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Exploratory Report

The Ganzflicker experience: High probability of seeing vivid and complex pseudo-hallucinations with imagery but not aphantasia

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ABSTRACT

There are considerable individual differences in visual mental imagery ability across the general population, including a "blind mind's eye", or aphantasia. Recent studies have shown that imagery is linked to differences in perception in the healthy population, and clinical work has found a connection between imagery and hallucinatory experiences in neurological disorders. However, whether imagery ability is associated with anomalous perception—including hallucinations—in the general population remains unclear. In the current study, we explored the relationship between imagery ability and the anomalous perception of pseudo-hallucinations (PH) using rhythmic flicker stimulation ("Ganz-flicker"). Specifically, we investigated whether the ability to generate voluntary imagery is associated with susceptibility to flicker-induced PH. We additionally explored individual differences in observed features of PH. We recruited a sample of people with aphantasia (aphants) and imagery (imagers) to view a constant red-and-black flicker for approximately 10 min. We found that imagers were more susceptible to PH, and saw more complex and vivid PH, compared to aphants. This study provides the first evidence that the ability to generate visual imagery increases the likelihood of experiencing complex and vivid anomalous percepts.

Visual mental imagery is the ability to mentally simulate visual sensory information. There are individual differences in reported visual mental imagery vividness (i.e., the richness or intensity of images seen with the "mind's eye"), including the complete lack of voluntary visual imagery (*aphantasia*; Keogh & Pearson, 2018; Zeman et al., 2015). Over the past six years—since Zeman and colleagues' 2015 paper on the topic gained popular media attention—there has been a surge in

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research into aphantasia, particularly concerning the advantages and disadvantages associated with having a blind mind's eye. Currently, the disadvantages garner far more attention: aphantasia often presents itself with severely deficient autobiographical memory, deficits in human face recognition (prosopagnosia), and difficulties with atemporal and future imagination (e.g., *imagine yourself on a tropical beach*; Milton et al., 2020). Nevertheless, its advantages offer an intriguing side to what is commonly thought of as a deficiency.

People with aphantasia (*aphants*) generally have intact visuospatial skills when compared to people with typical imagery abilities (*imagers*; Dawes et al., 2020), and report the use of efficient alternative cognitive strategies for tasks that are commonly thought to require visual imagery (such as precise visual working memory; Pearson & Keogh, 2019). Very recent research further suggests that aphants are less negatively affected by written descriptions of disturbing content (Wicken et al., 2021). A less explored avenue of research is the interaction between imagery and perception, particularly anomalous perception. A previous study from our lab found evidence that more vivid imagery is associated with a higher susceptibility to pareidolia (i.e., illusory faces in visual noise; Salge et al., 2020) and there is some evidence that imagery vividness is also positively linked to hallucination proneness in the normal population (Aynsworth et al., 2017).

Hallucinations are an often disturbing and debilitating symptom of diverse neurological disorders such as Parkinson's Disease (Shine et al., 2015), age-related macular degeneration (with hallucinatory experience specifically referred to as *Charles Bonnet Syndrome*; Schadlu et al., 2009), and schizophrenia (Bauer et al., 2011). Clinical evidence suggests that stronger imagery is linked to a higher susceptibility to hallucinations. For example, mental imagery is enhanced in schizophrenic patients (Benson & Park, 2013; Matthews et al., 2014; Sack et al., 2005). Furthermore, Parkinson's patients who experienced visual hallucinations were found to have elevated mental imagery compared to Parkinson patients (and controls) who did not experience visual hallucinations (Shine et al., 2015). Interestingly, visual imagery ability is also associated with intrusive memories (Morina et al., 2013) and flashbacks in patients with post-traumatic stress disorder (Bryant & Harvey, 1996). These findings suggest that mental imagery and anomalous perceptual experience (such as hallucinations) may be influenced by the same or overlapping neural mechanisms; however, whether such a relationship is also present in the general population has not yet been investigated.

Real hallucinations are unpredictable and difficult to investigate, but there are a few ways of inducing anomalous percepts and altered states of consciousness that mimic the effects of real hallucinatory phenomena in a controlled environment (Becker & Elliott, 2006; Bressloff et al, 2001, 2002; Pearson et al., 2016; Schwartzman et al., 2019). We will refer to these experiences as pseudo-hallucinations (PH), which have at least two characteristics distinct from real hallucinations: they can be induced or alleviated in a controlled way, and they are not coupled with pathology or a change in cognitive function; thus, observers remain aware that the experiences are not real. PH can be induced after several hours of sensory deprivation (e.g., blindfolding; Merabet et al., 2004), or several minutes of perceptual deprivation (e.g., filling the visual field with unstructured, uniform luminance called "Ganzfeld"; Schmidt & Prein, 2019; Zdravkovic, 2019). An under-explored method of inducing often intense and immediate PH (within seconds) is the use of rhythmic visual flicker (Allefeld et al., 2011; Gulbinaite et al., 2017; Sumich et al., 2018). Its easy implementation and immediate, robust effects make it a promising technique to investigate anomalous perception in an experimental setting.

For the current paper, we recruited individuals with different imagery abilities (aphantasia, imagery) to investigate whether and how visual imagery is associated with anomalous experiences during display-wide visual flicker (termed "Ganzflicker",[1] to distinguish the flickering paradigm from classic uniform Ganzfeld; Schmidt & Prein, 2019). We conducted the current study to explore whether inherent and stable individual variations in visual imagery abilities are related to susceptibility to pseudo-hallucinations and different features of pseudo-hallucinations (vividness, complexity, emergence time, duration, and frequency).

1. Methods

No part of the study procedures or analysis plans was preregistered prior to the research being undertaken. We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

1.1. *Participants*

The Ganzflicker is continually attracting participants, and as such, we have a constantly developing sample (see the study website at https://forms.gle/5yATop8syhsKibsd9 for the most up-to-date summary of responses). The sample analyzed for the current paper is composed of 179 Internet volunteers (which was the total number of participants as of the latest analysis of the data on 27/11/2020) and 28 Psychology students.

1.1.1. *Internet volunteers*

Participants were 178 (one did not report an imagery vividness rating) anonymous individuals recruited from *Reddit*, a social discussion forum made up of topic-specific sub-forums called "subreddits". The "Ganzflicker Experience" was posted to the subreddit *r/aphantasia* on 27/08/2019, titled "Would you like to experience Ganzfeld Imagery? Experiment" (Reeder R.). We chose to post to *r/aphantasia* because this subreddit attracts a large number of people with different imagery abilities (mainly aphantasia, but also individuals with imagery), with over 20,300 subscribers. Our internet-based data collection methods were approved by the ethics committee of Otto-von-Guericke University and adhered to the tenets of the Declaration of Helsinki.

[1] Furthermore, we needed to give "flickering ganzfeld" an interesting and memorable name, particularly when advertising the study with members of the general population.

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Our experiment was approved by a moderator prior to posting it to the subreddit, and participants were informed before taking part that their participation in the experiment was entirely voluntary and there was no obligation to take part. They were informed that by responding to the questionnaire, they consented to the public availability of their data, and that all materials are freely available to use as desired (for the exact wording and full experiment description given to participants, please see the supplementary materials on OSF). Having read this information, participants clicked a link that took them to a webpage that contained specific experiment instructions and background information, a link to the Ganzflicker experience, and a link to an optional questionnaire. The questionnaire did not collect names, locations, e-mail addresses, or any other self-identifying information. Participants optionally provided their age ($N = 172$) and gender ($N = 176$; see Table 2).

1.1.2. *Psychology students*

Because our Internet volunteers overwhelmingly reported having aphantasia (recruited via *r/aphantasia*; see Table 2), we additionally collected data from 28 students of the Institute of Psychology at Otto-von-Guericke University (OVGU), who were naive to the concept of aphantasia and were not recruited based on their visual imagery abilities. We therefore sought to add to our imagery distribution, but we did not exclude individuals who ultimately reported having aphantasia. We stopped collecting data at the end of the academic summer semester (30/09/2020).

All students participated in the Ganzflicker experience online for course credit. Participants were recruited from an e-mail list obtained by the senior author after advertising the experiment in a course. Further participants were recruited by posting an advertisement on an online course page through the university. All participants reported their age and gender (see Table 2). Participants provided digital informed consent by signing their name to a standard consent form prior to filling out the questionnaire. This method was approved by the ethics committee of OVGU and adhered to the tenets of the Declaration of Helsinki. There were no student data exclusions.

1.2. *Environment*

The experiment was conducted online (note that all participants performed the experiment online due to university closures during the COVID-19 pandemic), and therefore participants could participate on any device with internet connection, in any environment. Nevertheless, participants were asked to view the Ganzflicker on a computer (rather than on a mobile phone), in a dark room, and while listening to white noise with headphones. These measures could not be strictly controlled, but we asked participants to report whether they followed these instructions (see Table 2 for a breakdown of responses).

1.3. *Stimuli*

The Ganzflicker experience is a full-screen visual flicker at 7.5 Hertz (Hz) frequency, alternating at 15 Hz between full-red and full-black, and embedded in an infinite while loop. Red flicker at various frequencies has previously been used to investigate both simple and complex anomalous experiences (Sumich et al., 2018), and was earlier found to produce larger differences in photic driving effects between visualizers and non-visualizers compared to green or blue flicker (Brown, 1966). We therefore used red flicker so that we could investigate anomalous percepts in the current study, and potentially use the same Ganzflicker protocol in a future study to investigate photic driving effects on the brain. The program was coded in html and uploaded to a Ganzflicker-dedicated github page (*Ganzflicker*, n.d.).

All participants viewed the Ganzflicker on the senior author's webpage (screenshots of the historical webpage as it was seen by volunteers can be found in the supplementary materials; the current webpage can be found at the following reference: *Online Experiments* (*Reshanne Reeder UK*, n.d.). This page contains background information in both English and German, a warning that individuals with photo-sensitivities should not participate, a link to the Ganzflicker github page, two.mp3 files of pure white noise to choose from (10 min or 50 min), and links to an English (*Ganzflicker Questionnaire*, n.d.) or German (*Fragebogen Zu Ganzflicker*, n.d.) version of the post-Ganzflicker questionnaire. The questionnaires were written by the first and senior author.

1.4. *Procedure*

Once participants clicked the link to the experiment webpage, they were asked to start the white noise, then click the link to the Ganzflicker github page. Internet volunteers were recommended to view the Ganzflicker for about 10 min, but they ultimately could view it for as long as they wished, or terminate the stimulation early if they were bothered by it. Participants were told to click the appropriate duration of white noise (10 min or 50 min) to help time their experience (the Ganzflicker occurs infinitely, so the white noise could be used as an experiment timer). Psychology students were first instructed to only listen to 10 min of white noise while viewing the Ganzflicker, before filling out the questionnaire. Students were then allowed to view the Ganzflicker for a longer time (up to 50 min) and fill out the questionnaire a second time to receive additional course credit. Students could receive course credit for a maximum of 10 + 50 min of Ganzflicker, but were otherwise free to view it for as long as they wished after the first session. All participants were instructed to fill out the questionnaire immediately following the Ganzflicker experience.

For Internet volunteers, the questionnaire began by collecting demographic information, and visual and auditory imagery vividness ratings on a scale from 0 to 10 (0 = complete lack of imagery, 10 = as vivid as real perception). These ratings were used in place of the Vividness of Visual Imagery Questionnaire (VVIQ) to cut down on experiment time for non-reimbursed volunteers. Participants were then required to indicate how long they viewed the Ganzflicker, whether they had listened to white noise, and whether they had been in a darkened room. Finally, they were asked to rate the pleasantness of the experience. For Psychology students, the questionnaire began with a consent form. After agreeing to participate, they were required to write their full name and

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university-provided e-mail address before continuing to the same introductory questions as those of Internet volunteers.

Following these questions, all participants were asked about their visual, auditory, and state experiences during the Ganzflicker. Participants could choose from pre-written statements describing different experiences (see Table 1, below), or "Other"; if "Other" was chosen, participants could write in their own descriptions about their experiences. If participants indicated that they saw something other than the red-black flickering, they were asked to rate and describe five features of PH (complexity, vividness, emergence time, duration, frequency). They were then provided a space to describe their visual experience in as much detail as possible. If participants indicated that they heard something other than white noise during the experience, they were asked to rate and describe four features of auditory illusions (duration, frequency, vividness, complexity), and then describe their auditory experience in as much detail as possible. For the sake of brevity, and because auditory experiences were not the focus of this study, we do not report the auditory results in the current paper (although the data are provided on the Open Science Framework; OSF at the following link: https://osf.io/6dvh9/). To simplify analyses, detailed descriptions of visual experiences, as well as "Other" responses (always made in addition to checkbox responses), were not coded for the current study. All other responses were coded as detailed in Table 1.

For Internet volunteers, this was the end of the questionnaire. For Psychology students, participants additionally provided ratings on two extra measures of visual and auditory imagery vividness and form, which were created by the authors for this experiment. Finally, Psychology students completed an online version of the Creative Experiences Questionnaire (Merckelbach et al., 2001), which measures fantasy proneness. These additional measures are also not reported in the current paper, but the data can be found on OSF.

After the questionnaire, Internet volunteers had the option of sharing their experiences in the comments of the experiment page posted to *r/aphantasia*. Psychology students were required to e-mail the senior author to confirm participation in one or two sessions of the experiment. Students were awarded participation credit when the university re-opened.

2. Analyses and results

Although a second Ganzflicker session was optional for Psychology students, all analyses reported in the paper were performed on data from only a single (first) session for each participant. All analyses were performed in JASP or Python. JASP outputs and Python scripts are available on OSF (https://osf.io/6dvh9/).

2.1. *Coding subjective responses*

Reports on the different features of PH were collected as responses on a post-experience questionnaire. Although there was no real-time response collection in this study, previous data from our lab (also available on OSF: https://osf.io/6gewm/)

Table 1 – Response codes for PH features (complexity, vividness, emergence time, duration, frequency). Each individual participant was allowed to indicate various levels of PH features in their responses. We therefore took the maximum value for each participant so that our ratings would reflect the highest level of the different features (e.g., the highest frequency, the longest duration) of illusions experienced at some point during the Ganzflicker.

Rating (max)	Complexity	Vividness	Emergence time	Frequency	Duration
1	Colors other than red and black	Weak, faint, or insubstantial	5–7 min	1-2 times in the whole experiment	Brief moment or flash
2	Simple shapes or patterns (e.g., ball of light, lines, grids, spiderwebs, geometric shapes)	Clear, but not vivid	1–2 min	Infrequently	1–2 sec
3	[coded if the participant saw both illusory colors and shapes]	Clear and moderately vivid	A few seconds	Frequently	Persisting several seconds
4	Complex objects (e.g., animals, faces, buildings)	Vivid, clear, or bright	They began to emerge immediately	Constantly	Constant, morphing from one image to the next
5	Complex environments (e.g., cityscapes, forests)	Very vivid, almost real	Other	Other	Other
6	[coded if the participant saw both illusory complex objects and environments]				

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Table 2 – A breakdown of the differences between Internet volunteers and Psychology students in terms of group membership, environment, age, and total experiment time. Internet volunteers contributed a higher number of aphants to our sample, and were less likely to listen to white noise during Ganzflicker viewing, compared to Psychology students.

Factor	Internet volunteers (N = 178)	Psychology students (N = 28)	Total	BF_{10}
Imagery ability:				
Aphantasia	140	3	143	
Imagery	38	25	63	Contingency tables test[c]: 5.674e+9
Environmental factors:				
WN-Y[a]	129	27	156	
WN-N[a]	49	1	50	Contingency tables test: 11.043
D-Y[a]	144	21	165	
D-N[a]	33	7	40	Contingency tables test: .216
Age:	Mean = 27.180, SD = 11.416	Mean = 21.607, SD = 3.143		Mann–Whitney *U* test[d]: .297
Total experiment time[b]:				
<10min.[a]	89	3	92	
~10min.[a]	69	24	93	Contingency tables test: 3176.775

[a] WN-Y = listened to white noise; WN-N = did not listen to white noise; D-Y = observed Ganzflicker in a darkened room; D-N = did not observe Ganzflicker in a darkened room; <10min. = participants reported viewing the Ganzflicker for less than 10 min; ~10min. = participants reported viewing the Ganzflicker for approximately 10 min.

[b] All but 4 participants reported viewing the Ganzflicker for 10 min or less, so we removed those 4 so we could perform 2 × 2 contingency tables tests. The results of those 4 are reported in Footnote 2.

[c] Bayesian contingency tables tests (prior concentration = 1 (default), 1000 seeds for repeatability) were performed in the JASP statistical toolbox (JASP Team, 2018) on the count data presented in the table.

[d] Bayesian independent-samples Mann–Whitney *U* tests (Cauchy scale = .707 (default), 5 chains of 1000 iterations, 1000 seeds for repeatability) were also performed in JASP.

suggests a high correlation between real-time illusory stimulus detection and post–experiment stimulus frequency estimations ($N = 79$, $\tau_B = .502$, $BF_{10} = 2.197e+8$), despite post–experiment responses being limited to 5 discrete choices (About how many faces did you see in a block?: "0–2", "5–10", "15–20", "50–100", and "Other"). Although post–experiment responses cannot replace the precision of real-time responses, we were only able to collect our unique sample at the current time by providing the experiment in an easily accessible format for online use. With that in mind, response codings for the different features of PH (complexity, vividness, emergence time, duration, frequency) are reported in Table 1.

2.2. *Group splits*

We obtained a high number of pure aphants (visual imagery vividness rating of 0; $N = 85$), plus a distribution of low-imagery (hypophantasia) scores skewed toward 0, and a statistically normal distribution of moderate-to-high imagery scores, forming a bimodal distribution (see Fig. 1). We decided to group aphants and hypophants into the same distribution, to remain consistent with previous studies that consider vague or dim imagery as part of the aphantasia spectrum (Dance et al., 2021; Zeman et al., 2015).

A visual inspection of the distribution puts the likely boundary between aphants and imagers between imagery vividness ratings of either 3 and 4 or 4 and 5. We calculated the Bayes decision boundary between the two distributions, either including ratings of 4 in the aphantasia or imagery distribution, in two separate tests (using code developed by VanderPlas, 2016). In both cases, the boundary was calculated between a rating of 3 and 4 (see Fig. 1); furthermore, including ratings of 4 in the aphantasia distribution led to high kurtosis (indicating a poor peak-to-tail ratio; see Fig. 1b). Therefore, we performed all subsequent analyses on an aphantasia distribution of ratings from 0 to 3 ($N = 143$) and an imagery distribution of ratings from 4 to 10 ($N = 63$). These numbers also contributed to our analyses presented in Tables 2 and 3.

We performed two tests on each distribution in Fig. 1a to determine its skew (s) and kurtosis (k) using scipy.stats in Python. This confirmed a high amount of right skew ($s = 4.403$) within the aphantasia distribution; the kurtosis test revealed an acceptable peak-to-tail ratio ($k = 1.652$), as if the data formed one half of a normal curve (the other half being impossible due to no negative vividness ratings). In contrast, the imagery distribution showed no large amount of skew ($s = -.828$) or kurtosis ($k = -.372$).

Rating visual imagery vividness on a single 0–10 scale requires very little metacognition compared to rating oneself on the VVIQ, which asks participants to imagine various visual scenarios prior to rating vividness (Marks, 1973). We did not provide the VVIQ immediately prior to Ganzflicker viewing because we did not want participants to have specific images in mind, in case it biased what they saw in the Ganzflicker (which occurred during a pilot session). We also did not provide the VVIQ after Ganzflicker viewing mainly to keep the questionnaire short, but also in case Ganzflicker alters individual ability to activate imagery (anecdotally, one individual with typically vivid imagery felt that their imagery was "blocked" or suppressed for a short time following the Ganzflicker). Nevertheless, our unconventional technique for taking imagery vividness ratings produced a statistically normal distribution of ratings within the imagery group (see Fig. 1a). This shows that participants made a range of responses with

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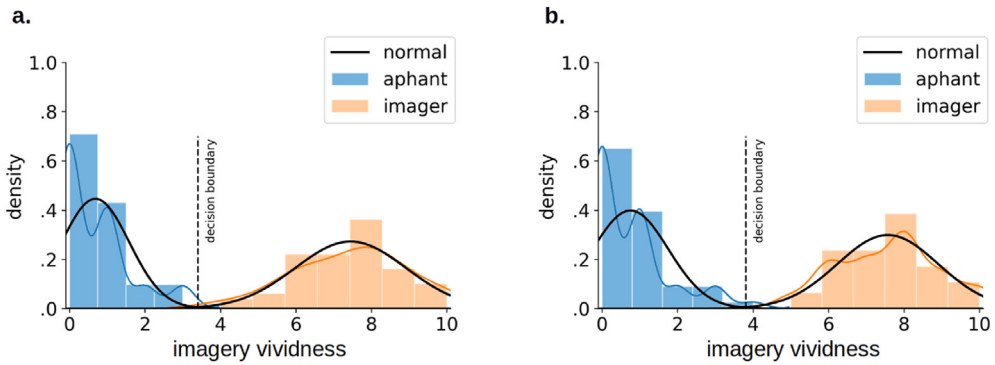

Fig. 1 – a.) The aphantasia (blue) and imagery (orange) distributions with the two groups manually split between imagery vividness ratings of 3 and 4. Imagery vividness ratings from 0 to 10 are shown on the x-axis, and the density of each score is on the y-axis. A normal curve (black line) is shown overlaid on the density trajectories of vividness ratings for aphants (blue line) and imagers (orange line). The likely boundary between aphants and imagers was calculated to be between a score of 3 and 4 (decision boundary, dashed line). b.) This figure was created in the same way as 1a, but with the groups manually split between vividness ratings of 4 and 5. The decision boundary was still estimated to be under 4 for the aphantasia distribution, so we ultimately determined that vividness ratings of 4 belonged to the imagery distribution.

Table 3 – A breakdown of the analyses between aphants and imagers in terms of environment, age, and total experiment time. There was no evidence for a difference between aphants and imagers on any of these factors.

Factors	Aphants (N = 143)	Imagers (N = 63)	Total	BF_{10}
Environmental factors:				
WN-Y[a]	105	51	156	
WN-N[a]	38	12	50	Contingency tables test[c]: .350
D-Y[a]	118	47	165	
D-N[a]	25	15	40	Contingency tables test: .377
Age:	Mean = 27.400, SD = 11.485	Mean = 24.067, SD = 8.735		Mann–Whitney *U* test[d]: .279
Total experiment time[b]:				
<10min.[a]	66	26	92	
~10min.[a]	59	34	93	Contingency tables test: .350

[a] WN-Y = listened to white noise; WN-N = did not listen to white noise; D-Y = observed Ganzflicker in a darkened room; D-N = did not observe Ganzflicker in a darkened room; <10min. = participants reported viewing the Ganzflicker for less than 10 min; ~10min. = participants reported viewing the Ganzflicker for approximately 10 min.

[b] All but 4 participants reported viewing the Ganzflicker for 10 min or less, so we removed those 4 so we could perform 2 × 2 contingency tables tests. The results of those 4 are reported in Footnote 2.

[c] Bayesian contingency tables tests (prior concentration = 1 (default), 1000 seeds for repeatability) were performed in the JASP statistical toolbox (JASP Team, 2018) on the count data presented in the table.

[d] Bayesian independent-samples Mann–Whitney *U* tests (Cauchy scale = .707 (default), 5 chains of 1000 iterations, 1000 seeds for repeatability) were also performed in JASP.

most ratings concentrated above a middle rating of 5 (median = 8) but not as vivid as actually perceiving (10), similar to the typical distribution of VVIQ scores (see Salge et al., 2020, Figure S5).

2.3. *Aphantasia versus imagery distribution*

2.3.1. *PH-susceptibility*

We first analyzed whether there was a difference in the likelihood of participants to report any PH during the Ganzflicker ("saw PH" = PH-Y, "saw no PH" = PH-N) across the two groups (aphants, imagers). We visualized the data using stacked bar plots of counts for PH-Y and PH-N (illustrated in salmon and gray, respectively), with a logistic regression of the probability of seeing PH for each imagery vividness rating overlaid in blue (see Fig. 2), generated in Python using scipy.stats. Here we were interested to illustrate the different proportions of PH-Y and PH-N responses within each imagery group. The proportion of PH-N responses shows a marked decrease from aphants to imagers (see gray sections of the bar plots, as well as individual data points for each response shown above and below the bars in blue). Specifically, there is a much higher proportion of people with no, or weak, imagery who do not see PH in the Ganzflicker compared to imagers. Although people with typical imagery abilities are much less likely to report no PH, people of all imagery abilities can see PH. A logistic regression analysis (blue line in Fig. 2, with 95% CIs illustrated in blue shading), indicates that aphants had a probability of .671 to see PH, whereas this probability climbed to .921 among imagers.

The odds of aphants seeing PH compared to seeing no PH were 2.043 (96/47), whereas the odds of seeing PH to seeing no

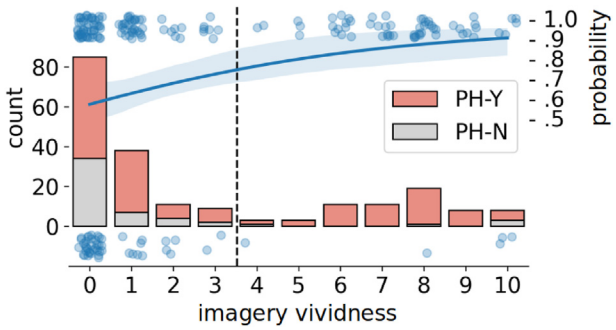

Fig. 2 – Stacked bar plots showing the proportion of people who did (PH–Y; salmon) and did not see PH (PH–N; gray) at each imagery vividness rating. Individual data points (with an x jitter of .3 to show overlapping data points) are plotted above and below the bars. A logistic regression line is shown in blue, with blue shading illustrating 95% CIs.

PH in imagers were 11.6 (58/5). A Bayesian contingency tables test performed in JASP, with 1000 seeds for repeatability, revealed extremely strong evidence for a difference between groups ($BF_{10\ \text{Independent multinomial}} = 477.790$, $N = 206$). The prior concentration was set to 1 (default prior width), but prior widths up to 10 still showed very strong evidence for a difference between groups, suggesting robust effects that are not dependent on specific priors. Table 4 reports additional analyses performed to determine if there were any environment or demographic differences between those who did and did not see PH.

2.3.2. *Features of PH*

Next, we were interested in exploring group (aphants, imagers) differences in features of PH reported during the Ganzflicker, among the sub-sample that saw PH at some point during the experiment.

2.3.2.1. PH-VIVIDNESS.

We visualized PH-Vividness ratings across the aphantasia and imagery distributions on a scatterplot applied with a Gaussian Mixture Model–Expectation Maximization (GMM-EM) cluster analysis in the scikit-learn toolbox in Python (adapting code from VanderPlas, 2016). Here our goal was to visualize the likely shapes of the distributions, and the estimated boundary between aphantasia and imagery distributions based on PH-Vividness rather than imagery vividness ratings (see Fig. 3: PH-Vividness). We fitted two GMM-EM probability distributions to the data, with 42 random states and a full covariance model.

The highest density of the aphantasia distribution concentrates around reports of seeing "weak, insubstantial" PH, whereas the most common responses from the imagery distribution tend to fall between "clear, not vivid" and "clear, moderately vivid" PH. Interestingly, very vivid PH are not only experienced by imagers with high imagery vividness ratings, but were reported across ratings from 5 to 10. Related, although aphants were much less likely to experience vivid PH, a few still did–two individuals even reported "very vivid, almost real" PH.

2.3.2.2. PH-COMPLEXITY.

Next, we visualized the difference in PH-Complexity ratings between aphants and imagers using the same technique reported for PH-Vividness (see Fig. 3: PH-Complexity). To reiterate, a complexity rating of 3 or below indicates that the participant saw, at most, simple geometric patterns; a complexity rating of 4 or above indicates that the participant saw, at some point in the experiment, complex naturalistic objects (e.g., faces, animals) and/or complex environments (e.g., landscapes, cityscapes).

The highest density of PH-Complexity responses from aphants concentrated around seeing "geometric patterns" and "simple combined". Compared to this, responses from imagers were much more widely dispersed across the different complexity ratings, but the center of density overlapped with

Table 4 – A breakdown of analyses performed between people who did (PH–Y) and did not see PH (PH–N) at some point during Ganzflicker viewing in terms of environment, age, and total experiment time. There was anecdotal evidence for a difference in total experiment time. Of the four individuals who viewed the Ganzflicker longer than 10 min (and did not contribute to the below contingency tables test), one did not see PH during Ganzflicker viewing.

Factors	*PH-Y (N = 154)*	*PH-N (N = 52)*	Total	BF_{10}
Environmental factors:				
WN-Y[a]	119	37	156	
WN-N[a]	35	15	50	Contingency tables test[c]: .265
D-Y[a]	121	44	165	
D-N[a]	32	8	40	Contingency tables test: .262
Age:	Mean = 25.517, SD = 9.608	Mean = 28.980, SD = 13.554		Mann–Whitney *U* test[d]: .223
Total experiment time[b]:				
<10min.[a]	63	29	92	
~10min.[a]	76	17	93	Contingency tables test: 1.354

[a] WN-Y = listened to white noise; WN-N = did not listen to white noise; D-Y = observed Ganzflicker in a darkened room; D-N = did not observe Ganzflicker in a darkened room; <10min. = participants reported viewing the Ganzflicker for less than 10 min; ~10min. = participants reported viewing the Ganzflicker for approximately 10 min.

[b] All but 4 participants reported viewing the Ganzflicker for 10 min or less, so we removed those 4 so we could perform 2 × 2 contingency tables tests. The results of those 4 are reported in Footnote 2.

[c] Bayesian contingency tables tests (prior concentration = 1 (default), 1000 seeds for repeatability) were performed in the JASP statistical toolbox (JASP Team, 2018) on the count data presented in the table.

[d] Bayesian independent-samples Mann–Whitney *U* tests (Cauchy scale = .707 (default), 5 chains of 1000 iterations, 1000 seeds for repeatability) were also performed in JASP.

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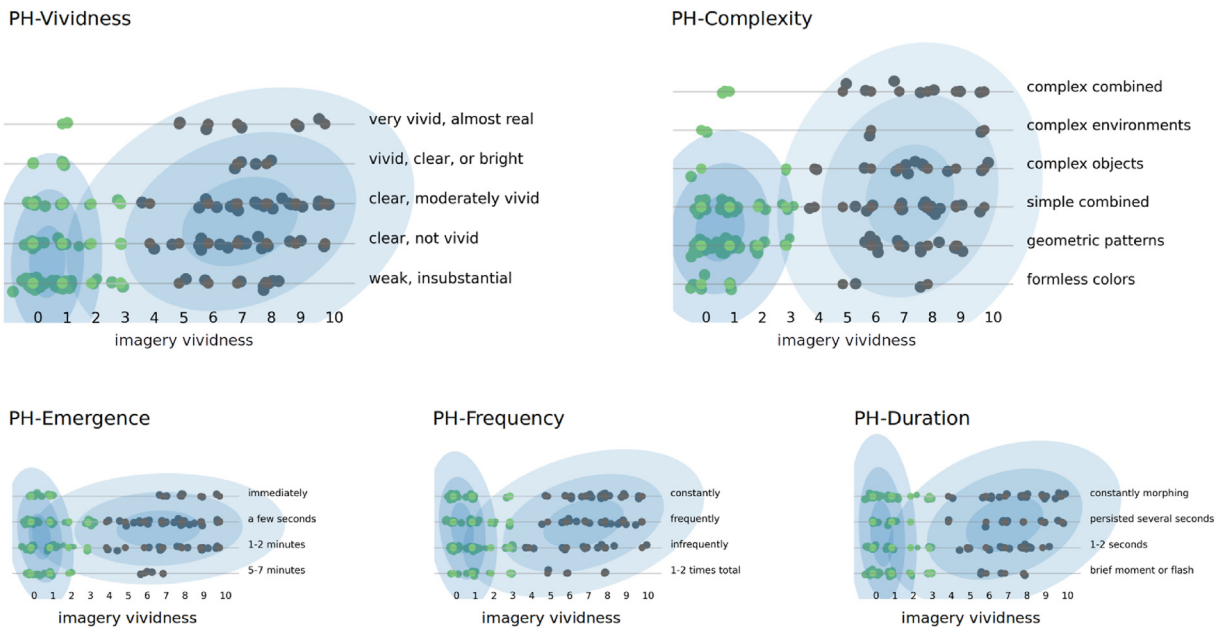

Fig. 3 – Scatterplots of subjective reports plotted for each imagery vividness rating, with an overlaid Gaussian Mixture Model–Estimation Maximization (GMM-EM). Darker blue shading indicates a higher likelihood of the position of the center of the distribution. Lighter blue shading indicates more uncertainty about the inclusion of certain data points in the distribution. Individual data points are color-coded green if they belonged to the aphantasia distribution and gray if they belonged to the imagery distribution.

reports of both simple and complex PH. Seeing a combination of complex objects and environments was much more likely among imagers compared to aphants. Similar to PH-Vividness, reports of complex PH were provided across the imagery spectrum from ratings of 5–10. Complex PH were rarely experienced by aphants.

2.3.2.3. Other features of PH. For completeness, we also present scatterplots overlaid with a GMM-EM for PH-Emergence, PH-Duration, and PH-Frequency in Fig. 3. Both aphants and imagers who experienced PH commonly reported that they emerged within a few seconds, occurred frequently, and typically persisted for more than 1 sec.

We performed 5 Bayesian Mann–Whitney *U* tests in JASP to determine the amount of evidence for a difference between aphants and imagers in terms of the vividness, complexity, emergence time, frequency, and duration of PH reported. These tests revealed extremely strong evidence for a difference in terms of PH-Vividness (W = 1031.500, Rhat = 1.001, BF_{10} = 271.718, aphant *N* = 84, imager *N* = 56) and PH-Complexity (W = 1678.000, Rhat = 1.001, BF_{10} = 53.632, aphant *N* = 96, imager *N* = 58).[2] There was no evidence for a difference between aphants and imagers on the other three features of PH, i.e., emergence time, frequency, and duration of PH (all $BF_{10} < 1$), rather showing anecdotal evidence for true null effects ($1 < BF_{01} < 3$). The Cauchy scale for all tests was set to .707 (default prior width), although prior widths up to the maximum of 2 produced similar results (very strong evidence for PH-Vividness and -Complexity; no evidence for the other three features of PH), suggesting robust effects that are not dependent on specific priors.

3. Discussion

The results of the current study suggest that imagers are much more likely than aphants to experience pseudo-hallucinations (PH) during Ganzflicker stimulation. Among those who experienced PH at some point during the experiment, imagers also saw more vivid and complex PH. There were no group differences in terms of PH emergence time, duration, or frequency. Overall, this study provides evidence for a distinction between aphants and imagers in their anomalous perceptual experiences.

3.1. *Imagery ability and the complexity of pseudo-hallucinations*

Although it seems intuitive that the subjective vividness of PH is strongly connected to imagery ability, the relationship between imagery and perceived complexity of PH is less clear. Bressloff et al. (2001, 2002) highlighted that simple form constants (e.g., spirals, funnels, web-like patterns) can appear in various situations that influence perception (e.g., psychoactive

[2] We also conducted a Bayesian Mann–Whitney *U* test to determine whether total experiment duration was related to maximum PH-Complexity experienced. This revealed no evidence for a difference in PH-Complexity between <10- or ~10-min Ganzflicker exposure, W = 2138.000, Rhat = 1.001, BF_{10} = .252, <10-min *N* = 63, ~10-min *N* = 76. Four individuals reported viewing the Ganzflicker longer than 10 min (reporting 15, 25, 30, and 50 min). One did not experience PH, and the other three reported maximum PH-Complexity ratings of 2, 3, and 3 (at most simple forms).

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substance use, rhythmic flicker, sensory deprivation). The authors proposed that these experiences originate in V1, a region that responds selectively to low-level visual features. They demonstrated that form constants correspond to *planforms* that can be mathematically derived from the eigenfunctions of the dynamics of V1 activity (for further details on how form constants and planforms were computed in V1 coordinates, see Bressloff et al., 2001; 2002).

If the geometry of simple form constants is a direct consequence of activity in V1, we inferred that PH beyond such simple shapes (i.e., more "realistic" percepts) cannot be explained solely on the basis of V1, but rather point to the involvement of higher cortical areas. Recent research suggests there is a higher neural overlap between perception and imagery in higher-order brain areas (frontal and object-selective cortices) compared to early visual areas (Dijkstra et al., 2017). Thus, our finding that imagers experienced more complex PH than aphants (i.e., going beyond form constants), points to a greater involvement of higher cortical areas in the perception of PH in imagers.

3.2. *Imagery and the susceptibility to pseudo-hallucinations*

One important question is what brain mechanisms lead to the experience of PH during the Ganzflicker, and why the susceptibility to such experiences is linked to imagery ability. Flicker-induced PH are most often reported during stimulation frequencies that resemble brain oscillatory frequencies at or around the alpha band (8–14 Hz; Allefeld et al., 2011; Mauro et al., 2015; Sokoliuk & VanRullen, 2013). Alpha band activity in the brain is generally associated with top-down processing, active inhibition, and the gating of information (e.g., Klimesch et al., 2007), and has been associated with higher cognitive functions such as attention (e.g., Klimesch, 2012) and mental imagery (Bartsch et al., 2015). Interestingly, flicker-induced PH (such as those experienced in the current study) are more likely to occur in individuals with higher resting cortical alpha power (Sokoliuk & VanRullen, 2013; but see; Carhart-Harris et al., 2016).

Importantly, there is some evidence that individual differences in alpha oscillatory activity may explain the current finding that imagers are much more likely to experience PH compared to aphants. A recent study found that lower individual cortical excitability levels in the visual cortex are associated with stronger imagery. Furthermore, decreasing cortical excitability using transcranial direct current stimulation increases imagery strength (as measured by a stronger priming effect by imagery during binocular rivalry; Keogh et al., 2020). Interestingly, other research has found that lower cortical excitability is associated with increased alpha power (Romei et al., 2008), which is in line with the notion that brain oscillations in the alpha band are a neural substrate for inhibitory processes (Klimesch et al., 2007). Another study has shown that alpha power increases during a mental imagery task (Bartsch et al., 2015). Taken together, this could suggest that stronger imagers, who tend to show lower visual cortex excitability at rest, also display higher resting alpha power. This potentially enhanced resting alpha power in imagers compared to aphants could contribute to a higher susceptibility to flicker-induced PH.

Another factor that would be interesting to investigate further is the relationship between Ganzflicker frequency and individual alpha peak frequency. A previous study found that flicker-induced visual phenomena are more likely to occur if the flicker frequency resembles an individual's peak alpha frequency more closely (Sokoliuk & VanRullen, 2013); in our experiment, the Ganzflicker was presented at a frequency of 7.5 Hz, which is slightly below the alpha frequency band. It is not yet known if aphants and imagers show different peak alpha frequencies, but one possibility is that aphants' peak frequency is more distant, on average, from the current study's Ganzflicker frequency, compared to the peak frequency of imagers. If this is the case, then it is possible that this contributed to aphants' lower susceptibility to PH. Of course, such a finding alone would not explain why flicker frequencies that stimulate at (or near) an individual's peak alpha frequency would increase the likelihood of PH more than other flicker frequencies. However, one explanation might be derived from a recent study on somatosensory cortex, in which the authors found that stimulating at an individual's peak alpha frequency modulated connectivity between somatosensory regions and the rest of the brain (Gundlach et al., 2020). Hence, stimulating visual cortex at its alpha peak frequency may alter its interactions with other brain areas (such as higher-order visual and prefrontal areas involved in imagery) to a greater extent than stimulation at a different frequency. This could induce stronger perceptual effects, including the evocation of anomalous perceptual experiences.

3.3. *A predictive processing account of the current results*

'Predictive processing' is a framework in which the perception of sensory information is achieved through a balanced weighting of predictions based on prior knowledge about the world (top-down) and incoming sensory information from the environment (bottom-up; Walsh et al., 2020). Various perceptual anomalies may occur due to an imbalance in the weighting of priors and sensory evidence. Weighting priors more strongly than sensory evidence leads to an over-reliance on top-down information, which can result in hallucinatory experience (Corlett et al., 2019; Powers et al., 2017); whether such an over-reliance on priors also increases proneness to psychosis is controversially discussed (Sterzer et al., 2018; Teufel et al., 2015). On the contrary, weighting sensory evidence more strongly than priors leads to an over-reliance on bottom-up information, which can result in decreased susceptibility to illusions and difficulties with Gestalt processing (Bölte et al., 2007).

It is currently unknown to what extent mental imagery ability and sensory priors are related. Previous studies have found that imagery is more vivid in schizophrenic spectrum disorders (Oertel et al., 2009) and synaesthesia (Barnett & Newell, 2008), both conditions that are thought to rely on strong, inflexible priors (van Leeuwen et al., 2020). Furthermore, there is neural evidence that imagery is generated by activating abstract representations and "passing them" from high-level brain areas to low-level sensory brain areas in a top-down way (Breedlove et al., 2020; Dentico et al., 2014;

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Dijkstra et al., 2020). This leads to the hypothesis that the mechanisms underlying imagery ability or strength overlap with those involved in high-level priors; the absence of imagery might, then, implicate a decreased influence of—or weaker—priors. In the context of the current results, this points to the possibility that aphants are likely to have weaker high-level priors (which will make them less prone to PH, including less vivid and complex PH), whereas imagers are more likely to have stronger high-level priors (which makes them more prone to vivid and complex PH).

3.4. Follow-up: laboratory-based studies

One limitation of the current study is that our data are entirely composed of subjective reports that were collected after Ganzflicker viewing had terminated. This was an efficient and accessible method for collecting a large number of responses from a unique online sample, but it is necessary to perform follow-up experiments in the laboratory to better quantify subjective experiences. The first laboratory follow-up will quantify discrete visual experiences with button presses, with the duration of individual experiences measured as the time from button-press to -release. Another important behavioral adaptation that should be made in future laboratory-based experiments, is the implementation of catch trials. Someone who expects to see nothing in the Ganzflicker may come in with more conservative criteria as to what constitutes a visual experience, and this should be emulated in response patterns to different intensities of real visual stimuli. We will, therefore, create a version of the Ganzflicker in which real, PH-like stimuli occur at different contrast levels throughout the experiment. If response bias contributes to our pattern of results, we should observe a negative correlation between PH-susceptibility and visual contrast sensitivity. This design would also allow us to investigate patterns of top-down and bottom-up information weighting in aphantasia and imagery within the context of a predictive processing framework.

Another problem with relying on subjective reports, aside from the possibility of response bias, is that some individuals may have non-visual anomalous experiences in the Ganzflicker, which may be difficult to verbalize. One possible explanation for our pattern of results in individuals with different imagery abilities is based on the hypothesis that all individuals have the ability to simulate the spatial aspects of sensory information (e.g., size, location, distance, relations between parts), but aphants lack an additional visual dimension of that simulation. In line with this, a recent study found that aphants may even have enhanced spatial representation abilities compared to imagers, due to a necessity to rely on spatial representations in the absence of imagery (Bainbridge et al., 2020); this would explain why aphants often have intact mental rotation and precise spatial memory capabilities (Bainbridge et al., 2020; Zeman et al., 2010). Spatial representations are not necessarily visual, and thus, may be difficult to report. In this context, we could explain why a large proportion of aphants in our sample (roughly 46%) reported no PH (even simple PH) in the Ganzflicker: they may have experienced anomalous phenomena, but were simply unaware of them or unable to verbalize them. These possibilities could be tested with eye tracking measures: for example, PH are often reported with some amount of dynamicity (e.g., spinning, drifting, shrinking), which the eyes might follow automatically. Eye tracking could thus expose weak or amodal PH that are difficult to verbalize.

More generally, a related limitation of collecting data online is that the environment in which participants viewed the Ganzflicker could not be controlled, including display size and observer distance from the screen; these factors could have had an effect on Ganzflicker experiences, so it is important to control these parameters in a laboratory setting.

3.5. Clinical significance

Finally, these investigations are important because previous studies have proposed a link between modal imagery vividness and hallucination proneness in pathology. More vivid imagery is correlated with a higher susceptibility to intrusive imagery (Pearson & Westbrook, 2015) and hallucinations (Aleman et al., 2000), which could be severely detrimental to mental health at a pathological level. This is crucial for an aging population, because elderly individuals (and especially those with progressive neurological disorders like Parkinson's Disease or Alzheimer's Disease) have an increased susceptibility to hallucinations (Barnes & David, 2001; Harding et al., 2002), especially if they have vivid sensory imagery (Shine et al., 2015). Conversely, based on our results, it can be argued that attenuated imagery abilities might represent an advantageous natural buffer against such susceptibility. Homing in on the neural mechanisms that dissociate the likelihood of experiencing PH among imagers and aphants might, therefore, offer important insights into alleviating the frequency and vividness of hallucinations in pathological contexts.

Another topic to explore further is the ability to predict the complexity of hallucinations in pathology. There is no known cortical distinction between simple and complex hallucinations, in that both have been linked to dysfunction across the visual hierarchy and beyond (Teeple et al., 2009). Exploring the relationship between imagery ability, PH-Susceptibility, and PH features in normative samples (in the absence of pathology) would provide much-needed insight about the relationship between imagery and anomalous perception, which may predict susceptibility to hallucinatory experience.

A related avenue of future exploration in clinical samples, is a comparison between PH experiences and real hallucinatory experiences, and their association with voluntary and involuntary mental imagery. As mentioned in the introduction, one major difference between PH and real hallucinations is that inducing or alleviating PH can be controlled by applying or removing visual stimulation, whereas real hallucinations are often unpredictable and uncontrollable. This is reminiscent of the connection between voluntary and involuntary imagery: voluntary imagery is the ability to control the generation of mental images, whereas involuntary imagery is the uncontrolled generation of images (as experienced in anxiety disorders or post-traumatic stress disorder; Pearson & Westbrook, 2015). Similar to PH, voluntary imagery can be a pleasant experience, whereas involuntary (i.e., intrusive) imagery can be fearful and debilitating (Pearson & Westbrook, 2015), similar to hallucinations. It is, therefore, important to investigate the connection between involuntary imagery and hallucinations.

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4. Conclusion

This exploratory report presents the first evidence that people with different visual mental imagery abilities have different anomalous perceptual experiences. Specifically, people who report a weak, or absent, ability to activate voluntary visual imagery are much less likely to experience complex and vivid visual pseudo-hallucinations than people who report having typical visual imagery vividness. This study will be followed up with objective behavioral and electrophysiological measures.

Credit authorship statement

Reshanne R. Reeder: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing–original draft; Writing–review & editing.

Johanna Bergmann: Investigation; Methodology; Validation; Visualization; Writing–review & editing.

Varg T. Königsmark: Data curation; Formal analysis; Validation; Visualization; Writing–review & editing.

Open practices

The study in this article earned Open Data and Open Materials badges for transparent practices. Data and Materials for this study can be found at https://osf.io/6dvh9/ and https://osf.io/6gewm/.

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