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# Imagine that: elevated sensory strength of mental imagery in individuals with Parkinson's disease and visual hallucinations

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Visual hallucinations occur when our conscious experience does not accurately reflect external reality. However, these dissociations also regularly occur when we imagine the world around us in the absence of visual stimulation. We used two novel behavioural paradigms to objectively measure visual hallucinations and voluntary mental imagery in 19 individuals with Parkinson's disease (ten with visual hallucinations; nine without) and ten healthy, age-matched controls. We then used this behavioural overlap to interrogate the connectivity both within and between the major attentional control networks using resting-state functional magnetic resonance imaging. Patients with visual hallucinations had elevated mental imagery strength compared with patients without hallucinations and controls. Specifically, the sensory strength of imagery predicted the frequency of visual hallucinations. Together, hallucinations and mental imagery predicted multiple abnormalities in functional connectivity both within and between the attentional control networks, as measured with resting-state functional magnetic resonance imaging. However, the two phenomena were also dissociable at the neural level, with both mental imagery and visual misperceptions associated with specific abnormalities in attentional network connectivity. Our results provide the first evidence of both the shared and unique neural correlates of these two similar, yet distinct phenomena.

## 1. Introduction

It is easy to take visual perception for granted. For the overwhelming majority of people, conscious perception seems to mirror the external world with high validity. However, individuals with a variety of neuropsychiatric disorders regularly experience situations in which this relationship breaks down and they experience something that is not there—an 'hallucination'. Although these symptoms are associated with varying and extensive pathology [1,2], the precise neural mechanisms underlying hallucinations remain a mystery, due largely to the inherent difficulties associated with reproducibly eliciting hallucinatory symptoms in the research setting.

Work in Parkinson's disease (PD) has been able to bridge this issue. Recent conceptual advances suggest that visual hallucinations in PD are related to an inability to rapidly and flexibly use attention [3]. More specifically, impaired recruitment of exogenous attention networks has been proposed as a contribution to visual hallucinations [3], leading to an over-reliance on endogenous attention systems, which are ill-equipped to interpret the contents of exogenous perceptual abnormalities.

These mechanistic insights have been largely driven by the creation of a novel behavioural paradigm capable of reproducibly eliciting visual hallucinations [4]. Known as the Bistable Percept Paradigm (BPP; figure 1*b*), this task requires participants to view a series of stable and bistable monochromatic images and subsequently identify any 'hidden' items they perceive. PD patients that experience visual hallucinations in daily life are far more likely to perceive

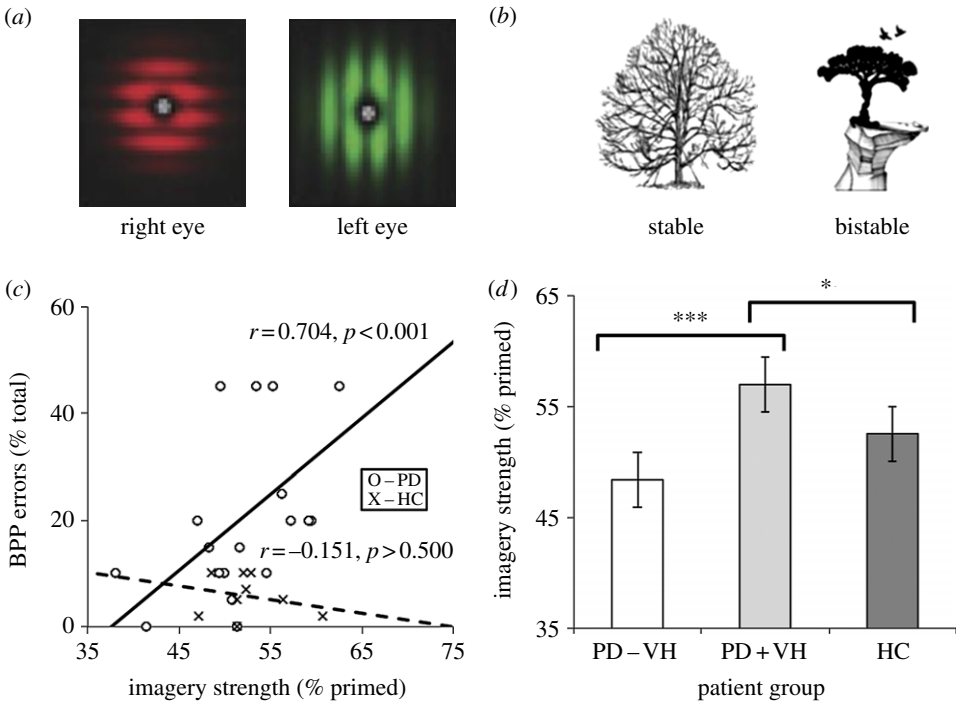


**Figure 1.** Relationship between mental imagery and visual hallucinations: (*a*) binocular rivalry—subjects view a different monocular pattern in each eye (right eye = horizontal stripes (red online); left eye = vertical stripes (green online)), however their perceptual experience vacillates back and forth between the two; and (*b*) BPP—participants view a series of monochromatic images and have to determine whether they are stable (e.g. a tree) or bistable (e.g. a tree with the silhouettes of faces etched into the trunk). In our experiment, subjects spent 5 s imagining either pattern prior to a brief stimulus presentation, effectively priming the conscious perception of the imagined stimulus; (*c*) there was a strong positive correlation ($r = 0.632$, $p = 0.002$) between impaired performance on the BPP (*y*-axis—percentage of misperceptions) and the strength of imagery on binocular rivalry (*x*-axis—percentage of trials with strong influence of imagery of perception). The correlation remains significant after removing the single outlier; and (*d*) hallucinators (PD + VH) had higher mental imagery strength than healthy controls (HC; $t = 2.1$, $p = 0.046$) and patients without hallucinations (PD − VH; $t = 3.2$, $p = 0.006$). (Online version in colour.)

'hidden' images in stable pictures, whereas non-hallucinators see none (figure 1*a*) [4]. That is, susceptible patients see something that is no*t* there—the very definition of a hallucination.

Although hallucinations occur in a number of neuropsychiatric disorders, dissociations between visual perception and external reality can also readily occur in healthy individuals (e.g. in low light conditions or upon entering into the early stages of sleep). Perhaps the most interesting example of this phenomenon is in the case of mental imagery, whereby an individual can voluntarily 'bring to mind' a vivid visual experience of an item, without requiring that item to be present [5]. The ability to imagine a visual image can also directly impact on subsequent conscious experience [6]. By simply imagining an object in the period prior to the brief presentation of a perceptual binocular rivalry stimulus, the dominant pattern in rivalry tends to match that imagined [6]. That is, imagination is able to prime subsequent conscious perception. This 'top-down' influence of mental imagery on conscious experience suggests an intriguing commonality with the current conceptual framework applied to visual hallucinations in PD. However, to date, a specific role for mental imagery in visual hallucinations has not been explored.

Here, we used these two objective perceptual tasks to explore the role of imagery strength in the pathophysiology of visual hallucinations in 19 patients with PD and 10 age-matched healthy controls. Each individual performed the BPP and a mental imagery task, along with resting-state functional magnetic resonance imaging. Our objective was to directly test the hypothesis that the strength of mental imagery would be related to visual hallucinations as assessed by impaired performance on the BPP and then use this information to interrogate patterns of functional connectivity within the resting brain.

## 2. Material and methods

### (a) Participants

Nineteen adults with PD (mean age = 68.4 years; 70% males) and 10 age-matched healthy controls (mean age = 67.9 years; 70% males) were recruited from the Parkinson's Disease Research Clinic at the Brain and Mind Research Institute at the University of Sydney. Demographic details for the patients with PD are presented in table 1.

### (b) Neuropsychological tests

Performance data are included in table 1. None of the patients showed evidence of clinical dementia [7]. The Montreal Cognitive Assessment (MoCA) was used as general measure of cognition [8] and the Beck Depression Inventory (BDI-II) was used to assess for the presence of affective disturbance [9]. To explore the role of attentional set-shifting (the ability to shift attention between competing targets), all patients performed the Trail Making Test (TMT) parts A and B [10], allowing for the calculation of a difference score ($TMT_{B-A}$).

### (c) Bistable percept paradigm

The BPP was programmed using EPRIME Software (Psychology Software Tools, USA) and consisted of a battery of 40 monochromatic images that were classified *a priori* as either stable or bistable images [4]. As shown in figure 1*b*, bistable images contained two or more interpretations (e.g. silhouette of faces within a landscape

**Table 1.** Demographic details for the patients with PD. (BDI-II, Beck Depression Inventory; DDE, dopamine dose equivalence; MoCA, Montreal Cognitive Assessment; $TMT_{B-A}$, Trail Making Test difference score; UPDRS III, motor subscale of the Unified Parkinson's Disease Rating Scale.)

| | BPP + | BPP − | controls | *p*-value |
|---|---|---|---|---|
| *N* | 10 | 9 | 10 | |
| age | 69.5 ± 8 | 67.1 ± 7 | 63.5 ± 8 | 0.509 |
| MoCA | 26.0 ± 3 | 27.6 ± 2 | 28.5 ± 1 | 0.116 |
| BDI-II | 15.5 ± 14 | 8.9 ± 7 | 7.9 ± 7 | 0.197 |
| disease duration | 6.9 ± 4 | 4.4 ± 3 | n.a. | 0.214 |
| UPDRS III | 34.0 ± 15 | 32.0 ± 15 | n.a. | 0.780 |
| DDE, mg $d^{-1}$ | 819.5 ± 516 | 512.5 ± 225 | n.a. | 0.100 |
| imagery strength | 57.0 ± 7 | 48.4 ± 5 | 52.3 ± 4 | **0.006** |
| $TMT_{B-A}$ | 110.5 ± 88 | 39.6 ± 20 | 43.1 ± 15 | **0.025** |

scene), whereas stable images had no such ambiguity (e.g. a simple black image of a tree on a white background). The patient's left and right hands were positioned over corresponding response buttons that controlled both the initial response to the cue as well as to the answers of subsequent questions [4].

Each trial was signalled by the appearance of a black fixation cross in the middle of a white screen. After a delay of 50 ms, the fixation cross disappeared and participants were randomly presented with one of the images. Subjects were required to study the image until they were confident as to whether it represented a stable or bistable image, before pressing a response button. This response triggered a screen where participants indicated by button press whether they had identified a stable or bistable image by pressing the associated button. The fixation cross then re-appeared signalling the start of the next trial. Impaired performance on the BPP was measured by calculating the percentage of trials that an individual subject incorrectly perceived a stable image as containing a 'hidden' percept.

In keeping with previous studies, a cut-score (BPP error score = 11%), which was defined using a separate group of 18 healthy control subjects [4], was then used to split the patients into two groups: hallucinators and non-hallucinators. Controls in this study displayed a similar average BPP error score to the previous study (6.44 ± 2.7%). Importantly, all subjects defined as hallucinators via the BPP also scored positively on Movement Disorders Society Criteria for a classification of visual hallucinations (i.e. more than one month of symptoms, which began after formal diagnosis of PD and were not attributable to any other causes) [11]. Although three subjects from the non-hallucinator group self-reported visual illusion symptoms, none of these lasted longer than one month, and as such, were not classified as overt hallucinations. All subjects classified as hallucinators also suffered from concomitant visual illusions. To ensure that these subjects were not impacting on the results, we also re-ran each analysis in the study after removing these three subjects.

## (d) Binocular rivalry

Similar to previous experiments [6], the rivalry display consisted of a green vertical grating shown to the left eye and a red horizontal grating shown to the right eye (figure 1*a*). The mean luminance of both Gabor patterns was 7.8 $cdm^2$. Both patterns were presented in an annulus around a fixation spot. The relative strength of the two stimuli was adjusted on a case-by-case basis so as to minimize any pre-existing eye bias (see [6] for details).

## (e) Strength of mental imagery

To investigate the effects of imagery on rivalry, subjects were instructed to imagine one of the two rivalry patterns (a green-vertical or red-horizontal grating) during the blank intervening period (6 s) between rivalry presentations (750 ms). During rivalry presentations, participants were instructed to indicate which image was dominant by pressing the corresponding keys ('1' = green, '2' = equal mix and '3' = red). The specific image that each patient was cued to imagine on each trial was randomized, with an equal number of red and green cues. Each patient performed two blocks of trials, each containing 40 trials. The percentage of trials in which the imagined pattern matched subsequent reported rivalry pattern was taken as our measure of imagery strength (see [12,13] for definitions of imagery strength).

Mock rivalry displays were also included to ensure that there was no bias related to demand characteristics [14]. If participants' responses were due to demand characteristics, we would expect to see priming (higher than 50%) for mock trials. Analysis of mock trials demonstrated that participants displayed no decisional bias, with the average priming of mock trials not being significantly different from chance (PD: mean = 50.46 ± 2.5; $t = 0.8$, $p = 0.430$; controls: mean = 50.46 ± 1.4; $t = 1.0$, $p = 0.350$).

## (f) Statistical analysis

Owing to the lack of a consensus *gold standard* for the diagnosis of visual hallucinations [15], we opted to split the cohort of patients using scores on the BPP [3,4]. Demographic variables were compared between groups using independent-samples *t*-tests. Pearson correlation coefficients were used for continuous data and a Hotelling's *t*-test was used to compare correlation coefficients. Scores on both outcomes measures showed strong internal consistency (BPP: $r = 0.560$, $p = 0.005$; imagery: 0.381, $p = 0.047$). All behavioural data analysis was performed using SPSS v. 20 (Chicago, IL, USA), all analyses used an $\alpha$ of 0.05 and were one-tailed.

## (g) Neuroimaging analysis

The 19 individuals with PD also underwent a single 10-min resting-state scan in which patients were instructed to lie still with their eyes open and to let their minds wander freely. Images were acquired on a General Electric 3 Tesla MRI (General Electric, Milwaukee, USA). T2*-weighted echo planar functional images were acquired in sequential order with repetition time (TR) = 3 s, echo time (TE) = 32 ms, flip angle 90°, 32 axial slices covering the whole brain, field of view = 220 mm, interslice gap = 0.4 mm and raw voxel size = 3.9 × 3.9 × 4 $mm^3$ thick. T1-weighted images were also acquired, consisting of a set of 126 adjacent axial cuts parallel to the anterior commissure–posterior commissure line, with a slice thickness of 1.5 mm and a voxel size of 1 × 1 × 1 $mm^3$.

Preprocessing and analysis were conducted using Statistical parametric mapping software (SPM8, Wellcome Trust Centre for Neuroimaging, London, UK, http://www.fil.ion.ucl.ac.uk/

**Table 2.** Coordinates for regions of interest.

| network | MNI coordinates |
|---|---|
| dorsal attention network | |
| bilateral superior parietal lobule | ±27 −52 57 |
| bilateral frontal eye fields | ±25 −8 54 |
| default mode network | |
| midline precuneus | 0 −73 40 |
| midline medial prefrontal cortex | 0 59 10 |
| bilateral hippocampal formation | ±22 −22 −22 |
| ventral attention network | |
| bilateral anterior insula | ±42 24 −20 |
| bilateral dorsal anterior cingulate cortex | ±12 26 28 |
| visual network | |
| bilateral occipital cortex | ±8 −94 4 |

spm/software/). Regions of interest (ROIs) for the study were defined according to previously published coordinates [4,16] and mapped onto known hubs within the putative attention control networks (see table 2). Pre-processed images were imported into the Functional Connectivity ('conn') toolbox (http://www.nitrc.org/projects/conn) in SPM8, which allowed for the calculation of both within- and between-network connectivity (see electronic supplementary materials for details).

To assess the shared neural correlates between mental imagery and visual hallucinations, we performed a series of multiple regression analyses in which each individual subject's BPP error score and their strength of mental imagery was regressed against the *Z*-score representing the average strength of connectivity for each within- and between-network score. In the measures that displayed a significant regression value, we separately correlated the connectivity scores against the imagery strength and BPP error scores using Spearman's rank-order correlation, to determine whether the neurobiological differences were driven by one or the other measure.

# 3. Results

## (a) Association between mental imagery and bistable percept paradigm error score

Across all PD patients, there was a strong positive correlation between the strength of mental imagery and impaired performance on the BPP ($r = 0.704$, $p = 0.001$), which was not observed in control subjects ($r = -0.151$, $p > 0.500$) (figure 1*c*). In addition, both of the primary outcome measures were positively correlated with a measure of impaired attentional set-shifting ($r = 0.457$, $p = 0.05$ and $r = 0.763$, $p < 0.001$, respectively) and a multiple regression involving all three factors was strongly significant ($F_{2,17} = 12.2$, $p < 0.001$), accounting for almost 60% of the variance in the BPP error score ($R^2 = 0.59$). Finally, the relationship between imagery strength and misperceptions appeared to be driven by the frequency of misperceptions in stable images ($r = 0.632$, $p = 0.002$), rather than any perceptual abnormalities in the bistable images ($r = 0.037$, $p = 0.877$) and the difference between the two correlations was significant ($t = 2.16$, $p < 0.05$). Each of these results remained significant after the removal of the three non-hallucinators who self-reported minor misperceptions (all *p*s $< 0.05$).

The group of subjects in our study with impaired performance on the BPP displayed significantly stronger mental imagery ($t = 3.17$, $p = 0.006$), which was also higher than that observed in control subjects ($t = 2.25$, $p = 0.037$) (figure 1*d*). Catch trials in the imagery task showed no decisional bias ($t = 0.82$, $p = 0.430$), ensuring our measure was perceptual.

Importantly, none of the outcome measures in our study were correlated with impaired visual acuity, general cognitive deficits, the severity of motor symptoms or the duration of disease, all factors that have been previously proposed as causative factors in visual hallucinations [2,5]. There was a trend towards a correlation between mental imagery and the level of dopaminergic medication dose ($r = 0.441$, $p = 0.060$); however, this relationship was not observed between medication dose and impaired BPP scores ($r = 0.190$, $p = 0.211$). In addition, each of the significant effects described above remained following partial correlation with dopaminergic equivalence scores.

## (b) Resting-state functional connectivity

A multiple regression using the frequency of misperceptions on the BPP as well as the strength of mental imagery predicted increased connectivity within the ventral attention network ($R = 0.636$, $F_{2,16} = 5.45$, $p = 0.008$) and default mode network ($R = 0.492$, $F_{2,16} = 2.57$, $p = 0.049$) (figure 2), suggestive of a relative over-reliance on endogenous attention networks in hallucinators (figure 3). The two measures also predicted decreased connectivity between the dorsal and ventral attention networks ($R = 0.542$, $F_{2,16} = 3.34$, $p = 0.030$), the ventral attention and visual networks ($R = 0.632$, $F_{2,16} = 5.34$, $p = 0.008$) and the dorsal attention and visual networks ($R = 0.552$, $F_{2,16} = 3.51$, $p = 0.025$), implicating decreased between-network connectivity in the neurobiological mechanism of both mental imagery and visual hallucinations. However, given the presence of reduced imagery strength in non-hallucinators (relative to healthy controls), it bears mention that these connectivity deficits may have been due to reduced imagery performance in the non-hallucinator group.

The severity of BPP visual hallucinations alone predicted increased connectivity within the ventral attention network ($\rho = 0.585$, $p = 0.004$) and the default mode network ($\rho = 0.493$, $p = 0.0160$), as well as impaired connectivity between the ventral and dorsal attention networks ($\rho = -0.430$, $p = 0.033$). By contrast, the strength of mental imagery did not predict any of these relationships ($\rho < |0.400|$), but instead was related to the degree of impaired connectivity between the ventral attention and visual networks ($\rho = -0.496$, $p = 0.015$). Neither measure predicted the strength of impairment between the dorsal attention and visual networks ($\rho < |0.400|$). After removing the three non-hallucinators who self-reported infrequent misperceptions, we observed similar effects, however the correlation between the BPP error score and impaired DAN–VAN connectivity was only significant at trend levels ($r = -0.455$, $p = 0.08$).

# 4. Discussion

To our knowledge, these results provide the first evidence that links visual misperceptions and visual hallucinations with the influence of mental imagery on conscious perception. Although previous studies have investigated these concepts indirectly in other disorders [6,17], the novel measures used here offer a more objective method for observing the

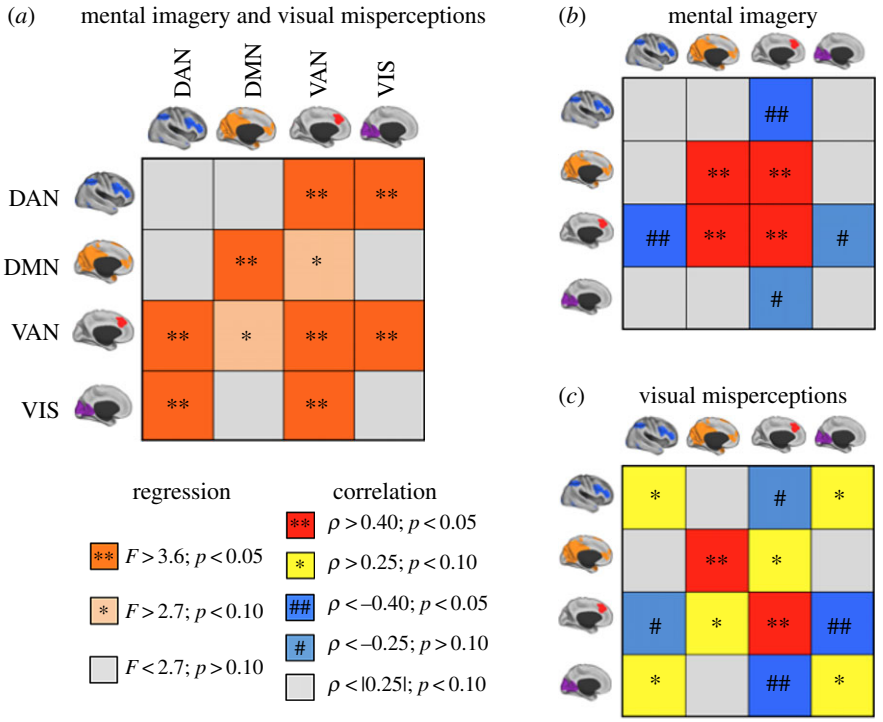


**Figure 2.** Impairments in within- and between-network connectivity associated with visual hallucinations and strength of mental imagery: (*a*) matrix where individual values represent the strength of prediction (average *Z* score) of within- and between-network connectivity arising from a multiple regression utilizing both BPP error score and the sensory strength of mental imagery; (*b*) individual Spearman's correlations between strength of mental imagery and network connectivity measures; and (*c*) individual Spearman's correlations between BPP error score and network connectivity measures. The inset contains the key (in colour online) for displaying the statistical significance of results for each analysis: multiple regression: dark orange – $F_{2,16} > 3.6, p < 0.05$ (denoted by **); $F_{2,16} > 2.7, p < 0.10$ (*); $F_{2,16} < 2.7, p < 0.10$; correlation: red – $\rho > 0.40, p < 0.05$ (**); orange – $\rho > 0.25, p < 0.10$ (*); dark blue – $\rho < -0.40, p < 0.05$ (##); light blue – $\rho < -0.25, p < 0.10$ (#); grey – $\rho < |0.25|$, $p > 0.10$. Key: DAN, dorsal attention network; DMN, default mode network; VAN, ventral attention network; VIS, visual network. (Online version in colour.)

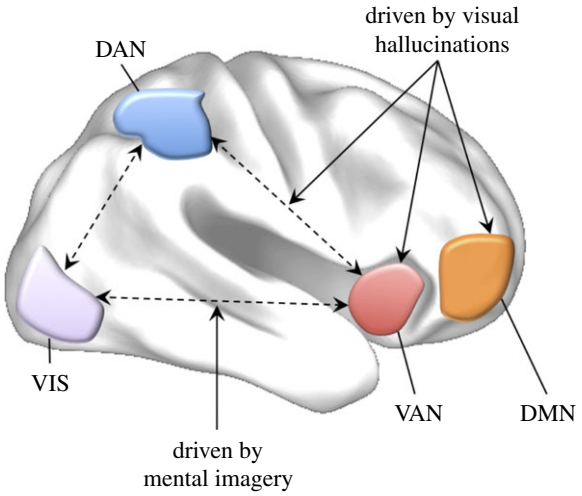


**Figure 3.** Putative neurological mechanism for visual hallucinations [2]. Abnormal connectivity between exogenous (dorsal attention network; DAN—blue), endogenous (ventral attention network; VAN—red) and primary visual (VIS—purple) networks, along with increased connectivity in ventral attention and default mode network (DMN—orange) predisposes individuals with PD to hallucinate visual images. Although these connectivity changes are strongly related to both imagery and visual hallucinations ($R > 0.45$, $p < 0.05$), individual connectivity scores are dissociable and strongly driven by one or the other mechanism (dotted lines represent impaired pathways of neural communication). (Online version in colour.)

pathophysiological effects of visual misperceptions in PD, as they do not rely solely on introspection and self-report. Importantly, the BPP is able to avoid this issue, providing an objective measure of visual misperceptions and hallucinations in susceptible patients with PD [4]. Together, these results suggest that mental imagery and visual misperceptions (which we demonstrate are strongly related to the presence of clinically defined visual hallucinations) may be differing manifestations of a similar neurobiological mechanism, with the former due to a voluntary process and the latter the result of an involuntary, pathological process.

Although visual misperceptions and mental imagery are distinct phenomena, we provide evidence to suggest that they share a common neurobiological mechanism. Namely, both behavioural phenomena were predictive of increased connectivity within the ventral attention and default mode networks, as well as impaired connectivity between the ventral attention, dorsal attention and visual networks (figure 2). Consistent with previous predictions [3,6], these results suggest that visual hallucinations arise in the context of impaired coordination between exogenous attentional networks and the primary visual cortex, whereby attention towards exogenous stimuli is less effective. Without the usual exogenous attentional alerts to novel or unexpected stimuli, ambiguities in visual processing might be rendered open to exaggerated endogenous interpretations. Such an over-reliance on internal interpretations might allow the evolution of small ambiguities in visual processing to grow into more salient and even autobiographical interpretations [7,18]. Importantly, this mechanism is consistent with accounts of mental imagery [5,8], which similarly propose that top–down influences over primary visual cortex underlie the capacity to imagine visual images [9,19]. Together, these results highlight the possibility of a common neural mechanism underlying both visual hallucinations and mental imagery.

Despite overlap in the neurobiological mechanisms of misperceptions and mental imagery, misperceptions and imagery are not identical processes, differing distinctly in regard to volitional control and also in the way they are experienced. Hence, it is not surprising that we observed some dissociable patterns of brain connectivity between the two behavioural measures. Specifically, the severity of misperceptions was strongly predictive of increased within-network connectivity in endogenous networks and impaired connectivity between the dorsal and ventral attention networks, whereas the strength of mental imagery was associated with impaired interactions between the ventral attention network and the visual network. This dissociation highlights the fact that, although imagery strength and hallucinations likely share a common neurobiological mechanism, they also reflect distinct processes. For instance, recent imaging studies have implicated increased activity within cortical regions used for attention [10,20], whereas visual hallucinations in PD have been related to impaired interactions between neural systems involved in the attentional modulation of perception [4,16,21,22].

Imagery and visual misperceptions were also associated with varying degrees of within-network connectivity. However, these resting-state differences appeared to be driven most strongly by the severity of visual misperceptions (figure 2). These results are consistent with the notion that patients with visual hallucinations are unable to recruit activity within networks subserving exogenous attention, and instead rely on other attentional networks, such as the ventral attention and default mode networks, to compensate for this deficiency. Interestingly, the default mode network is commonly associated with self-referential processes [4,23] and endogenous attention [4,24], including periods of task-independent thought, or 'mind wandering' [11,18,25]. Given the lack of exogenous attention demonstrated by patients with hallucinations in both behavioural [4,6] and neuroimaging studies [6,16], the association with increased default-mode connectivity could reflect an over-reliance on endogenous networks to interpret and inform the current contents of perceptual experience.

Together, these data help to clarify the pathophysiological mechanism of visual hallucinations, which might occur paroxysmally due to impaired communication between attentional and perceptual systems (figure 3) [3,12,16]. That is, abnormal activity in the visual cortex may be misinterpreted due to faulty interactions with frontoparietal networks normally used to focus exogenous attention [2,3,14,21,22]. However, hallucinations in PD are often of complex objects (such as faces or people), suggesting that these perceptual abnormalities only occur once neural activity in the primary visual system interacts with the ventral visual stream in the temporal lobe, a known site of Lewy body pathology in PD patients with hallucinations [15,26]. In addition, a number of recent studies have highlighted pathological impairments in the visual system of individuals with hallucinations, both in the retina [27] and dorsal visual stream [21,22], suggesting that hallucinations are due to a combination of impaired visual input with concomitant exogenous attentional dysfunction [3,28]. This accords with recent investigations into pareidolia—visual misperceptions closely related to hallucinations [29]—which are similarly mediated by top–down attentional control mechanisms [30,31]. This is an exciting avenue for future research, which should seek to determine whether unprovoked hallucinations occur due to a top–down priming from ventral temporal structures or to emergent activity within primary visual cortex.

Previous investigations have suggested that mental imagery may be decreased in patients suffering from visual hallucinations in the context of Charles Bonnet syndrome or dementia [32,33]. Although seemingly in contrast to our findings, there are crucial task-based differences relative to this study. These prior studies measured attentional ability applied within a mental image, whereas we directly assessed the sensory strength of mental imagery [13].

Many of the findings here have also been demonstrated in other neuropsychiatric disorders with visual hallucinations and illusions. For example, patients with either schizophrenia [34] or post-traumatic stress disorder [35,36] have been shown to have increased resting activity within the ventral attention network and report more vivid mental imagery [37,38]. In addition, both disorders have displayed impairments in cognitive flexibility [39,40]. Furthermore, default mode network over-activity [41] and dissociation with cognitive control regions [42] have also been reported in patients with schizophrenia. Intriguingly, hallucinations in disorders classically associated with primary retinal impairment, such as Charles Bonnet Syndrome, are also associated with visual attentional impairments [32,33], suggesting a common neural mechanism for hallucinations across all disorders [2,43]. Future studies should thus be designed to delineate the precise combination of deficits across attentional and perceptual domains that lead to the manifestation of visual hallucinatory symptoms across the broad range of neuropsychiatric disorders.

In conclusion, our data suggest a possible overlap in the neurological mechanisms supporting mental imagery and those that are dysfunctional in visual hallucinations, as demonstrated in PD.

Ethics statement. All participants with PD were diagnosed according to UKPD Brain Bank Criteria. Permission for the study was obtained from the local research ethical committee and all patients gave written informed consent.

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