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Exploratory Report

Item-specific overlap between hallucinatory experiences and cognition in the general population: A three-step multivariate analysis of international multi-site data

Abhijit M. Chinchani [a,b], *Mahesh Menon* [c], *Meighen Roes* [a,d], *Heungsun Hwang* [e], *Paul Allen* [f,g], *Vaughan Bell* [h], *Josef Bless* [i], *Catherine Bortolon* [j], *Matteo Cella* [k,l], *Charles Fernyhough* [m], *Jane Garrison* [n], *Eva Kozáková* [o,p], *Frank Larøi* [i,q,r], *Jamie Moffatt* [s], *Nicolas Say* [p], *Mimi Suzuki* [t], *Wei Lin Toh* [u], *Yuliya Zaytseva* [o,v], *Susan L. Rossell* [u,w], *Peter Moseley* [x] and *Todd S. Woodward* [a,b,c,*]

[a] BC Mental Health and Substance Use Services, Vancouver, UK

[b] Department of Bioinformatics, University of British Columbia, Vancouver, UK

[c] Department of Psychiatry, University of British Columbia, Vancouver, UK

[d] Department of Psychology, University of British Columbia, Vancouver, UK

[e] Department of Psychology, McGill University, Montreal, UK

[f] Department of Psychology, University of Roehampton, London, UK

[g] Department of Psychosis Studies, Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, UK

[h] Research Department of Clinical, Educational and Health Psychology, University College London, London, UK

[i] Department of Biological and Medical Psychology, University of Bergen, Bergen, Norway

[j] Univ. Grenoble Alpes, Laboratoire Inter-universitaire de Psychologie, University Grenoble Alpes, Grenoble, France

[k] Department of Psychology, Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, UK

[l] South London & Maudsley NHS Foundation Trust, Maudsley Hospital, London, UK

[m] Department of Psychology, Durham, UK

[n] Department of Psychology, University of Cambridge, Cambridge, UK

[o] Department of Applied Neurosciences and Brain Imaging, National Institute of Mental Health, Klecany, Czech Republic

[p] Department of Psychology, Faculty of Arts, Charles University, Prague, Czech Republic

[q] Psychology and Neuroscience of Cognition Research Unit, University of Liege, Liege, Belgium

[r] NORMENT—Norwegian Center of Excellence for Mental Disorders Research, University of Oslo, Oslo, Norway

[s] School of Psychology, University of Sussex, Falmer, UK

[t] Division of Psychiatry, University College London, London, UK

[u] Cognitive Neuropsychiatry Lab, Centre for Mental Health, Swinburne University, Melbourne, Australia

[v] Department of Psychiatry and Medical Psychology, 3rd Faculty of Medicine, Charles University, Prague, Czech Republic

[w] Department of Mental Health, St Vincent's Hospital, Melbourne, VIC, Australia

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[*] *Corresponding author.* BC Mental Health and Substance Use Services, Vancouver, UK.

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[x] *Department of Psychology, Northumbria University, Newcastle-Upon Tyne, UK*

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ABSTRACT

Hallucinatory experiences (HEs) can be pronounced in psychosis, but similar experiences also occur in nonclinical populations. Cognitive mechanisms hypothesized to underpin HEs include dysfunctional source monitoring, heightened signal detection, and impaired attentional processes. Using data from an international multisite study on non-clinical participants ($N = 419$), we described the overlap between two sets of variables - one measuring cognition and the other HEs - at the level of individual items. We used a three-step method to extract and examine item-specific signal, which is typically obscured when summary scores are analyzed using traditional methodologies. The three-step method involved: (1) constraining variance in cognition variables to that which is predictable from HE variables, followed by dimension reduction, (2) determining reliable HE items using split-halves and permutation tests, and (3) selecting cognition items for interpretation using a leave-one-out procedure followed by repetition of Steps 1 and 2. The results showed that the overlap between HEs and cognition variables can be conceptualized as bi-dimensional, with two distinct mechanisms emerging as candidates for separate pathways to the development of HEs: HEs involving perceptual distortions on one hand (including voices), underpinned by a low threshold for signal detection in cognition, and HEs involving sensory overload on the other hand, underpinned by reduced laterality in cognition. We propose that these two dimensions of HEs involving distortions/liberal signal detection, and sensation overload/reduced laterality may map onto psychosis-spectrum and dissociation-spectrum anomalous experiences, respectively.

1. Introduction

Hallucinations are a prominent symptom of schizophrenia spectrum disorder, with 60–80% of diagnosed patients experiencing auditory hallucinations, and a smaller percentage experiencing visual and other types of hallucinations (Bauer et al., 2011; Lim et al., 2016; Waters et al., 2014). Research has shown that approximately 10–15% of the general population also report experiences similar to hallucinations (Sommer et al., 2010), leading to the proposal of a continuum model of hallucinatory experiences (HEs) from health to disease (Aleman & Larøi, 2008; Powers et al., 2017; Siddi et al., 2019). Similarities have been reported in terms of featural and clinical characteristics, such as vivid and frequent voices, third-person hallucinations, personification, a recurrent course of hallucinations, and an increased risk for adverse negative events (Waters & Fernyhough, 2017). This proposed continuum presents an accessible opportunity to investigate the cognitive mechanisms underpinning HEs in a healthy sample, avoiding the potential influence of antipsychotic medications, stigma, and institutionalization. Candidate underpinning cognitive mechanisms include dysfunctional source monitoring, heightened signal detection, impaired attentional processes, and cortical hyperactivity (Braithwaite et al., 2013; Fong et al., 2019; Moseley et al., 2021). Through this approach, researchers can develop mechanistic models to better understand distressing or disabling experiences and assist in developing interventions based on the recognition that pathological hallucinations can be understood as extreme versions of healthy cognitive biases.

Previous attempts to study the cognitive mechanisms underlying HEs, either in clinical samples or in healthy populations under the assumption of a continuum, have shown inconsistent and sometimes contradictory findings. For example, although a number of studies have shown that a bias in source monitoring (i.e., externalization of internal cognition) is related to HEs in schizophrenia patients reporting hallucinations (Bentall et al., 1991; Brookwell et al., 2013; Morrison & Haddock, 1997; Woodward et al., 2007; Woodward & Menon, 2011), others have reported no link between misattribution of internal cognition to an external source with non-clinical hallucinations (Alderson-Day et al., 2019; Garrison et al., 2017), although one study has reported a link in the general population (Larøi et al., 2004). Auditory signal detection tasks have been used to study the cognitive and sensory mechanisms underlying hallucinations, with results suggesting a link between false alarm rates (of detecting a signal in white noise) and the severity of HEs in patients (Varese et al., 2012) and the general population (Barkus et al., 2011; Rankin & O'Carroll, 1995). There has also been evidence suggesting that reduced language lateralization in the brain is related to HEs. To assess this, studies have mainly used a consonant-vowel dichotic listening task, where the aim is to differentiate between auditory stimuli presented simultaneously to both ears. Typically, a left-hemisphere lateralization (i.e., right-ear advantage) is observed in the general population (Bless et al., 2015), with reduced lateralization reported for hallucinating psychosis patients (Ocklenburg et al., 2013). However, studies in the general population have shown no such reduction for hallucination prone participants (Aase et al., 2018; Conn & Posey, 2000).

In order to bring clarity to the literature using a standardized protocol and a large sample size, Moseley et al. (2021) carried out a pre-registered international multisite study (N = 1394) to investigate the link between the aforementioned theoretically and empirically important measures of cognition and HEs. Using an online protocol, non-clinical participants performed source monitoring, dichotic listening, backwards digit span, matrix reasoning, and auditory signal detection tasks; along with assessments of HEs with the 32 items of the Cardiff Anomalous Perceptions Scale (CAPS; Bell et al., 2006) and the 16 items of the Launay-Slade Hallucination Scale - Extended (LSHS-E; Larøi & Van Der Linden, 2005) across 11 data collection centers. Although most cognitive tasks were selected based on theoretical models on HE (e.g., Waters et al., 2012), the matrix reasoning task was included to provide a general index of non-verbal intelligence. It was found that the false alarm rate in auditory signal detection was associated with HEs, with the latter measured by the aggregate scores for the CAPS and LSHS-E items. No associations between the HE scales and other cognition measures were reported.

When studying overlap between two sets of variables, summed aggregate scores are often used, due to concerns regarding Type I errors associated with assessment of multiple tests of statistical significance when each variable is individually analyzed. Although this approach is valid, by definition it restricts the analysis to only the aggregated variance, and neglects the specific variance measured by each individual variable. For example, the CAPS and LSHS-E inquire about anomalous perceptions in multiple sensory modalities (namely, vision, sound, taste, temperature, and pressure); therefore, a summary score would not capture modality-specific information. This neglect is not strictly necessary. We propose a method that allows the study of overlap between two sets of variables at the level of individual items on different dimensions, without increased concern over reporting spurious results. It involves variance constraints, dimension reduction, split-half reliability, and permutation tests at the level of individual items, invoked in a three-step process, described in detail below.

The published, preregistered study that provided the data for this work (Moseley et al., 2021) measured HEs by summing scores for all items on the CAPS, and four hypotheses were preregistered for how each domain of cognition would relate to this summary scale. The purpose of pre-registering hypotheses, and using only one summed-score predictor variable for HEs, was to avoid publishing Type I errors (false positives) by limiting the number of statistical tests performed. The current study uses a subset of the data published by Moseley et al. (2021), but instead of controlling Type I errors by preregistration and computing one summary variable, an exploratory approach involving a three-step statistical method is used to uncover associations between cognition and HEs at individual item level. *Step 1* involved constraining the variance in the criterion variables (cognition) to that explained by the predictor variables (HEs) and extracting components that summarize the overlap between these two sets of variables. The components from *Step 1* structurally associate the criterion and predictor variables, but without providing item-level associations. This is followed by two additional steps designed to detect which specific individual variables are responsible for this overlap, with *Step 2* applied to the set of predictor variables, and *Step 3* to the set of criterion variables (in this case, HEs and cognition, respectively). These steps involved split-half reliability and permutation tests to determine which specific combinations of individual items reliably describe the associations between the two sets of variables.

This three-step process simultaneously avoids reporting spurious results and includes individual-item-specific variance which might be considered off-limits when summary scores are analyzed, potentially providing finer delineation of the nature of the overlap between two sets of variables. The approach is exploratory in the sense that one item is not given a higher theoretical importance than any other item, and interpretation is focused on the combination of individual items which provide the most reliable signal with respect to overlap between HE and cognition.

2. Methods

2.1. *Participants*

As part of a larger study (Moseley et al., 2021), data from 647 participants were collected in person at one of 11 data collection sites: Durham University, University of Roehampton, King's College London, University College London, University of Cambridge (all UK), University Paul Valéry (France), University of Groningen (Netherlands), Charles University (Czech Republic), University of Bergen (Norway), University of British Columbia (Canada), and Swinburne University (Australia). Data were also collected for a subset of tasks on 866 participants online, but were not included in the present analysis, because not all tasks of interest (namely, auditory signal detection) were collected online, and the multivariate nature of the current analysis required all subjects to have all measures. Participants were required to be aged 18–75 years, fluently speak the native language of the respective country, and have no diagnosed hearing impairments. Participants were given a nominal honorarium for participation at the discretion of each participating site, or were rewarded with course credits, where applicable. All sites obtained ethical clearance from their relevant institutional review board, in accordance with the Declaration of Helsinki.

In the present work, first, we applied the exclusion criteria described in the pre-registration of the original study (Moseley et al., 2021), which reduced the sample size to 594, largely based on quality control (e.g., people who reported diagnosed hearing impairments, or who failed attention checks). Second, task-by-task exclusion was performed as described in the Methods section for each task. Due to the multivariate nature of the analysis, we included only participants who had valid data for all questionnaire items (CAPS and LSHS-E) and all cognition measures (consonant-vowel dichotic listening, matrix reasoning, source monitoring, auditory signal detection, and backwards digit span tasks). This resulted in a final sample of 419.

2.2. Questionnaires

2.2.1. *Cardiff Anomalous Perceptions Scale (CAPS)*

The CAPS (Bell et al., 2006) consisted of 32 items inquiring about anomalous perceptions in the sensory modalities of vision, sound, taste, temperature, pressure, and smell (e.g., 'Do you ever notice that sounds are much louder than they normally would be?'), and provides yes/no as response options. Conventionally, the total number of items for which the participant responded 'yes' (scored as 1, so that scores varied from 0 to 32) is used as a metric for indicating the degree of HEs, with higher values indicating higher levels of HEs. For each item that the participants responded to as 'yes', they were also prompted to rate how much distress it caused them, how disruptive or intrusive, and how frequent the experiences were on a Likert scale of 1–5. In this study, to keep the ratio of participant to predictor variables high, only yes/no responses to the main 32 items were included in the analysis, considered separately, with no summary score computations.

2.2.2. *Launay-Slade Hallucination Scale - Extended (LSHS-E)*

The LSHS-E (Larøi & Van Der Linden, 2005) consisted of 16 items inquiring about anomalous perceptions in the sensory modalities of vision, sound, pressure, and smell (e.g., 'I often hear a voice speaking my thoughts aloud'), and participants were asked to respond on a 5-point Likert scale as to how much each item applies to them (0 = Certainly does not apply to me, 4 = Certainly applies to me). Conventionally, the overall score is calculated as the sum of the score for each item (0–64). In this study, the Likert scale responses recorded for each of the 16 items were analyzed, and no summary score was computed.

2.3. Tasks

2.3.1. *Source Monitoring task (SM)*

Source monitoring task required participants to recall whether words had been presented as spoken stimuli through headphones (HEAR trials), or whether they had simply been instructed to imagine hearing the words (IMAGINE trials). Three lists of 24 words were assembled and matched for the number of letters, syllables, frequency of use, concreteness, and imageability. For each participant, one list was randomly assigned to the HEAR trials, and another to the IMAGINE trials. The third list was assigned to the NEW condition in the second stage of the task.

In the first stage of the task, participants were presented with a series of words in the center of the screen (duration = 3s), each preceded by the word HEAR or IMAGINE (duration = 1s). For trials on which they heard the stimuli, a word from the HEAR condition was presented in the center of the screen, and an audio clip of that word being spoken by a male, in a neutral tone, was presented concurrently. For trials on which participants were instructed to imagine the word, a word from the Imagine condition was presented on the screen, but no speech clip was played. The HEAR and IMAGINE trials were randomly interleaved. The second stage of the task began immediately after the first was completed. Participants were presented with all 48 words from Stage 1, presented in random order, as well as 24 new words. For each word, they were instructed to decide whether they had heard the word, imagined the word, or whether the word was new. Nine source monitoring (SM) variables were included in the analysis - three correct response counts (Hear–Hear, Imagine–Imagine, and New–New), and six incorrect response counts [Hear-Imagine (internalization), Imagine-Hear (externalization), Hear-New (miss), Imagine-New (miss), New-Hear (false positive external), and New-Imagine (false positive internal)]. Data from four participants (out of 594) for this task were excluded due to scoring below 33.3% overall accuracy, below 50% on old-new accuracy, or both.

2.3.2. *Consonant-vowel Dichotic Listening (DL)*

The dichotic listening task is designed to assess language lateralization in an unforced condition and two 'forced attention' conditions. The task involved the simultaneous presentation of two audio clips of spoken consonant-vowel syllables, with a different syllable presented to each ear. The presented syllables are 'ba', 'da', 'ka', 'ta', 'pa', and 'ga', with each clip lasting approximately 350 msec. In the 'non-forced attention' condition, the participant was required to select the syllable they could hear most clearly. In the 'forced right' and 'forced left' conditions, the participant was instructed to select the syllable they believe had been presented to the right or left ear, respectively. Participants provided a response via mouse click on a visual display of all 6 syllables spelled out in capital letters. Participants first performed the non-forced task, followed by the forced ones. The order of the forced left and right was counterbalanced across participants.

There were 36 trials in each condition, presented in a random order, including 6 homonym trials (with the same syllable presented to each ear). The homonym trials were excluded from data analysis and were used only as a data quality check (see below). The remaining 30 trials consisted of all possible combinations of the 6 syllables presented to each ear. The total number of selected syllable responses matching presentations to the right ear (right ear score, RES) and the left ear (left ear score, LES) were counted for all three conditions ('non-forced', 'forced right' and 'forced left'). A laterality index was calculated for each condition as follows: Laterality Index = $[(\text{RES} - \text{LES})/(\text{RES} + \text{LES})] * 100$, and these were submitted to the multivariate analysis. 36 participants (out of 594) were excluded from the dichotic listening task performance due to scoring $< 50\%$ accuracy on homonymous trials in any of the three task conditions, scoring a laterality index of 100% to one ear, or both, as per Bless et al., 2015.

2.3.3. *Auditory Signal Detection (SgD)*

The auditory signal detection task required the participant to respond whether they believed a speech clip had been embedded in noise. The signal-to-noise ratio (SNR; that is, the ratio of the volume of the voice clip to the noise) was determined individually at each site using a short calibration task, in which participants, who did not participate in the main study (N = 10 per site), were presented with speech clips embedded in noise at a variety of SNRs.

In the main task, the participants were presented with 72 bursts of 'pink noise' of 3.5s duration, with a 1.5s speech clip in the middle, presented at one of four SNRs in 36 trials (speech-present), and with no speech clip presented at all in 36 trials (speech-absent). The speech clips were the same as those used in previous studies using this task (Barkus et al., 2011), consisting of a male voice reading a text (taken from an instruction manual) in an emotionally neutral tone. After each burst of noise, participants were presented with the text “Did you hear speech?” and they responded by clicking a mouse button for Yes or No. For each trial, they were also then prompted to enter a confidence rating. Confidence ratings were not analyzed as part of this study. Signal detection measures sensitivity (d′), and response bias (β) were estimated (Stanislaw & Todorov, 1999). The hit rate, false alarm, sensitivity, and response bias were included in the analysis. Data from 11 participants (out of the 594 in-lab participants) were excluded from the auditory signal detection task data due to scoring a d′ of ≤ 0 (indicating at or below chance performance), or a hit rate of $\leq 10\%$, or both.

2.3.4. *Matrix Reasoning (MR)*

This task was included to provide a brief assessment of non-verbal reasoning ability. 10 items were taken from the International Cognitive Ability Resource (previously tested in a general population sample of >97,000 participants; Condon David & Revelle, 2014). The task is based on Raven's Progressive Matrices, with participants completing a 3 × 3 grid of shapes, choosing from six options, within 60s. The raw number of correct responses (maximum 10) was used as an assessment of non-verbal reasoning ability, and this matrix reasoning score was included in the analysis.

2.3.5. *Backwards Digit Span (DS)*

The digit span task assessed verbal working memory performance in participants. In each trial, a series of numeric digits were shown, and then the participants were asked to recall these digits in reverse order. Digits (1–9) were randomly sampled without replacement (until after trial length of 10) and were presented on the center of the screen for 1s each. In each trial, the length started at 2 digits, and was varied according to the rules set out in Woods et al., 2011; that is, when the participant correctly recalls the digit string, trial length is increased by 1, whereas the trial length was decreased by 1 if there are two consecutive incorrect responses. Participants completed 14 trials and responded using a mouse to click the digits they wished to input on an on-screen keypad. Performance was assessed using the mean span metric, that is, the length of the trial at which the participant performs with 50% accuracy.

2.4. *Data analysis*

Step 1: Variance Constraints and Dimension Reduction through Constrained Principal Component Analysis (CPCA). In order to determine the links between cognition measures and HE items, CPCA was used, which combines the variance constraints of multivariate multiple regression and the dimension reduction of PCA into a unified framework (Takane & Hunter, 2001; Takane & Shibayama, 1991). The current application of CPCA involves extraction of orthogonal dimensions in the criterion variables (cognition) that are optimized to be predictable from a set of predictor variables (HEs). The component loadings indicate the importance of each criterion variable (cognition) for each component, and predictor loadings indicate the importance of each predictor variable (HEs) for each component. Component loadings and predictor loadings must be interpreted in conjunction because they are different pieces of information about the same components. More specifically, component loadings and predictor loadings are computed as correlations with rotated component scores, but these correlations are computed with the variance-constrained cognition variables and the HE variables, respectively. Since the component and predictor loadings are correlation coefficients, (Pearson's r), they also provide effect sizes, because the loading value squared (r^2) is the variance explained between variables, equivalent to the η^2 effect size used in analysis of variance (Cohen, 1992). The CPCA methodology used here is described in greater detail in the Supplementary Material (see Fig. S1).

Step 2: Identifying Reliable Predictor Loadings (HEs). CPCA analysis described in Step 1 provides components that structurally associate the criterion and predictor variables, but as with standard PCA, it does not indicate the reliability of the individual items. To test the reliability of the predictor items, we performed 1,000 iterations of a split-half reliability test. First, component reliability proportions were computed for each full-sample CPCA component: the proportion of the 1,000 iterations for which component pairs were not only deemed reliable by way of split-half methodology, but also passed the criteria for being declared a match to a component from the full sample. Components with reliability proportions <.5 were rejected from the analysis due to unreliable component loading structure. A detailed explanation regarding the methodology can be found in the Supplementary Material; for details regarding selection of various thresholds in the three-step process, see Supplementary Material, section on Rationale for Thresholds. Then, in order to determine the reliability of individual predictor variables (HEs), a predictor loading reliability proportion was computed for each predictor variable (only for components with reliability proportions $\geq$.5): the proportion of the reliable components from the 1,000-iteration procedure described above that showed predictor loadings greater than or equal to .19 in both split-half solutions. This process, including the selected reliability threshold, is described in more detail in the Supplementary Material (see Fig. S2). This cutoff was applied separately for positive loadings ($\geq$ .19) and negative loadings ($\leq -$.19). Predictor variables with loading reliability proportions $\geq$ .48 were deemed reliable.

Step 3: Identifying Criterion Variables for Interpretation (Cognition). CPCA provides component loadings that indicate the importance of each criterion variable (cognitive measures) for each component. Conventionally, in PCA, the dominant loadings greater than an arbitrary threshold are interpreted. Here, leveraging the additional information provided by the reliability checks on the predictor loadings in Step 2, we provide a data-driven leave-one-out procedure to select sets of component loadings for interpretation, based on information about reliability of the predictor loadings. Specifically, the variance attributable to each criterion variable was regressed out of the remaining criterion variables (leave-one-out procedure for cognitive measures), and the predictor loading reliability proportions recomputed (as in Step 2) for the predictor variables deemed reliable at Step 2 (on the full Z matrix) for each component separately. Interpretable criterion variables were those that produced a reduction in predictor loading reliability proportions when regressed out. Next, we tested whether all the reliable predictor variables identified in Step 2 (full Z matrix) remained reliable when only the subset of criterion variables selected for interpretation was included. Towards this end, we performed Step 1 and Step 2 with the full Z matrix, but recomputed component scores using only the component loadings corresponding to the set of criterion variables selected for interpretation (detailed explanation can be found in the Supplementary Material, section on Three-Step CPCA, Step 3: Identifying Criterion Variables for Interpretation), and the corresponding recomputed predictor loadings, and re-computed the predictor loading reliability proportions. Thus, we interpret only the combination of predictor and criterion items that were deemed reliable in both CPCA analyses: one with the full set of items (Step 1 and 2), and the other with only a set of criterion variables selected for interpretation (Step 3). More details regarding this methodology can be found in the Supplementary Material (see Fig. S3).

2.5. *Data availability and transparency statement*

All the data and code necessary to reproduce the results in the paper have been uploaded to a publicly accessible repository (https://osf.io/aeg5d/). The full dataset used in the original study can be found here (https://osf.io/eqy76/). No part of the secondary analysis reported in this paper was preregistered prior to the research being conducted. We report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to secondary data analysis, all manipulations, and all measures in the study (see Methods, section on Participants).

3. Results

Step 1: Variance Constraints and Dimension Reduction through Constrained Principal Component Analysis (CPCA). CPCA was performed with 18 cognitive measures as the criterion variables and 48 HE questionnaire items as the predictor variables. The multivariate overlap between cognition and HEs revealed that HE items accounted for 13% of the total variance of the cognition variables, and six components (determined by the scree plot, Fig. S4; Cattell & Vogelmann, 1977) were extracted from PCA on the predicted score matrix of cognition variables. These six components captured 77.02% of the variance in the set of predicted scores, and were varimax rotated. In-detail explanations of CPCA methodology can be found in Supplementary Material (see Methods section in Supplementary Material and Fig. S1).

Step 2: Identifying Reliable Predictor Loadings (HEs). Table 1 lists the component loadings for all six extracted components. A permuted split-half reliability->match permutation test for component loadings determined that Component 6 should be excluded from further interpretation due to a low component reliability proportion score (.35). An example correlation matrix from one of the 1,000-iteration reliability iterations is shown in Table S1, and the component reliability proportions that resulted from the completion of the reliability->match process are presented in Table S2. Table 2 lists all predictor loadings for the full sample (relating HE variables to components). Split-half permutation tests for predictor loadings served to identify those which reliably loaded onto the CPCA components, and these predictor loading reliability proportions are presented in Table S3 (positive loadings) and Table S4 (negative loadings). Reliable predictor loadings are listed in Table 3 and are indicated by bold font in Table 2, based on positive predictor loading reliability proportions tabulated in Table S3. All negative predictor loading reliability proportions (Table S4) were extremely low, and therefore no negative predictor loadings were interpreted. Step 2 is described in further detail in the Supplementary Material (see Fig. S2).

Table 1 – Component loadings for the predicted (GC) solution.

	Components					
	1	2*	3*	4	5	6
Dichotic Listening (DL) Laterality Indices						
Non-forced	−.03	.09	**−.23**	−.05	−.01	.15
Forced left	.03	.07	**.24**	−.12	.05	.16
Forced right	.06	−.05	**−.31**	−.01	.02	−.03
Source Memory Task (SM) Measures (Source - Response)						
Hear - Hear	.12	−.01	−.04	−.01	.29	−.01
Hear - Imagine	−.25	−.08	.04	.11	−.17	.03
Hear - New	.13	.11	.01	−.11	−.19	−.03
Imagine - Imagine	.02	−.01	.03	.03	.21	.17
Imagine - Hear	−.02	.03	−.01	−.05	.01	−.27
Imagine - New	−.01	−.01	−.03	−.00	−.26	.03
New - New	.34	.08	.02	.15	.03	.08
New - Hear	−.11	.01	−.01	−.33	.01	−.08
New - Imagine	−.33	−.10	−.02	.00	−.04	−.05
Matrix Reasoning (MR)						
MR Score	.21	.02	−.14	.11	−.04	−.08
Digit Span (DS)						
Mean Span	−.03	.13	−.03	.15	.06	−.01
Signal Detection Task (SgD)						
Hit Rate	.13	**.32**	−.02	.07	.07	−.05
False Alarm Rate	.12	**.35**	−.01	−.04	−.03	.04
Sensitivity (d′)	−.01	**−.20**	−.03	.07	.1	−.05
Response bias (β)	−.03	**−.29**	−.03	−.06	−.01	.04

Note. *Components that were deemed reliable according to the component reliability proportions presented in Table S2 and predictor loading reliability proportions in Tables S3 and S4. Component reliability proportions for components 1–6 are as follows – 1.00, 1.00, .83, .64, 1.00, and .35. Dominant component loadings, determined in Step 3, are highlighted as bold. CPCA requires Table 2 (component loadings) and Table 3 (predictor loadings) to be interpreted in conjunction.

Step 3: Identifying Criterion Variables for Interpretation (Cognition). To determine sets of criterion variables for interpretation, using a leave-one-out procedure, we regressed out each criterion variable from the remaining set of criterion variables (cognitive measures) and recomputed the predictor loading reliability proportions, as described in Steps 1 and 2. The average predictor loading reliability proportions for all the reliable HE items (which were determined

Table 2 – Predictor loadings for the predicted (GC) solution.

	Components					
	1	2*	3*	4	5	6
CAPS Questionnaire Items						
1: Do you ever notice that sounds are much louder than they normally would be?	.14	.19	.19	−.08	−.08	.12
2: Do you ever sense the presence of another being, despite being unable to see any evidence?	.01	**.32**	.13	−.19	−.08	−.22
3: Do you ever hear your own thoughts repeated or echoed?	.04	.11	.26	.08	−.03	.03
4: Do you ever see shapes, lights or colours even though there is nothing really there?	−.09	.12	.11	.12	−.08	.06
5: Do you ever experience unusual burning sensations or other strange feelings in or on your body?	.06	.11	−.19	.02	−.27	−.07
6: Do you ever hear noises or sounds when there is nothing about to explain them?	.14	.02	.24	−.05	−.2	.16
7: Do you ever hear your own thoughts spoken aloud in your head, so that someone near might be able to hear them?	.15	.03	.29	.00	−.09	.10
8: Do you ever detect smells which don't seem to come from your surroundings?	.23	.17	.25	−.05	−.21	−.04
9: Do you ever have the sensation that your body, or a part of it, is changing or has changed shape?	−.03	−.07	.05	.20	−.07	−.02
10: Do you ever have the sensation that your limbs might not be your own or might not be properly connected to your body?	.16	.25	−.12	.22	−.01	.14
11: Do you ever hear voices commenting on what you are thinking or doing?	.22	−.12	.12	−.14	−.1	.08
12: Do you ever feel that someone is touching you, but when you look nobody is there?	−.06	.11	.03	.09	−.1	.08
13: Do you ever hear voices saying words or sentences when there is no-one around that might account for it?	.13	**.48**	−.13	−.05	−.05	.25
14: Do you ever experience unexplained tastes in your mouth?	−.02	.22	.20	.10	.06	−.02
15: Do you ever find that sensations happen all at once and flood you with information?	.19	.14	**.39**	.12	−.08	.08
16: Do you ever find that sounds are distorted in strange or unusual ways?	−.02	.24	.18	.01	−.09	.08
17: Do you ever have difficulty distinguishing one sensation from another?	.24	.28	.26	.12	.03	−.05
18: Do you ever smell everyday odours and think that they are unusually strong?	.04	.21	.04	.06	−.36	−.01
19: Do you ever find the appearance of things or people seems to change in a puzzling way, e.g., distorted shapes or sizes or colour?	−.11	.30	.12	−.17	.00	.04
20: Do you ever find that your skin is more sensitive to touch, heat or cold than usual?	.04	−.07	.02	.03	.17	.21
21: Do you ever think that food or drink tastes much stronger than it normally would?	.13	−.01	.13	.20	.13	−.35
22: Do you ever look in the mirror and think that your face seems different from usual?	−.10	.16	.09	.11	.15	.06
23: Do you ever have days where lights or colours seem brighter or more intense than usual?	−.01	.07	.04	.03	−.04	−.04
24: Do you ever have the feeling that of being uplifted, as if driving or rolling over a road while sitting quietly?	.20	.33	−.10	.04	−.02	−.03
25: Do you ever find that common smells sometimes seem unusually different?	−.02	.23	.15	.21	−.24	.09
26: Do you ever think that everyday things look abnormal to you?	.19	**.41**	.19	−.22	.09	.20
27: Do you ever find that your experience of time changes dramatically?	.15	.10	.03	.10	.19	−.01
28: Have you ever heard two or more unexplained voices talking with each other?	.15	.15	.03	−.04	.15	.16
29: Do you ever notice smells or odours that people next to you seem unaware of?	.06	.20	.01	.07	−.12	−.20
30: Do you ever notice that food or drink seems to have an unusual taste?	−.12	.14	.17	.09	−.11	−.16
31: Do you ever see things that other people cannot?	.30	.03	.17	.23	−.18	.21
32: Do you ever hear sounds or music that people near you don't hear?	.28	.29	.01	.14	−.05	.02
LSHS-E Questionnaire Scores						
1: Sometimes a passing thought will seem so real that it frightens me	.03	.21	.26	−.14	−.07	−.03
2: Sometimes my thoughts seem as real as actual events in my life	−.02	.21	.24	.03	−.15	.03
3: No matter how hard I try to concentrate on my work unrelated thoughts always creep into my mind	−.10	.01	.11	.08	−.12	.13
4: In the past, I have had the experience of hearing a person's voice and then found that no one was there	.03	.30	.10	.13	.09	.12
5: The sounds I hear in my daydreams are generally clear and distinct	.15	.10	.23	−.07	.25	.04
6: The people in my daydreams seem so true to life that I sometimes think that they are	.04	.20	.35	.17	.08	.11
7: In my daydreams I can hear the sound of a tune almost as clearly as if I were actually listening to it	.02	.02	.19	.04	.09	.05
8: I often hear a voice speaking my thoughts aloud	.09	.00	.06	−.09	−.17	−.05
9: I have been troubled by hearing voices in my head	.25	**.36**	.24	−.19	−.12	−.05
10: On certain occasions, I have seen the face of a person in front of me, but there was no one	.04	.17	.33	.01	.04	.33
11: Sometimes, immediately prior to falling asleep or upon awakening, I have had the experience of having seen or felt or heard something or someone that wasn't there or the feeling of being touched even though no one was there	.05	.04	−.07	−.36	.00	.19
12: Sometimes, immediately prior to falling asleep or upon awakening, I have had a sensation of floating or falling or that I left my body temporarily	.04	.09	−.19	.07	.10	−.09
13: On certain occasions I have had the feeling of the presence of someone close who has deceased	−.15	−.01	.25	−.19	.03	−.09

(*continued on next page*)

Table 2 – (*continued*)

	Components					
	1	2*	3*	4	5	6
14: In the past, I have smelt a particular odour when there was nothing there	−.05	.21	.34	−.12	−.05	−.12
15: I have had the feeling of touching something or being touched and then found that nothing or no one was there	.15	.11	.11	−.09	−.07	.00
16: Sometimes I have seen things or animals when nothing was in fact there	−.23	.19	.06	−.01	−.04	.15

Note: *Components that were deemed reliable according to the component reliability proportions presented in Table S2 and predictor loading reliability proportions in Tables S3 and S4. Reliable predictor loadings are highlighted in bold font, and this is based *not* on the magnitude seen in this table, but on the reliability proportions for positive and negative predictor loadings presented in Table S3 and S4, respectively. Component 2 corresponds to lower sensitivity and more liberal responses in the auditory signal detection task and Component 3 is associated with reduced laterality measured by the dichotic listening task. Component 6 is not interpreted due to low component reliability proportions (see Table S2). Components 1, 4, and 5 are not interpreted due to low predictor loading reliability proportions (see Table S3 and S4). CPCA requires that Table 2 (component loadings) and Table 3 (predictor loadings) be interpreted in conjunction. CAPS = Cardiff Anomalous Perceptions Scale; LSHS-E = Launay-Slade Hallucination Scale - Extended.

on full Z matrix), after regressing out each criterion variable from the remaining set of criterion variables, is plotted in Fig. 1A for Component 2 and Fig. 1B for Component 3 (the only two components with reliable predictor loadings computed on the full Z matrix). Components 1, 4, and 5 were not analyzed further due to having no reliable predictor loadings at Step 2, and Component 6 was rejected due to low component reliability proportions at Step 2. The criterion variables in Fig. 1A,B are sorted left-to-right based on ascending values of mean predictor loading reliability proportions, averaged over all predictor loadings reliable at Step 2 (full Z matrix), once the criterion variable in question has been regressed out of the remaining criterion variables. Thus, the criterion variables that substantially reduce the mean predictor loading reliability proportions, when regressed out, are selected for interpretation. For example, regressing signal detection false alarm rate out of all other criterion variables resulted in a reduction in the average reliability of the four full-Z-reliable predictor loadings (i.e., those that were reliable in the main analysis in Steps 1 and 2) to essentially zero (Fig. 1A), suggesting that false alarm rate must be retained. Using criteria similar to scree plots for component selection (Cattell & Vogelmann, 1977), we interpret the first 4 variables in Fig. 1A as component loadings for Component 2 – signal detection false alarm rates, hits, response bias (β), and sensitivity (d'). Similarly, for Component 3, regressing dichotic listening forced right laterality index resulted in a reduction in the reliability of sensory overload (reliable in the main analysis) to essentially zero, suggesting that dichotic listening forced right laterality index must be retained, along with dichotic listening forced left laterality index, and dichotic listening laterality index. More details on Step 3 can be found in the Supplementary Material (see Fig. S3).

3.1. *Component interpretation*

The interpretation of components is based on the information summarized in Table 3 and/or Fig. 2. Interpretation is limited to Components 2 and 3 because these were the only ones with reliable predictor loadings (as described in Step 3). Component 2 was dominated in the cognition domain by loadings for auditory signal detection features: positive loadings for hits (r = .32) and false alarms (r = .35), and negative loadings for sensitivity (d′, r = −.20) and response bias (β, r = −.29). This indicates that high component scores corresponded to participants using a liberal threshold when detecting speech against background noise. This component was dominated in the HE domain by four predictor items, with two being related to auditory HEs: 'Do you ever hear voices saying words or sentences when there is no-one around that might account for it?' (CAPS 13, r = .48) and 'I have been troubled by hearing voices in my head' (LSHS 9, r = .36), and the other two related to perceptual distortions: 'Do you ever think that everyday things look abnormal to you?' (CAPS 26, r = .41) and 'Do you ever sense the presence of another being, despite being unable to see any evidence?' (CAPS 2, r = .32).

Component 3 consisted of the dichotic listening measures sensitive to laterality. It had dominant positive component loadings for forced left laterality index (r = .24), and strong negative loadings for forced right laterality index (r = −.31) and non-forced laterality index (r = −.23). This indicates that higher scores on this component correspond to higher left-ear advantage, interpreted as reduced left-brain lateralization for phoneme detection. This component had high predictor loading reliability proportions (see Table 3) for only one item: 'Do you ever find that sensations happen all at once and flood you with information?' (CAPS 15, r = .39). This indicates a link between reduced left-brain lateralization and feeling overwhelmed by an overload of sensory information.

Components 1, 4, and 5 were dominated by component loadings for source-monitoring-based cognition measures. Although the component loading structures were reliable, no individual predictor loadings passed the reliability criteria for Components 1, 4, or 5 (see Table S3 and S4). Therefore, more details regarding these components are reported only the Supplementary Materials. As mentioned above, Component 6 was excluded from interpretation due to low component reliability proportions.

4. Discussion

In this international multisite study, the overlap between two sets of variables was investigated, one measuring cognition, and the other HEs. This overlap was studied at the level of

Table 3 – Summary of component characteristics and interpretations.

Dominant component loadings (Cognitive Variables)	Reliable predictor loadings (HE Variables)	Interpretation
Component 2		
SgD Hits (.32)	CAPS 2: Presence of being (.32)	Liberal SgD/perceptual distortions
SgD False alarms (FA) (.35)	CAPS 13: Hear voices (.48)	
SgD Sensitivity (d′) (−.20)	CAPS 26: Things look abnormal (.41)	
SgD Response bias (β) (−.29)	LSHS-E 9: Troubled by voices (.36)	
Component 3		
DL Non-forced laterality index (−.23)	CAPS 15: Sensations flood (.39)	Reduced laterality/sensory overload
DL Forced left laterality index (.24)		
DL Forced right laterality index (−.31)		

Note. The component and predictor loading values (in parenthesis) are a measure of effect size. HE = hallucinatory experiences; SgD = signal detection; DL = dichotic listening; CAPS = Cardiff Anomalous Perceptions Scale; LSHS-E = Launay-Slade Hallucination Scale - Extended.

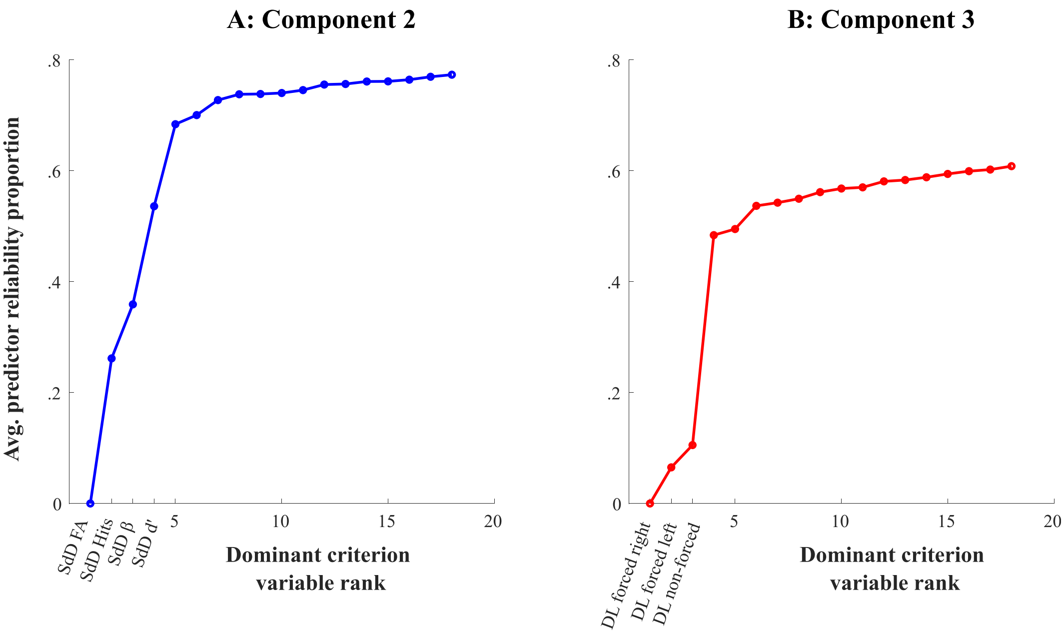

Fig. 1 – A: Average predictor loading reliability proportions obtained by regressing each criterion variable out of the remaining criterion variables (see Supplementary Material, section on Step 3: Identifying Criterion Variables for Interpretation), for Component 2. For example, regressing SgD FA out of all other criterion variables resulted in a reduction in average reliability of all four-predictor loading (those that were reliable in the main analysis) to essentially zero, suggesting that SgD FA is essential to the dimensional structure of the results. Using a criteria similar to component selection in a scree plot (Cattell & Vogelmann, 1977), we retain first 4 variables as dominant component loadings for Component 2 – SgD FA, hits, β, and d'. SgD = signal detection task; FA = False alarms; β = response bias; d' = sensitivity. B: Average predictor loading reliability proportions obtained when regressing each criterion variable out of the remaining criterion variables, for Component 3. For example, regressing DL forced-right laterality index out of all other criterion variables resulted in a reduction in reliability of sensory overload (reliable in the main analysis) to essentially zero, suggesting that DL forced right laterality index is essential to the dimensional structure of the results. Using a similar criterion as above (Fig. 1A), we retain 3 variables – DL forced right laterality index, DL forced left laterality index, and DL non-forced laterality index. DL = dichotic listening task.

individual items, and avoided reporting spurious results by using variance constraints, dimension reduction, split-half reliability tests, and permutation tests. The results showed that HEs overlapped with cognition on two reliable dimensions: (1) HEs involving sensory distortions (hearing voices, troubled by voices, everyday things look abnormal, and sensing the presence of another being) were associated with a lowered threshold for signal detection of auditory stimuli, and (2) HEs involving experiences of sensory overload were associated with reduced laterality in the dichotic listening task. Based on these results, the overlap between HEs and cognition variables can be conceptualized as bi-dimensional: one involving distortions/liberal signal detection, and the other involving overload/reduced laterality.

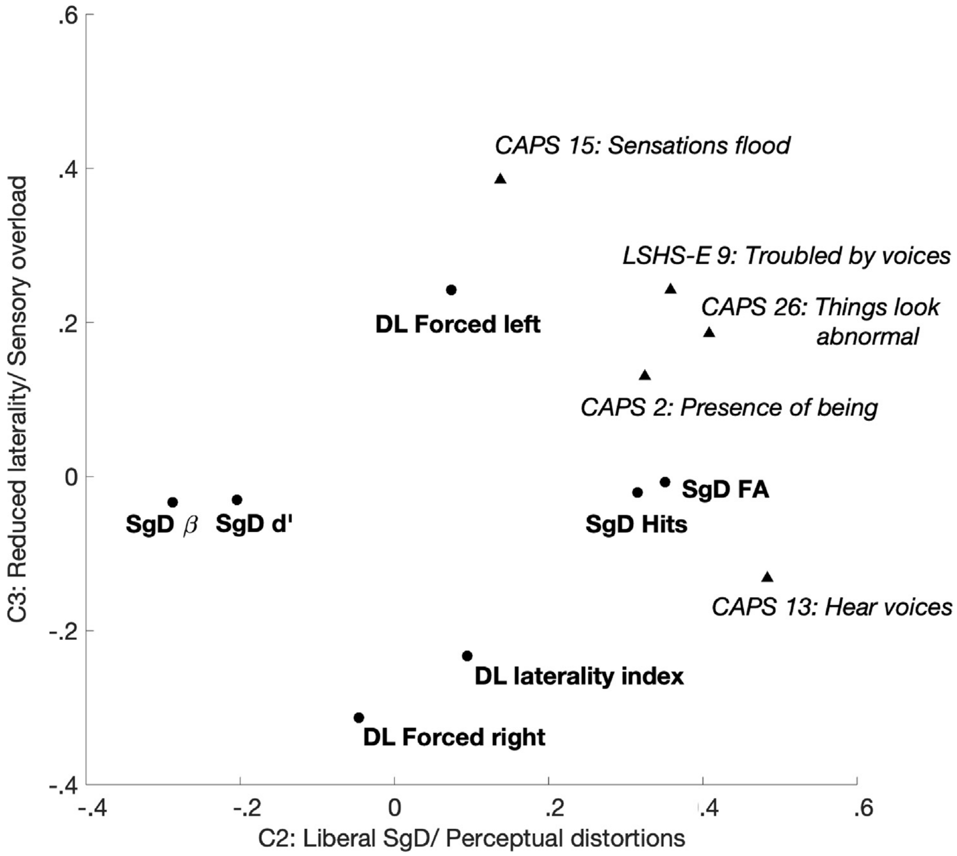

Fig. 2 – Dominant component loadings (circles and bold font) and predictor loadings (triangles and italic font) with Component 2 plotted against Component 3, for values displayed in Tables 2 and 3. C2 = Component 2; C3 = Component 3; SgD β = signal detection response bias; SgD d′ = signal detection sensitivity; DL = dichotic listening; SgD Hits = signal detection hit rate; SgD FA = signal detection false alarm rate. Component loadings and predictor loadings must be interpreted in conjunction because they display different pieces of information about the same components.

The cognition aspect of Component 2 was composed of auditory signal detection measures, such that lower sensitivity (d′) and a lower response bias (β), and the ensuing higher hits and false alarms, were associated with modality-general HEs involving sensory distortions (hearing voices, troubled by voices, everyday things look abnormal, and presence of being). In the pre-registered study (Moseley et al., 2021), one of the hypotheses was that false alarms would be positively associated with HEs, which was supported in that work by a correlation between false alarms and the CAPS summary score; in addition, significant correlations between the CAPS summary score and hit rate and response bias (β) in signal detection were also reported, as was an association with sensitivity (d′), although the latter was non-significant, but reported to be not statistically equivalent to 0. Thus, the cognition side of the results (strong contributions for false alarms, hit rate and response bias, and weaker but still meaningful contributions for sensitivity) were similar to the previously reported results based on data collected in the same study (Moseley et al., 2021). However, using the current individual-item-level analysis allowed specification of the four HE items (collectively interpreted as perceptual distortions) that were underlying the previously reported association between signal detection parameters and the CAPS summary score. This more refined result is novel relative to the literature, because all previous signal detection studies either (1) compared between schizophrenia and controls (Chhabra et al., 2016), (2) grouped participants based on scale summary scores (Barkus et al., 2007, 2011; Bentall & Slade, 1985; Rankin & O'Carroll, 1995), (3) grouped based on one general symptom rating scale item (Vercammen et al., 2008), or (4) correlated with/grouped based on scale summary scores (Moseley et al., 2016; Varese et al., 2012), meaning that the dimensional contribution of individual HE items has not previously been reported. The link between distorted perception and the signal detection parameters can be described as increased perceptualization (Beck & Rector, 2003), which can be explained by an increased overlap between signal and noise distributions, compensated for by a more liberal decision criteria, and which may become exacerbated by the stress often associated with hallucinatory experiences (Beck & Rector, 2003). Accordingly, it has been demonstrated that fewer available cognitive resources, and a negative emotional state, lead to increased false alarms in signal detection tasks, and that the degree of certitude is correlated with a higher degree of hallucination proneness (Laloyaux et al., 2019).

The cognition aspect of Component 3 involved dichotic listening measures, showing strong positive loadings for forced left laterality index, and strong negative loadings for forced right laterality index and non-forced laterality index, indicating that higher scores on this component correspond to reduced left-brain lateralization for phoneme detection. The HE aspect of this component involved feeling overwhelmed by sensory overload. In the pre-registered study (Moseley et al., 2021), effects for dichotic listening did not emerge; therefore, the reliable effects involving dichotic listening measures in the present set of results suggests that the CAPS and LSHS-E summed scores were less sensitive than the individual items, possibly leading to a Type II error with respect to a relationship between dichotic listening and HE in the pre-registered study. This result is novel relative to the literature because contribution of individual HE items in relation to cognition has not previously been reported. All previous dichotic listening studies focusing on hallucinations either (1) grouped participants based on scale summary scores (Conn & Posey, 2000), (2) grouped participants based on general symptom rating scale item/s, or (3) correlated with a general symptom rating scale item (Hugdahl et al., 2012, 2013; Hugdahl, Løberg, Jørgensen, et al., 2008; Hugdahl, Løberg, Specht, et al., 2008; Levitan et al., 1999; Løberg et al., 2004; Rominger et al., 2016). The current set of results suggests that reduced laterality measured by the dichotic listening task may index sensory overload, which is one aspect of what is measured in hallucinations scales.

In addition to the “Sensations flood” CAPS 15, two marginally sub-threshold (<.48) predictor loading reliabilities on Component 3 (see Table S3) may assist with interpretation: “On certain occasions, I have seen the face of a person in front of me, but there was no one” (LSHS-E 10; .44), and “The people in my daydreams seem so true to life that I sometimes think that they are” (LSHS-E 6; .41). Consideration of these items provides a richer interpretation of the sensory overload interpretation, because these items overlap substantially with the absorption – dissociation spectrum of anomalous experiences (Carleton et al., 2010). Daydream-themed intensity is included in the Tellegen Absorption Scale (TAS) (Jamieson, 2005) and the Dissociative Experiences Scale (DES) (Carlson & Putnam, 1993); specifically, ‘I find that I become so involved in a fantasy or daydream that it feels as though it were really happening to me’ (DES 18), and ‘If I wish, I can imagine (or daydream) some things so vividly that they hold my attention as a good movie or story does (TAS 7)’. Previous work in non-clinical populations has suggested that psychosis-spectrum and dissociation-spectrum anomalous experiences may be co-present, but represent distinct constructs (Humpston et al., 2016). This interpretation of the results presented here suggests that dissociation-spectrum anomalous experiences related to sensory overload/vividness of daydreams might be associated with reduced laterality, whereas psychosis-spectrum experiences of voices may be associated with liberal threshold when detecting speech against background noise. Several studies have suggested that the relationship between trauma and psychosis is mediated by dissociative processes (e.g., Perona-Garcelán et al., 2012; Sun et al., 2018), raising the possibility that reduced laterality of attentional processing is a candidate for a mediating mechanism, but that this would be related specifically to sensory overload/vividness aspect of the HE scales, not the HE items collectively interpreted as perceptual distortions (hearing voices, troubled by voices, and everyday things look abnormal, and presence of being).

Previous studies have shown links between hallucinations and liberal threshold during auditory signal detection task (Barkus et al., 2011; Rankin & O'Carroll, 1995); as well as reduced laterality of attentional processing during dichotic listening task (Hugdahl et al., 2012). The use of a single aggregate score in these studies prevented the dimensional perspective of splitting HEs into psychosis-spectrum distortion experiences of voices on one hand, and dissociation-spectrum sensory overload on the other. This demonstrates how using HEs aggregate scores may obscure more nuanced dimensional associations. Using novel methodology we were able to specify that the overlap between the HEs and cognition variables can be conceptualized as bi-dimensional: HEs involving psychosis-spectrum distortions (including voices) underpinned by low threshold for signal detection in cognition, and dissociation-spectrum sensation overload underpinned by reduced laterality in cognition. We hypothesize that these two distinct mechanisms could explain multiple pathways to the development of HEs in different individuals: hallucinations involving psychosis-spectrum experiences underpinned by low threshold for signal detection, and dissociation-spectrum anomalous experiences like vivid daydreams and sensory overload, underpinned by reduced laterality of attention. In the future, these item-level hypotheses could be tested using the pre-registered approach. Moreover, researchers should also focus on longitudinal studies involving neuroimaging like electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), to better understand the neural correlates of multiple pathways of HE development and develop efficacious neuromodulation treatments.

It should be noted that different sets of HE questionnaire items will be optimal for predicting distinct dimensions of criterion variables analyzed. Therefore, future research may benefit from an approach holding that (1) subscales of items (e.g., pre-set scales measuring HEs) need not be mandatory, and (2) sets of scale items of theoretical interest and empirical importance (e.g., items on HE scales) will change depending on the set of criterion variables analyzed. For example, different sets of HE scale items would optimally predict personality, cognition, daily functioning, demographics, brain activity, and other general measures of mental/physical health, opening up the possibility for more expansive and comprehensive exploration of how the items captured on HE scales relate to the more complete experiences of individuals.

Open practices

The study in this article earned an Open Data badge for transparent practices. Data from this study can be found at https://osf.io/aeg5d/.

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Credit author statement

Abhijit M. Chinchani: Methodology, Software, Formal analysis, Writing - Original Draft, **Mahesh Menon**: Methodology, Writing - Review & Editing, **Meighen Roes**: Methodology, Writing - Review & Editing, **Heungsun Hwang**: Methodology, Writing - Review & Editing, **Paul Allen**: Investigation, Writing - Review & Editing, **Vaughan Bell**: Investigation, Writing - Review & Editing, **Josef Bless**: Investigation, Writing - Review & Editing, **Catherine Bortolon**: Investigation, Writing - Review & Editing, **Matteo Cella**: Investigation, Writing - Review & Editing, **Charles Fernyhough**: Investigation, Writing - Review & Editing, **Jane Garrison**: Investigation, Writing - Review & Editing, **Eva Kozáková**: Investigation, Writing - Review & Editing, **Frank Laroi**: Investigation, Writing - Review & Editing, **Jamie Moffatt**: Investigation, Writing - Review & Editing, **Nicolas Say**: Investigation, Writing - Review & Editing, **Mimi Suzuki**: Investigation, Writing - Review & Editing, **Wei Lin Toh**: Investigation, Writing - Review & Editing, **Yuliya Zaytseva**: Investigation, Writing - Review & Editing, **Susan L. Rossell**: Investigation, Writing - Review & Editing, **Peter Moseley**: Conceptualization, Investigation, Writing - Review & Editing, **Todd S. Woodward**: Conceptualization, Methodology, Writing - Original Draft, Supervision.

Supplementary data

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