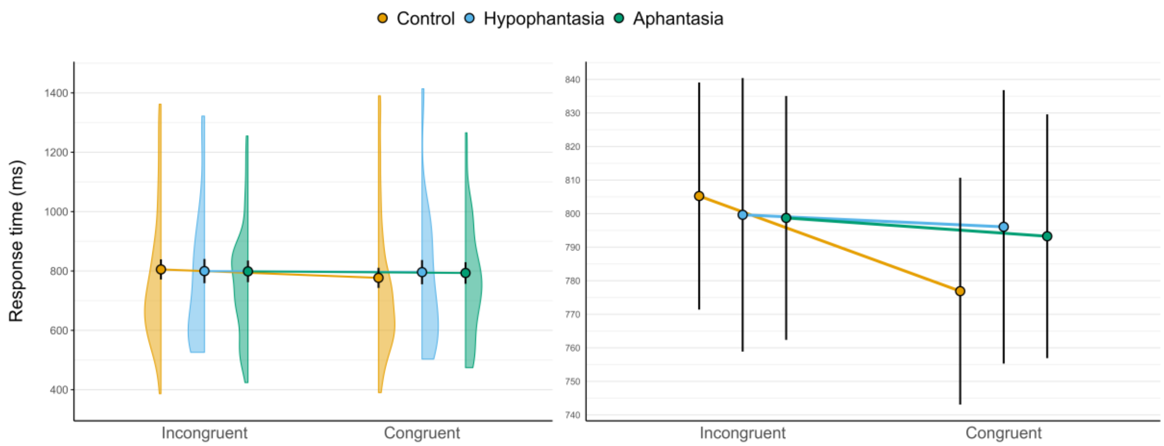

Figure 9: Visualizations of the interactions between Group and Congruence in the explicit task with redefined groups. The coloured dots the indicate the marginal means of the groups in each condition whereas the black bars represent the standard error of these estimates.

3.5 Correlations with the subjective questionnaires

	VVIQ	OSIQ-Object	OSIQ-Spatial	SUIS
Implicit task congruence effect	ρ = **0.21**	**ρ = 0.26**	r = 0.05	***r* = .27**
	p = 0.02*	***p*** = 0.003**	p = .57	***p*** = 0.002**
Explicit task congruence effect	ρ = 0.08	ρ = 0.12	ρ = -0.02	ρ = 0.16
	p = 0.43	p = 0.19	p = 0.83	p = 0.08

Table 1: Matrix of the pairwise Spearman correlation coefficients ρ between each questionnaire score and the congruence effect in both tasks.

Finally, Spearman correlations were computed to assess the monotonic relationship between the questionnaire scores and the *congruence effects* in both tasks. In the explicit task, the congruence effect was not correlated with the VVIQ (p = 0.43), the OSIQ-Object (p = 0.19), the OSIQ-Spatial (p = 0.43), or the SUIS (p = 0.43). Interestingly, the congruence effect in the explicit task also did not correlate with the effect observed in the implicit task (p = 0.57). In the implicit task however, the congruence effect correlated with the VVIQ (ρ = 0.21, 95% CI [0.05, 0.37], p = 0.02), the OSIQ-Object (ρ = 0.26, 95% CI [0.10, 0.40], p = 0.003) and the SUIS (ρ = 0.27, 95% CI [0.11, 0.41], p = 0.002), but no correlation with the OSIQ-Spatial (ρ = 0.05, 95% CI [-0.11, 0.21], p = 0.57). All the pairwise correlations between the scores and the congruence effects in both tasks are presented in Table 1. The three significant correlations of the implicit task congruence effects with the VVIQ, OSIQ-Object and SUIS are represented in Figure 10.

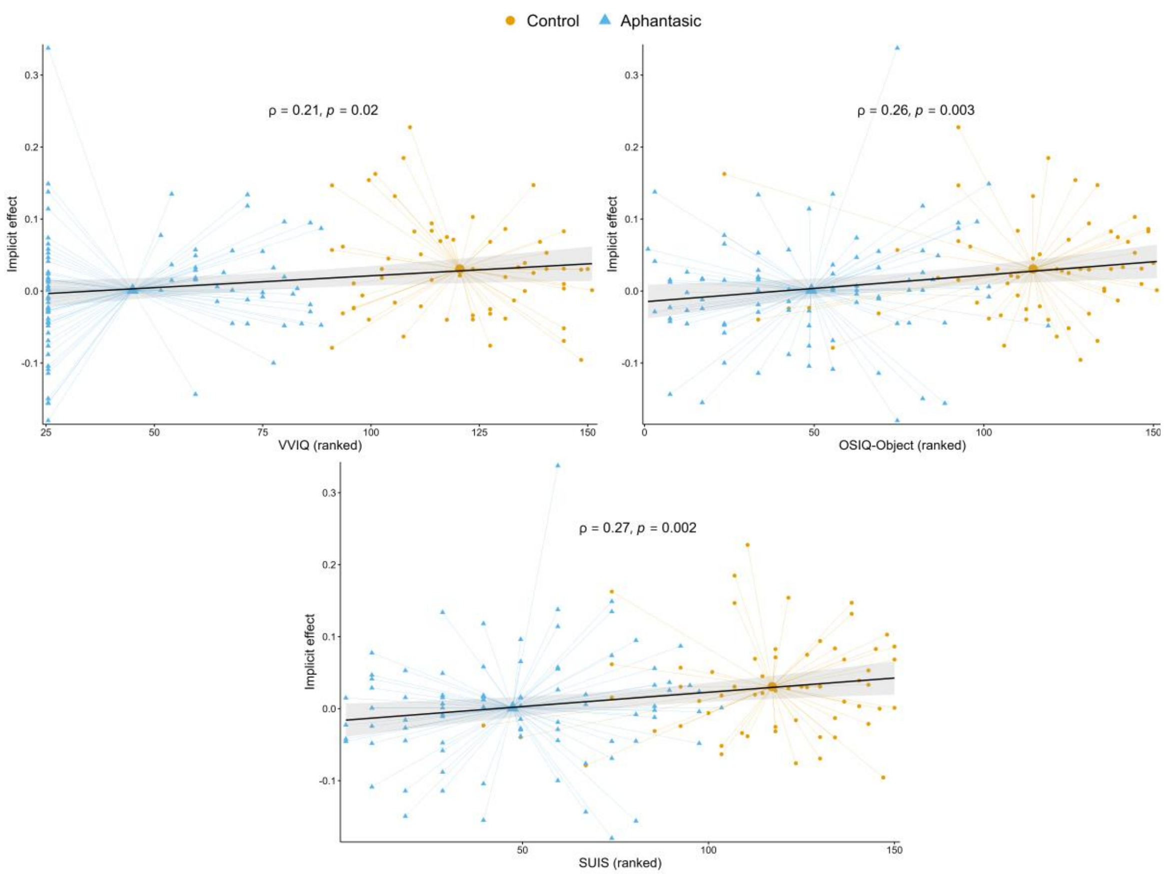

Figure 10: Visualizations of the correlation between the congruence effect (i.e. the mean difference between incongruent and congruent RTs) in the implicit task and the VVIQ, OSIQ-Object and SUIS ranked scores. Aphantasics are represented with blue triangles,

and controls with orange dots. All the observations are connected with a thin line to their group mean, represented as a bigger symbol. The black regression line denotes the Spearman correlation between the scores and the effect, independently of groups, along with its confidence interval.

4. Discussion

The objective of the present study was to examine whether aphantasics could form mental images but could not access them consciously, or whether they presented a genuine deficit in the generation of mental images. To this end, we built and tested implicit and explicit priming paradigms on aphantasic and control participants. Analyses revealed striking evidence that the control group showed a consistent congruence effect in both tasks, whereas the aphantasic group did not. The intensive study of Gabors in a preliminary association should have facilitated the decision for Gabors congruent with the prime, as demonstrated in the control group, an effect that can be interpreted as the influence of an unconscious mental image of the studied Gabors. However, this effect was not observed in the aphantasic group. This result was also present when adopting a more conservative definition of aphantasia by analysing groups restricted to aphantasics scoring at floor VVIQ. This result supports the hypothesis that aphantasics have difficulty generating both conscious and unconscious mental images, rather than only conscious ones.

4.1 Towards an implicit objective assessment of aphantasia

The priming task developed in the present study proved to be efficient to discriminate between groups of visual imagery ability, both when implemented with explicit instructions to use imagery and when implemented with implicit priming. The explicit task with instructions to produce mental imagery was inspired by the binocular rivalry paradigm developed by Keogh & Pearson (2018) and produced a similar pattern of results showing an absence of priming in aphantasia with a different task, thus validating the effectiveness of priming tasks to evidence conscious mental imagery differences. However, the main aim of our study was to go one step further and develop a task that could evidence mental imagery differences *without* relying on instructions to produce it. Thus, the implicit priming task developed here was designed to target specifically unconscious mental imagery without giving participants instructions. The results of this task consistently followed the same pattern as the explicit task, lending credence to the hypothesis that the implicit task involved an unconscious form of mental imagery. Moreover, an in-depth analysis of finer-grained groups dissociating "complete aphantasia" (VVIQ = 16) from "hypophantasia" (17 < VVIQ < 32) revealed striking differences that characterized the two sub-groups. While the complete aphantasia group showed no priming effect in either the implicit and explicit tasks, the hypophantasia group showed a mixed pattern, with traces of a priming effect in the implicit task but not in the explicit one. We propose to interpret this pattern of results as suggesting that aphantasics may differ fundamentally from hypophantasics in that they would have neither conscious nor unconscious imagery, while hypophantasics might retain some unconscious imagery, but without the ability to voluntarily generate conscious mental images (i.e., what was asked of them in the explicit task). In light of these results, we propose that this novel online paradigm provides a foundation to develop implicit, objective behavioural assessments of visual imagery using a minimal setup, thereby opening new avenues for a large-scale, objective characterization of aphantasia.

The correlations of the congruence effect in the implicit task with the VVIQ, OSIQ-Object scale and the SUIS corroborate the potential of our paradigm to assess individual differences in visual imagery. This relationship supports that implicit tasks may prove to be stable relative to various assessments of visual imagery, and encourages further investigation of such implicit effects on a real continuum to depart from group comparisons. Future work investigating implicit behavioural effects which are correlated with visual imagery and observed at a *by-participant* level will be crucial to further ascertain results on aphantasia and individual differences in mental imagery. Considering this result, we also argue that a wider diversity of psychometric questionnaires needs to be used along with efficient behavioural tasks when studying aphantasia, to better understand the complex construct that is mental imagery.

4.2 Unconscious mental imagery and sensorimotor simulation

A main novelty of our paradigm is that participants were not instructed to produce any specific mental content in the implicit task, thus avoiding demand bias. This design therefore relies on the assumption that the task would trigger an unconscious form of imagery for those capable of it. However, this raises the question of whether the concept of "unconscious" mental images is relevant. The concept was introduced in the field of research on aphantasia research by Nanay (2020), but its ability to explain behavioural findings on aphantasia has been debated debated since (see e.g., Blomkvist, 2022; Krempel & Monzel, 2024). These hypothetical unconscious mental images could neither be voluntarily produced by the participant nor consciously experienced, and are therefore by definition very hard to objectify. Muraki et al. (2023) suggest that the idea of "unconscious mental images" could be likened to the concept of "sensorimotor simulation" developed in the field of embodied cognition research. A sensorimotor simulation is the re-creation of the states in which the individual's perceptual and motor systems were in a previous experience, as well as their emotional and introspective states (e.g., Barsalou, 2008, 2009; Dijkstra & Post, 2015; Mille et al., 2021; Versace et al., 2009; Versace et al., 2014; Versace et al., 2018). From this re-creation emerges a representation that can reach consciousness in the form of a mental image of an object, if the neurons in the perceptual and motor systems that were activated during confrontations with this object are reactivated in the current situation. In support of this hypothesis, Petilli et al. (2021) have shown using implicit priming tasks that verbal cues affected subsequent processing of target words with related visual properties, even when visual processing was neither requested nor required. Various cross-modal priming studies have shown that such cues could also influence behavioural responses based on other modalities (e.g., verbal cues influencing decision tasks on images or sounds, see Brunel et al., 2010; Rey et al., 2015; Rey et al., 2017; Vallet et al., 2010). Similarly, Amit et al. (2017) have provided evidence that feature representations are generated in visual cortices during verbal cues, even in decision tasks based on verbal processing. This evidence supports the idea that multi-modal sensory representations emerge in priming tasks and influence behaviour. Consequently, following the association drawn by Muraki et al. (2023) between sensorimotor simulation and unconscious mental images, our results provide evidence that the simulation of the visual properties of incoming information could be reduced or absent in aphantasia.

4.3 Alternative strategies and forms of imagery

A recurrent challenge when studying aphantasia is that many tasks that are often considered to require visual imagery could also be solved by other non-visual strategies, such as the use of internal or covert verbalization Monzel et al. (2022). In that vein, it could be argued that our tasks could be completed using a verbal or propositional strategy based on the colour of the stimuli. For instance, in the association phase, participants may have used the propositional strategy of forming the abstract or semantic representation of an association between colour and line orientation of the Gabors (e.g., by internally repeating that “blue patches have vertical lines”). During the tasks, participants could then have used such a representation when a prime was presented, which may have facilitated their response when the target’s colour was congruent with the colour of the prime. However, our tasks have the advantage of making the use of this type of strategies more difficult to adhere to, thanks to a condition in which the targets are not coloured. As no semantic representations had been previously associated with uncoloured targets, a colour-based strategy was inappropriate for these stimuli. This type of strategy could even have been counter-productive, which could explain slower response times in the uncoloured condition than in the coloured condition. Thus, the persistence of the interaction between group and congruence independently of the colour conditions supports the idea that our results can not be explained purely by the reliance on propositional strategies.

Curiously, the analysis of questionnaire data yielded a significant difference between aphantasics and controls in reported spatial imagery, assessed by the spatial scale of the OSIQ, contrasting with previous studies on aphantasia that used this questionnaire and found no between-group differences (Bainbridge et al., 2021; Dawes et al., 2020; Keogh & Pearson, 2018). While this difference is hard to interpret on its own, it is worth noting that although significant, the difference in spatial imagery between the groups is much less pronounced than the difference observed on visual imagery scales. Large differences in spatial imagery ability also existed within the aphantasic group, as shown by the difference between the hypophantasic and aphantasic groups on the OSIQ-Spatial. This finding could be specifically tied to the choice of cut-offs used in aphantasia studies. In addition, there could exist various sub-types in aphantasia in our sample characterized by their variable reliance on different forms of mental representations (e.g., spatial, auditory, kinaesthetic). Nevertheless, it should be mentioned that our paradigm relied partially on spatial judgements (namely, orientation properties of items) that might be impacted by spatial imagery abilities. This hypothesis may also apply to a growing number of studies on aphantasia that used paradigms consisting in the detection of orientation changes of Gabor patches, thought to assess visual imagery or visual working memory (e.g., Chang, Wang, et al., 2023; Keogh et al., 2021; Keogh & Pearson, 2018, 2020; Knight et al., 2022; Slinn et al., 2023 inter alia). While our results did exhibit differing patterns between groups, future studies should still pay particular attention to this spatial imagery factor. On the one hand, this would require a more systematic investigation of spatial imagery, which has proved to have distinct characteristics from visual imagery in aphantasia (see Blazhenkova & Pechenkova, 2019; Palermo et al., 2022). On the other hand, this entails that care should be taken to design tasks that target visual imagery as specifically as possible, manipulating item properties such as colour or shape while accounting for semantic and spatial properties of items (see e.g., Liu & Bartolomeo, 2023).

4.4 Consequences on aphantasia

Finally, the functional implications of the differences in information processing found in aphantasia also need to be evaluated in the context of their "real-world" consequences. Aphantasics have demonstrated to live typical lives, most eloquently echoed by the fact that aphantasia often goes unnoticed for years (Zeman et al., 2015, 2020). Furthermore, it has been shown that aphantasia does not meet the criteria of a pathological disorder (see Blomkvist & Marks, 2023; Monzel et al., 2023 for a discussion). Thus, the finding of reduced unconscious mental imagery (or sensorimotor simulation) in aphantasia may be best interpreted as showing that these processes might not play a crucial role as previously thought, for instance on conceptual processing (see e.g., Meteyard et al., 2012; Pecher & Zeelenberg, 2018). Several recent studies even suggest that this attenuation of internal sensory representations in aphantasia could have positive consequences: Wicken et al. (2021) showed that aphantasics exhibited dimmed electrophysiological responses to frightening scenarios; Keogh et al. (2023) used a laboratory model of PTSD and noted that aphantasics reported fewer intrusive memories when confronted with traumatic films; Königsmark et al. (2021) demonstrated, using a rhythmic flicker paradigm to induce pseudo-hallucinations, that aphantasics experienced less anomalous percepts. In the present study we have brought evidence suggesting that aphantasics may simulate less sensory elements in their unconscious representations. The potential positive consequences of this reduction in sensory simulation in aphantasia is an interesting topic that deserves further research.

4.5 Conclusion

In sum, our findings provide evidence suggesting that "total" aphantasia (defined by a VVIQ score of 16) may not solely result from impaired metacognition but could indicate an underlying reduction in both conscious and unconscious mental imagery. Additionally, a trend in the results indicated that hypophantasia (i.e., reduced imagery, VVIQ scores between 17 and 32) may involve the presence of unconscious imagery, albeit without the capacity for voluntary imagery generation. The consistency of the congruence effect patterns obtained in both our implicit and explicit tasks for the control and aphantasic groups suggests that this priming paradigm provides a promising and reliable foundation for developing future behavioral tasks that objectively and implicitly characterize unconscious mental imagery, without depending on participant introspection.

Data and code availability

All the materials and implementations of the questionnaires and tasks, the anonymised data, the analysis scripts, and in-depth analysis notebooks are all freely available on the Open Science Framework (https://osf.io/635dv/?view_only=72898c1e036c456b97e688629563a47f).

Author contributions

Conceptualization: RP, EC, VR, CA, RV, GP. **Data curation**: RP, MD, VR. **Formal analysis**: MD. **Funding acquisition**: GP, EC. **Investigation**: VR, CA. **Methodology**: RP, EC, VR, CA, RV, GP. **Project administration**: GP, EC. **Resources**: VR, CA, GP. **Software**: MD. **Supervision**: GP, EC. **Visualization**: MD. **Writing - Original Draft Preparation**: RP, MD, EC, VR, GP. **Writing - Review & Editing**: All authors.

Declaration of interest

None.

References

Amit, E., Hoeflin, C., Hamzah, N., & Fedorenko, E. (2017). An asymmetrical relationship between verbal and visual thinking: Converging evidence from behavior and fMRI. *NeuroImage*, *152*, 619–627. https://doi.org/10.1016/j.neuroimage.2017.03.029

Bainbridge, W. A., Pounder, Z., Eardley, A. F., & Baker, C. I. (2021). Quantifying aphantasia through drawing: Those without visual imagery show deficits in object but not spatial memory. *Cortex*, *135*, 159–172. https://doi.org/10.1016/j.cortex.2020.11.014

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Barsalou, L. W. (2009). Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1521), 1281–1289. https://doi.org/10.1098/rstb.2008.0319

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv Preprint arXiv:1406.5823*.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

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

Blazhenkova, O., & Pechenkova, E. (2019). The two eyes of the blind mind: Object vs. Spatial aphantasia? *Russian Journal of Cognitive Science*, *6*(4), 51–65.

Blomkvist, A. (2022). Aphantasia: In search of a theory. *Mind & Language*, *n/a*(n/a). https://doi.org/10.1111/mila.12432

Blomkvist, A., & Marks, D. F. (2023). Defining and “diagnosing” aphantasia: Condition or individual difference? *Cortex*. https://doi.org/10.1016/j.cortex.2023.09.004

Brunel, L., Goldstone, R. L., Vallet, G., Riou, B., & Versace, R. (2013). When Seeing a Dog Activates the Bark. *Experimental Psychology*, *60*(2), 100–112. https://doi.org/10.1027/1618-3169/a000176

Brunel, L., Lesourd, M., Labeye, E., & Versace, R. (2010). The sensory nature of knowledge: Sensory priming effects in semantic categorization [10.1080/17470210903134369]. *Quarterly Journal of Experimental Psychology*, *63*(5), 955–964.

Bürkner, P.-C. (2017). Brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*, 1–28. https://doi.org/10.18637/jss.v080.i01

Cabbai, G., Dance, C., Dienes, Z., Simner, J., Forster, S., & Lush, P. (2023). Investigating relationships between trait visual imagery and phenomenological control: The role of context effects. *Unpublished*.

Ceschi, G., & Pictet, A. (2018). *Imagerie mentale et psychothérapie: Un ouvrage sur la psychopathologie cognitive*. Mardaga.

Chang, S., Wang, J., & Meng, M. (2023). The behavioral performance and cortical structural properties of aphantasia. *Journal of Vision*, *23*(9), 5985. https://doi.org/10.1167/jov.23.9.5985

Chang, S., Zhang, X., Pearson, J., & Meng, M. (2023). *Imageless imagery in aphantasia: Decoding non-sensory imagery in aphantasia*. https://www.researchsquare.com. https://doi.org/10.21203/rs.3.rs-3162223/v1

Dance, C. J., Ipser, A., & Simner, J. (2022). The prevalence of aphantasia (imagery weakness) in the general population. *Consciousness and Cognition*, *97*, 103243. https://doi.org/10.1016/j.concog.2021.103243

Dance, C. J., Jaquiery, M., Eagleman, D. M., Porteous, D., Zeman, A., & Simner, J. (2021). What is the relationship between aphantasia, synaesthesia and autism? *Consciousness and Cognition*, *89*, a103087 1–18. https://doi.org/10.1016/j.concog.2021.103087

Dance, C. J., Ward, J., & Simner, J. (2021). What is the Link Between Mental Imagery and Sensory Sensitivity? Insights from Aphantasia. *Perception*, *50*(9), 757–782. https://doi.org/10.1177/03010066211042186

Dawes, A., Keogh, R., Andrillon, T., & Pearson, J. (2020). A cognitive profile of multi-sensory imagery, memory and dreaming in aphantasia. *Scientific Reports*, *10*(1), 10022. https://doi.org/10.1038/s41598-020-65705-7

Dijkstra, K., & Post, L. (2015). Mechanisms of embodiment. *Frontiers in Psychology*, *6*.

Farah, M. J., Levine, D. N., & Calvanio, R. (1988). A case study of mental imagery deficit. *Brain and Cognition*, *8*(2), 147–164. https://doi.org/10.1016/0278-2626(88)90046-2

Faw, B. (2009). Conflicting Intuitions May Be Based On Differing Abilities. *Journal of Consciousness Studies*, 25.

Fox, J., Weisberg, S., & Price, B. (2023). *Car: Companion to applied regression*. https://r-forge.r-project.org/projects/car/

Fucci, E., Abdoun, O., Baquedano, C., & Lutz, A. (2023). Ready to help, no matter what you did: Responsibility attribution does not influence compassion in expert Buddhist practitioners. *Preprint*. https://doi.org/10.31234/osf.io/d6y4w

Galton, F. (1880). Statistics of mental imagery. *Mind*, *os-V*(19), 301–318. https://doi.org/10.1093/mind/os-V.19.301

Green, P., & MacLeod, C. J. (2016). SIMR : An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution*, *7*(4), 493–498. https://doi.org/10.1111/2041-210X.12504

Jacobs, C., Schwarzkopf, D. S., & Silvanto, J. (2018). Visual working memory performance in aphantasia. *Cortex*, *105*, 61–73. https://doi.org/10.1016/j.cortex.2017.10.014

Kass, R. E., & Raftery, A. E. (1995). Bayes Factors. *Journal of the American Statistical Association*, *90*(430), 773–795. https://doi.org/10.1080/01621459.1995.10476572

Kay, L., Keogh, R., Andrillon, T., & Pearson, J. (2022). The pupillary light response as a physiological index of aphantasia, sensory and phenomenological imagery strength. *eLife*, *11*, e72484. https://doi.org/10.7554/eLife.72484

Keogh, R., & Pearson, J. (2018). The blind mind: No sensory visual imagery in aphantasia. *Cortex*, *105*, 53–60. https://doi.org/10.1016/j.cortex.2017.10.012

Keogh, R., & Pearson, J. (2020). Attention driven phantom vision: Measuring the sensory strength of attentional templates and their relation to visual mental imagery and aphantasia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1817), 20190688. https://doi.org/10.1098/rstb.2019.0688

Keogh, R., Wicken, M., & Pearson, J. (2021). Visual working memory in aphantasia: Retained accuracy and capacity with a different strategy. *Cortex*, *143*, 237–253. https://doi.org/10.1016/j.cortex.2021.07.012

Keogh, R., Wicken, M., & Pearson, J. (2023). Fewer intrusive memories in aphantasia: Using the trauma film paradigm as a laboratory model of PTSD. *In Review*.

Knight, K. F., Milton, F. N., & Zeman, A. (2022). Memory without Imagery: No Evidence of Visual Working Memory Impairment in People with Aphantasia. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *44*, 8.

Königsmark, V. T., Bergmann, J., & Reeder, R. R. (2021). The Ganzflicker experience: High probability of seeing vivid and complex pseudo-hallucinations with imagery but not aphantasia. *Cortex*, *141*, 522–534. https://doi.org/10.1016/j.cortex.2021.05.007

Krempel, R., & Monzel, M. (2024). Aphantasia and involuntary imagery. *Consciousness and Cognition*, *120*, 103679. https://doi.org/10.1016/j.concog.2024.103679

Lange, K., Kühn, S., & Filevich, E. (2015). "Just Another Tool for Online Studies” (JATOS): An Easy Solution for Setup and Management of Web Servers Supporting Online Studies. *PLOS ONE*, *10*(6), e0130834. https://doi.org/10.1371/journal.pone.0130834

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology*, *49*(4), 764–766. https://doi.org/10.1016/j.jesp.2013.03.013

Liu, J., & Bartolomeo, P. (2023). Probing the unimaginable: The impact of aphantasia on distinct domains of visual mental imagery and visual perception. *Cortex*, *166*, 338–347. https://doi.org/10.1016/j.cortex.2023.06.003

Lo, S., & Andrews, S. (2015). To transform or not to transform: Using generalized linear mixed models to analyse reaction time data. *Frontiers in Psychology*, *6*.

Marks, D. F. (1973a). Visual Imagery Differences in the Recall of Pictures. *British Journal of Psychology*, *64*(1), 17–24. https://doi.org/10.1111/j.2044-8295.1973.tb01322.x

Marks, D. F. (1973b). Vividness of visual imagery Questionnaire. *Journal of Mental Imagery*.

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McKelvie, S. J. (1995). The VVIQ as a psychometric test of individual differences in visual imagery vividness: A critical quantitative review and plea for direction. *Journal of Mental Imagery*, *19*(3-4), 1–106.

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, *48*(7), 788–804. https://doi.org/10.1016/j.cortex.2010.11.002

Mille, J., Magnon, V., Versace, R., & Vallet, G. (2021). Les "Sens” de la mémoire. *Intellectica. Revue de l’Association Pour La Recherche Cognitive*, *74*(1), 185–209. https://doi.org/10.3406/intel.2021.1990

Milton, F., Fulford, J., Dance, C., Gaddum, J., Heuerman-Williamson, B., Jones, K., Knight, K. F., MacKisack, M., Winlove, C., & Zeman, A. (2021). Behavioral and Neural Signatures of Visual Imagery Vividness Extremes: Aphantasia versus Hyperphantasia. *Cerebral Cortex Communications*, *2*(2), tgab035. https://doi.org/10.1093/texcom/tgab035

Monzel, M., Keidel, K., & Reuter, M. (2021). Imagine, and you will find Lack of attentional guidance through visual imagery in aphantasics. *Attention, Perception, & Psychophysics*, *83*(6), 2486–2497. https://doi.org/10.3758/s13414-021-02307-z

Monzel, M., Vetterlein, A., & Reuter, M. (2022). Memory deficits in aphantasics are not restricted to autobiographical memory Perspectives from the Dual Coding Approach. *Journal of Neuropsychology*, *16*(2), 444–461. https://doi.org/10.1111/jnp.12265

Monzel, M., Vetterlein, A., & Reuter, M. (2023). No general pathological significance of aphantasia: An evaluation based on criteria for mental disorders. *Scandinavian Journal of Psychology*, *64*(3), 314–324. https://doi.org/10.1111/sjop.12887

Muraki, E. J., Speed, L. J., & Pexman, P. M. (2023). Insights into embodied cognition and mental imagery from aphantasia. *Nature Reviews Psychology*. https://doi.org/10.1038/s44159-023-00221-9

Nanay, B. (2020). Unconscious mental imagery. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1817), 20190689. https://doi.org/10.1098/rstb.2019.0689

Paivio, A., & Ernest, C. H. (1971). Imagery ability and visual perception of verbal and nonverbal stimuli. *Perception & Psychophysics*, *10*(6), 429–432. https://doi.org/10.3758/BF03210327

Palermo, L., Boccia, M., Piccardi, L., & Nori, R. (2022). Congenital lack and extraordinary ability in object and spatial imagery: An investigation on sub-types of aphantasia and hyperphantasia. *Consciousness and Cognition*, *103*, 103360. https://doi.org/10.1016/j.concog.2022.103360

Pearson, J. (2019). The human imagination: The cognitive neuroscience of visual mental imagery. *Nature Reviews Neuroscience*, *20*(10), 624–634. https://doi.org/10.1038/s41583-019-0202-9

Pecher, D., & Zeelenberg, R. (2018). Boundaries to grounding abstract concepts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1752), 20170132. https://doi.org/10.1098/rstb.2017.0132

Pek, J., & Flora, D. B. (2018). Reporting effect sizes in original psychological research: A discussion and tutorial. *Psychological Methods*, *23*(2), 208–225. https://doi.org/10.1037/met0000126

Petilli, M. A., Günther, F., Vergallito, A., Ciapparelli, M., & Marelli, M. (2021). Data-driven computational models reveal perceptual simulation in word processing. *Journal of Memory and Language*, *117*, 104194. https://doi.org/10.1016/j.jml.2020.104194

Posit team. (2023). *RStudio: Integrated development environment for r*. Posit Software, PBC. http://www.posit.co/

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Reeder, R., & Pounder, Z. (2024). *Non-visual spatial strategies are efficient for maintaining precise information in visual working memor*. https://doi.org/10.31234/osf.io/gx2dv

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.

Rey, A. E., Riou, B., Muller, D., Dabic, S., & Versace, R. (2015). "The mask who wasn't there": Visual masking effect with the perceptual absence of the mask. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(2), 567–573. https://doi.org/10.1037/xlm0000051

Rey, A. E., Riou, B., Vallet, G. T., & Versace, R. (2017). The automatic visual simulation of words: A memory reactivated mask slows down conceptual access. *Canadian Journal of Experimental Psychology / Revue Canadienne de Psychologie Expérimentale*, *71*(1), 14–22. https://doi.org/10.1037/cep0000100

Rey, A. E., Versace, R., & Plancher, G. (2018). When a reactivated visual mask disrupts serial recall: Evidence that refreshing relies on memory traces reactivation in working memory. *Experimental Psychology*, *65*(5), 263–271. https://doi.org/10.1027/1618-3169/a000414

Rights, J. D., & Sterba, S. K. (2019). Quantifying explained variance in multilevel models: An integrative framework for defining R-squared measures. *Psychological Methods*, *24*(3), 309–338. https://doi.org/10.1037/met0000184

Santarpia, A., Blanchet, A., Poinsot, R., Lambert, J.-F., Mininni, G., & Thizon-Vidal, S. (2008). Évaluer la vivacité des images mentales dans différentes populations françaises. *Pratiques Psychologiques*, *14*(3), 421–441. https://doi.org/10.1016/j.prps.2007.11.001

Sheehan, P. W. (1987). Toward understanding the variability in imagery test performance: Comments on unvividness paradox. *Journal of Mental Imagery*, *11*(1), 9–12.

Slatter, K. H. (1960). Alpha rhythms and mental imagery. *Electroencephalography and Clinical Neurophysiology*, *12*(4), 851–859. https://doi.org/10.1016/0013-4694(60)90133-4

Slinn, C., Nikodemova, Z., Rosinski, A., & Dijkstra, N. (2023). *Vividness of visual imagery predicts performance on a visual working memory task when an imagery strategy is encouraged*. PsyArXiv. https://doi.org/10.31234/osf.io/34wsv

Vallet, G., Brunel, L., & Versace, R. (2010). The Perceptual Nature of the Cross-Modal Priming Effect. *Experimental Psychology*, *57*(5), 376–382. https://doi.org/10.1027/1618-3169/a000045

Versace, R., Brouillet, D., & Vallet, G. (2018). *Cognition incarnée: Une cognition située et projetée*. Mardaga.

Versace, R., Labeye, É., Badard, G., & Rose, M. (2009). The contents of long-term memory and the emergence of knowledge. *European Journal of Cognitive Psychology*, *21*(4), 522–560. https://doi.org/10.1080/09541440801951844

Versace, R., Vallet, G. T., Riou, B., Lesourd, M., Labeye, É., & Brunel, L. (2014). Act-In: An integrated view of memory mechanisms. *Journal of Cognitive Psychology*, *26*(3), 280–306. https://doi.org/10.1080/20445911.2014.892113

Wicken, M., Keogh, R., & Pearson, J. (2021). The critical role of mental imagery in human emotion: Insights from fear-based imagery and aphantasia. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1946), 20210267. https://doi.org/10.1098/rspb.2021.0267

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., Milton, F., Della Sala, S., Dewar, M., Frayling, T., Gaddum, J., Hattersley, A., Heuerman-Williamson, B., Jones, K., MacKisack, M., & Winlove, C. (2020). Phantasia psychological significance of lifelong visual imagery vividness extremes. *Cortex*, *130*, 426–440. https://doi.org/10.1016/j.cortex.2020.04.003