Visual Imagery Vividness Predicts the Complexity of Induced Hallucinations

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Abstract

The current study utilizes the Ganzflicker paradigm—a flickering stimulus that induces visual hallucinations—to provide insight into the internally-generated visual experiences that correlate with individual differences in visual imagery. Here, we analyzed rich narrative descriptions of Ganzflicker hallucinations from 4,365 participants using natural language processing, sensorimotor norms, and AI visualizations. We find that overall perceptual richness and visual detail in descriptions increase with imagery vividness. Examining the specific content of these descriptions reveals that vivid imagers report more face and hand-related content than those with weaker imagery. Exploratory AI-generated visualizations of these descriptions provide additional insights, as those with weak imagery report patterns of simple visual features, like colors and geometric forms, while strong imagers' hallucinations are filled with complex real-world stimuli. These findings suggest imagery differences may lie not in early visual processing but in the integration of basic visual features into complex object- and scene-level representations.

Keywords: aphantasia, visual imagery, individual differences, hallucinations

Introduction

What are thoughts made of? Humans have a remarkable ability to guide behavior based on internally-generated representations rather than solely reacting to external environmental information. These representations allow us to time travel through memories (Rubin, 2020), plan the future (Aydin, 2018), solve problems (Gerlach et al., 2011), comprehend language (Zwaan, 2014), and perform a wide range of cognitive tasks (reviewed in Pearson, 2019). However, there are dramatic individual variations in the phenomenology of internal experiences—from those reporting constant internal monologues to those with silent thoughts (Nedergaard & Lupyan, 2024; Roebuck & Lupyan, 2020), and from those experiencing vivid mental movies to those unable to conjure even the simplest mental images (Zeman et al., 2020). These subjective differences have been predominantly studied via reports of mental imagery—the mental simulation of sensory information in the absence of a relevant external stimulus—characterizing people on a continuum from a complete lack of imagery (aphantasia) to photorealistic mental pictures (hyperphantasia; Marks, 1973; Zeman et al., 2020).

The functional significance of imagery differences remains puzzlingly unclear. Some studies show behavioral consequences—individuals with aphantasia exhibit differences in complex cognitive functions like visual scene memory (Bainbridge et al., 2021), moral decision-making (Amit & Greene, 2012), and mental health symptoms (Mawtus et al., 2024). Yet studies examining tasks thought to require visual imagery sometimes find no performance differences between imagery groups, including visual working memory (Reeder et al, 2024a; ,Weber et al., 2024) and visual priming (Cabbai et al., 2023).

Recent neuroimaging studies further complicate this picture, revealing that even individuals with aphantasia maintain decodable representations of spontaneous imagery in the early visual cortex (Cabbai et al., 2024; Chang et al., 2024). This surprising finding suggests that rather than completely lacking visual representations, aphantasic individuals might maintain access to certain visual features while possibly lacking others.

The inconsistencies in imagery research might be due, in part, to currently limited measurements of imagery differences, the most popular of which is the vividness of visual imagery questionnaire (Marks, 1973). This instrument only asks participants to rate the vividness of their imagery for specific complex objects and scenes without assessing other potentially important aspects such as the precision of mental images, their stability over time, or their ability to manipulate imagery details. Further, its focus on complex stimuli like faces and scenes may not reflect participants' ability to imagine simple visual features like colors or orientations—precisely the features that aphantasic individuals might still represent in the early visual cortex, and that have predominantly been used as stimuli in behavioral studies showing no group differences (Cabbai et al., 2023; Pounder et al., 2022; Weber et al., 2024).

Further evidence of the limitations of the vividness construct comes from qualitative reports of imagery experiences. For example, when imagining an apple,

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hyperphantasics may be able to see and feel it in their hand (a phenomenon called *prophantasia*; Reeder et al, 2024b). By contrast, aphantasics may be able to imagine spatial properties of the apple in a non-visual way, such as its size, shape, and the layout of parts (Reeder et al, 2024a). Abstract imagined representations may also include verbal labels or embodied (action-related) mental simulations (Muraki et al, 2023). Kosslyn et al. (1984) proposed additional mental imagery dimensions, including control (i.e., the ability to manipulate a mental image, such as rotating, zooming, adding or removing features) and precision (i.e., the accuracy of visual details in the mental image compared to a veridical image, such as the precise color hue, shape, and size). Together, the phenomenological reports combined with the behavioral and neuroimaging evidence, highlight the need to move beyond a simple vividness continuum toward a multidimensional framework that captures the complexity of internal experiences.

So, what do imagery experiences truly entail? While neuroimaging has revealed overlapping activations between imagery and perception (e.g., Dijkstra et al., 2019), the rich, individualized features of the imagination remain private, and its fidelity varies across sensory, motor, and spatial modalities. Can we glimpse these features? Possibly, by systematically decomposing mental imagery into its constituent components.

The Ganzflicker paradigm—a rhythmic alternation of colors on a computer screen that induces visual hallucinations (Reeder, 2022)—provides a unique window into imagery. Hallucinatory experiences in the Ganzflicker span a range in complexity, from simple to complex visual phenomena, and may reveal important distinctions in mechanisms underlying visual imagery. Simple hallucinations, characterized by geometric patterns, colors, and basic visual features, may reflect neuroanatomical properties of the visual system such as the structure of neural columns or ocular veins, and may emerge from bottom-up visual processing. The origin of complex hallucinations featuring recognizable objects, faces, and scenes is more difficult to understand as they lack clear retinotopic structure. Recent work suggests they likely involve top-down processes that integrate basic visual features into coherent percepts, potentially sharing mechanisms with voluntary mental imagery (Shenyan et al., 2024).

Königsmark and colleagues (2021) found that individuals with more vivid visual imagery were indeed more susceptible to induced hallucinations, and reported more intense and complex hallucinatory experiences compared to those with weak imagery. These findings were later replicated and expanded by Reeder (2022) in a large sample of 6,664 participants. While these studies primarily analyzed structured, close-ended responses to Likert-type questions, they also collected narrative descriptions of participants' hallucinatory experiences. Systematic analysis of these descriptions may reveal which specific visual processes are preserved or altered across imagery profiles.

Here, we analyzed Reeder's (2022) extensive dataset of participants' descriptions to characterize the multifaceted qualities of visual experience that differentiate imagery profiles. By "multifaceted qualities," we refer to the various perceptual, visual, and action-related elements that go beyond a simplistic *vividness* characterization of hallucinations. Our approach includes linguistic analysis using Lancaster Sensorimotor (LS) Norms (Lynott et al., 2019) to quantify perceptual and motor content, complemented by visualizations from *DALL·E 3* (Betker et al., 2023) to reconstruct participants' verbal hallucination descriptions. This combination of quantitative linguistic analysis and AI-based visualization allows us to examine aspects of hallucinatory experience—such as specific visual features, references to body parts, and qualitative content patterns—that might be present or absent across different imagery profiles. Through this multi-method approach, we hope to develop a more nuanced characterization of mental imagery differences beyond vividness.

Methods

To get a comprehensive picture of the qualitative differences in the imagination of individuals across the mental imagery spectrum, we conducted three complementary analyses of participants' Ganzflicker descriptions: (1) Sensory content analysis: We used three dimensions from the LS Norms—perceptual strength, visual strength, and interoceptive strength—to quantify the descriptions' perceptual and visual richness, while also examining abstract concepts mentioned in the descriptions; (2) Motor content analysis: We used action dimensions from the LS Norms to examine references to specific body parts and actions. While these references could potentially indicate embodied representations during hallucinations, they may more directly reflect participants' descriptions of animate figures and their physical characteristics; (3) Exploratory reconstruction of hallucinations: We used *DALL·E 3* to generate visualizations of participants' descriptions to glimpse potential differences in content and features of hallucinations that might not be captured by the linguistic analyses alone. This exploratory approach allowed us to examine and experience systematic differences in what individuals with varying imagery vividness "saw" during their Ganzflicker experiences.

Participants

A total of 6,664 individuals from around the world participated in the original Ganzflicker study by Reeder (2022). The study involved viewing the Ganzflicker stimulus, providing written descriptions of induced hallucinations, and providing a self-assessment of mental imagery vividness. After excluding participants whose descriptions were either missing or not written in English, the final sample consisted of 4,365 participants. All participants gave informed consent. Complete participant demographics are reported in Reeder (2022).

"I saw purple dots that were circling around like stars in a galaxy, also with spiral arms etc. They were going quite fast, I wanted them to slow down (to imitate a galaxy) but they didn't. Then in the next few seconds the purple dots would form other shapes like waves or pillars that were turning as well."

"There was this bird, almost like a Native American symbol, rising up from the SE corner that was blue and gold, looking down on a man in armor with his back to me holding a sword. Another was a space station—futuristic and circular, with ships flying in and out like a port, then eventually meteors crashing into it. I also kept seeing various images of knights and soldiers—war and fighting."

Figure 1. Two example hallucination descriptions and *DALL·E* visualizations. The top one emphasizes abstract shapes, colors, and movement, while the bottom describes a complex scene with recognizable objects.

Materials & Procedure

Detailed information about the materials and procedure can be found in Königsmark et al. (2021). To summarize, participants viewed the Ganzflicker stimulus, a full-screen, 7.5 Hz flicker alternating continuously between red and black for approximately 10 minutes. Before beginning, participants were informed about potential risks, including photosensitivity, and were advised not to proceed if they had a history of epilepsy. The questionnaire, including the link to the Ganzflicker and white noise audio file can be found at: https://forms.gle/tdKRKhva3uqC68tS9.

Following the Ganzflicker session, participants completed a questionnaire. After providing optional demographic information and a mental imagery vividness rating, they reported details about their experience, including exposure duration, adherence to recommended environmental conditions (e.g., lights off), and their emotional response to the stimulus. Participants then characterized their induced hallucinations by selecting from options such as "Colors other than red and black," "Simple shapes or patterns," "Complex objects (e.g., animals, faces, buildings)," and "Complex environments (e.g., cityscapes, landscapes)." They also reported the onset, frequency, and perceived vividness of these experiences. Finally, participants were instructed to provide detailed free-text descriptions of their hallucinations, which constituted the primary data for our analysis, though we acknowledge that such post-exposure reports naturally involve some degree of memory-based reconstruction. Figure 1 shows some example responses, along with their corresponding *DALL·E* visualizations.

Analysis

Individual Differences Participants rated their visual imagery vividness on a single Likert scale question: *"How would you describe your VISUAL imagery vividness on a scale from 0 (no mental imagery) - 10 (as vivid as real perception)?"* This concise assessment was chosen for efficiency and, as discussed in Reeder (2022), correlates strongly with established imagery instruments (Andrade et al., 2014; Marks, 1973), suggesting consistency in self-reported imagery across different scales. The participant pool stands out due to its large size and the notably high proportion of individuals with extreme imagery profiles (Figure 2, right).

Hallucination Descriptions We preprocessed descriptions using standard Natural Language Processing (NLP) techniques. This involved typo correction, text case standardization, punctuation removal, and word tokenization and lemmatization to prepare the narratives for further analysis. To characterize the features and content of participants' hallucinations we employed the LS Norms (Lynott et al., 2019), extending prior analytical approaches from Chkhaidze et al. (2023). The LS Norms provide ratings for 40,000 English words on 11 dimensions: six perceptual (visual, auditory, gustatory, olfactory, haptic, and interoceptive) and five motor/action dimensions (foot, hand, head, mouth, and torso). For each word, human raters indicated how much they experience that concept through each sensory modality or through actions involving each body part.

We used these norms to quantify hallucination descriptions across multiple dimensions: Their perceptual and visual richness, and references to abstract concepts, and motor-related content. Perceptual richness of each hallucination description was assessed using the *maximum perceptual strength* (hereafter referred to as perceptual strength) measure from the LS database. This composite measure is thought to index concept concreteness (Connell et al., 2018). It identifies the dominant sensory modality for each word (e.g., "bright" scores highest on visual, while "loud" scores highest on auditory) and provides its strength rating. For each description, we calculated the average perceptual strength across all words to quantify its overall perceptual richness. To specifically quantify visual richness of the hallucinations, we analyzed the *visual strength* ratings of words and calculated overall visual richness of each description. This measure indicates how much each word relates to visual experience, allowing us to assess the degree of visual detail in participants' descriptions. As an additional dimension, we examined *interoceptive strength* ratings, which have been found to correlate with certain abstract concepts and show negative relationships with word concreteness and visual strength (Connell et al., 2018), potentially providing a complementary perspective to our perceptual and visual measures. To examine the motor/action-related content mentioned in the hallucination descriptions, we used the five motor dimensions of LS Norms. These ratings indicate how much each word relates to different body parts. Figure 2 (left) shows the pipeline for description analysis using LS Norms.

We conducted three sets of analysis using generalized linear models (GLMs) with the *glm* function in the *stats* package in *R*, with visual imagery vividness ratings as the dependent variable in each model. The first model used

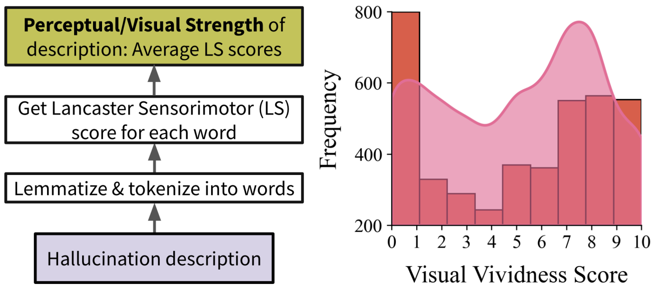

Figure 2. The left panel outlines the text analysis pipeline for quantifying hallucination descriptions with LS Norms. The right panel shows the distribution of visual imagery vividness ratings, highlighting the prevalence of vivid imagers and those with no imagery.

perceptual strength as a predictor. The second model included sensory dimensions from the LS Norms as predictors, but in this paper we focus specifically on visual and interoceptive strengths to quantify and contrast the visual and abstract information in hallucinations. The third motor model included all five motor dimensions to analyze body-part related content. All the predictors were z-scored.

Hallucination description length was a significant positive predictor of vividness ratings (B = .01, SE = .00, t = 6.80, p < .001), indicating that participants with more vivid imagery provided longer descriptions. We therefore conducted mediation analyses for all models to account for description length, and all reported results are adjusted for these mediation effects.

Exploratory *DALL·E* Visualization While the LS Norms analysis provides valuable insights into the perceptual and motor content of hallucination descriptions, linguistic analysis alone may not fully capture the visual structure or object-level details described by participants. To complement our quantitative analyses, we used the vision language model *DALL·E 3* as an exploratory visualization tool to illustrate potential qualitative differences between imagery groups' descriptions.

From 4,365 participants, we randomly sampled descriptions from 100 participants who reported no visual imagery (imagery rating = 0) and 100 imagers (imagery ratings > 4; for details regarding this cut-off score, see Reeder (2022)). To generate a representative visualization for each imagery group, we combined the individual descriptions of these 100 participants into a single composite description and used it as input for *DALL·E 3*. We repeated this process iteratively, resampling a new set of 100 participants (without replacement) from each imagery group, combining their descriptions into a new composite, and generating a new image using *DALL·E 3*. This process continued until the participant pool was exhausted. This approach ensured that the generated images captured a broad and representative range of hallucination descriptions across participants rather than being overly influenced by any single individual's response. Additionally, the random selection ensured an unbiased sampling of descriptions, preventing us from unintentionally overrepresenting certain types of hallucination content based on our own expectations or biases about how imagery groups should differ.

We acknowledge important limitations of this approach. First, image-generating AI models are trained on photographs and artwork created by humans, not on the contents of visual mental imagery or hallucinations, which differ in structure and detail from our internal experiences. Second, generative AI models might produce detailed visual outputs even from minimal textual inputs. To mitigate this, we used specific prompt engineering: *"Create an image based on this description. Represent as many objects and attributes mentioned as possible. Don't include things that are not mentioned in the description."* While this constraint cannot guarantee that *DALL·E* perfectly represents only what was in participants' descriptions, it helps minimize the addition of content not present in the original text.

These visualizations should be interpreted as illustrative tools that help conceptualize patterns in our linguistic data rather than as direct evidence of participants' hallucinatory experiences.

Results

Analysis of Ganzflicker hallucination descriptions revealed two key findings. First, individuals who reported more vivid visual imagery provided descriptions containing richer perceptual and visual details. Second, the content of these descriptions varied systematically with imagery vividness—more vivid imagers reported more real-like visual elements, particularly faces and hands. Exploratory *DALL·E* visualizations illustrated these patterns, with geometric shapes dominating weak imagers' descriptions and complex real-world objects characterizing vivid imagers' descriptions.

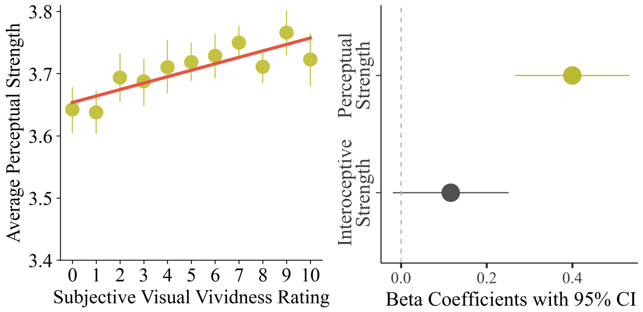

Figure 3. More vivid visual imagery is associated with perceptually and visually richer hallucination descriptions. Interoceptive strength does not predict visual imagery ratings.

Visual Imagery Vividness Predicts Perceptual Richness of Hallucinations

We first examined the relationship between self-reported visual imagery vividness and the perceptual strength of participants' textual descriptions, as reflected in LS Norms. Perceptual strength reliably predicted imagery vividness—stronger descriptions were associated with higher visual imagery scores ($B = .42$, $SE = .05$, $t(4055) = 8.34$, $p < .001$). Similarly, the visual strength of descriptions positively predicted imagery vividness ($B = .40$, $SE = .07$, $t(4055) = 5.86$, $p < .001$), suggesting that more vivid imagers' hallucinations had more visual details than those of weaker imagers. In contrast, interoceptive strength did not show a significant relationship to vividness ($B = .12$, $SE = 0.07$, $t(4050) = 1.68$, $p = .10$), suggesting that there was no difference in references to abstract concepts in hallucination descriptions across the imagery spectrum (Figure 3).

Motor Content of Hallucinations Varies with Visual Imagery Vividness

Analysis of motor dimensions from the LS Norms revealed distinct patterns across imagery profiles. Among the motor dimensions, head-related ($B = 0.25$, $SE = 0.05$, $t(4050) = 4.73$, $p < .001$) and hand-related ($B = 0.37$, SE = 0.07, $t(4050) = 5.58$, $p < .001$) content were both reliable positive predictors of imagery vividness, suggesting that vivid imagers' hallucinations feature hand and face-related elements more than those of weak imagers. The remaining motor dimensions did not significantly predict vividness ($p = .16$, $p = .09$, and $p = .76$, for mouth, foot, and torso, respectively) (Figure 4).

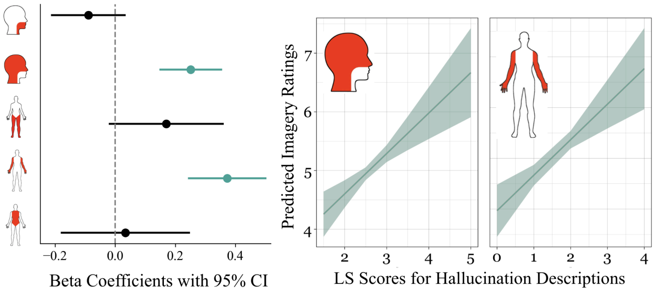

Figure 4. Hallucination descriptions vary with imagery vividness. The top panel shows beta coefficients predicting imagery ratings from motor norms, with head- and hand-related language as significant positive predictors (green). The right panel illustrates their partial effects on imagery ratings.

Visualizing Hallucinations with *DALL·E*

DALL·E-generated visualizations provided an illustrative representation of the patterns identified in our linguistic analyses. Descriptions from participants reporting no imagery produced images dominated by simple geometric patterns like circles, spirals, and checkerboards; while descriptions from imagers generated images containing recognizable real-world objects, including faces, landscapes, and buildings (Figure 5). These visualizations serve as a complementary illustrative tool that helps conceptualize the qualitative differences identified in our quantitative analyses.

Discussion

Our analysis of induced hallucination content revealed a systematic relationship between visual imagery vividness and the complexity and content of hallucinations experienced during Ganzflicker viewing. Using the Lancaster Sensorimotor Norms, we found that more vivid subjective visual imagery predicted increased overall perceptual richness of hallucination descriptions. We found a relationship specifically between the *visual* strength of the descriptions and visual imagery ratings, suggesting more visually descriptive hallucinations in strong compared to weak imagers. While previous Ganzflicker studies established that imagery vividness correlates with hallucination complexity, our study extends these findings to specific content differences.

Analysis of motor content of hallucinations revealed that vivid imagers' descriptions contained significantly more head- and hand- related content than weak imagers' descriptions. The prevalence of head-related content in hallucinations may reflect the special evolutionary significance of faces for humans. As a highly social species, humans have evolved specialized neural machinery for face perception (Kanwisher et al., 1997), reflecting the importance of face recognition for survival and social interaction throughout our evolutionary history (Lacruz et al., 2019). Similarly, the increased hand-related content in vivid imagers' hallucinations aligns with research showing that hands, like faces, constitute a unique category in visual processing with a dedicated neural circuitry (Bracci et al., 2010), signaling important social intentions regarding action and communication (Bracci et al., 2018).

We also examined the interoceptive strength of descriptions. While interoception ratings correlate with certain aspects of concept abstractness (Connell et al., 2018), we found no significant relationship between these scores and imagery vividness. Several factors may explain this null finding. First, while interoceptive scores correlate with word abstractness generally, they primarily capture interoception-specific terms relating to emotions and bodily sensations, which may not vary with imagery ability. Many abstract concepts (such as "justice" or "philosophy") may have minimal interoceptive content, while some concrete experiences (like physical pain) have high interoceptive ratings. Additionally, our data suggest that despite differences in overall perceptual richness, weak imagers still provided concrete, visually-detailed descriptions of their experiences (e.g., geometric patterns like spirals and checkerboards). Primary distinction between groups might lie not in the concreteness or abstractness of their experiences, but rather in how realistic and visually complex the hallucinated visual content is.

Our exploratory *DALL·E* visualizations illustrate the qualitative differences between those with no self-reported imagery and imagers' hallucinatory experiences. While both groups produced descriptions that led to colorful visualizations, non-imagers' descriptions generated images dominated by geometric patterns, spirals, and abstract forms, while more vivid imagers' descriptions produced scenes populated with recognizable real-world objects, faces, buildings, and landscapes. Importantly, these findings suggest that individuals with no imagery are not simply "staring into an empty void" during Ganzflicker exposure—they do experience visual phenomena, but these experiences appear to be visually less complex than those of strong imagers.

Our results suggest that individual variations in imagery may be more nuanced than a simple vividness continuum can capture. They align with recent neuroimaging evidence challenging earlier views that aphantasia reflects an absence of sensory representations in early visual cortex (EVC; Keogh & Pearson, 2018). Instead the differences may lie in the degree of contribution from visual areas in the ventral stream, particularly the fusiform gyrus, as suggested by imagers' complex, object-level hallucinations.

Recent work has shown, surprisingly, that imagery content can be decoded from EVC activity in people with aphantasia, despite their reports of no conscious experience of mental imagery (Chang et al., 2024). During passive listening tasks, aphantasic individuals showed decodable V1 representations of evocative sounds heard in the listening task with accuracy similar to controls (Cabbai et al., 2024). This finding that V1 imagery representations can exist without conscious imagery experience aligns with our observation that aphantasics can experience structured visual phenomena during Ganzflicker exposure, perhaps reflecting automatic visual processes that are unrelated to mental imagery. The fact that their hallucinations contain basic geometric patterns and low-level visual features such as colors is consistent with intact early visual cortex representation.

Importantly, while both aphantasics and imagers show EVC engagement during visual imagery, they appear to differ in how these representations are processed at higher levels (Dijkstra, 2024). For instance, in one study a key differences between imagery groups emerged in the precuneus region of the parietal cortex—while imagery content could be decoded from precuneus in imagers, no such decodable patterns were found in aphantasics (Cabbai et al., 2024). Additionally, functional connectivity between visual regions and other brain areas has been shown to differ along the visual imagery spectrum, with one study finding reduced connectivity between superior temporal gyrus (STG) and occipital regions in aphantasia (Chang et al., 2024), while another demonstrating stronger connectivity between prefrontal and occipital brain regions in hyperphantasic individuals (Milton et al., 2021).

Figure 5. *DALL·E* visualizations illustrate distinct patterns in hallucination descriptions across imagery groups. The imagers' visualizations feature complex, object-based scenes with faces, landscapes, and buildings, while the no imagery group is dominated by geometric patterns.

Together, these findings suggest that the neural basis of imagery differences may lie not in early visual processing regions, but in a network of distributed brain regions involved in executive function, attention, visual feature integration, and object and scene representation (Liu et al, 2023; Spagna et al, 2024). This could explain the previously puzzling findings of aphantasics achieving normal performance on tasks thought to rely on V1 representations, such as mental rotation (Dean & Morris, 2003; Zeman et al., 2010), visual working memory for orientations (Reeder et al, 2024; Weber et al., 2024), and attentional templates for colors (Cabbai et al., 2023).

Future research using Ganzflicker descriptions could also leverage deep learning techniques, such as convolutional neural networks (CNNs), to systematically characterize the multidimensional features of induced hallucinations. By analyzing the hierarchical representations of hallucinations, we could identify at which level differences between imagery groups emerge. As early CNN layers primarily capture low-level features like edges and colors, while later layers encode more complex patterns and objects (Zeiler & Fergus, 2014), this approach could reveal whether imagery differences stem from low-level featural representations or only emerge at a higher-order conceptual level. Based on our current findings, we predict the latter. Moving beyond the limited notion of vividness toward a comprehensive characterization of the nature of mental imagery, we hope, will get us closer to capturing the functional consequences of diversity in the content of thoughts.

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All code and materials available at:
`https://github.com/anachkhaidze/hallucinations_cogsci2025`

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