Correlates of hallucinatory experiences in the general population: an international multi-site replication study

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Abstract

Hallucinatory experiences (HEs) can occur in both clinical and non-clinical groups. However, previous studies of the general population that have investigated cognitive mechanisms underlying HEs have yielded inconsistent results. In this study, we ran a large-scale preregistered multi-site study, in which general population participants ($N = 1394$, across 11 data collection sites and online) completed assessments of HEs and source memory, dichotic listening, backwards digit span and auditory signal detection tasks, plus a measure of adverse childhood experiences. We found that HEs were associated with a higher false alarm rate on the signal detection task and a greater number of reported adverse childhood experiences, but not with any of the other cognitive measures employed. These findings are an important step in improving reproducibility in hallucinations research and suggest that the replicability of some findings regarding cognition in clinical samples need to be investigated.

1. Introduction

Hallucinations are often associated with a diagnosis of schizophrenia (Bauer et al., 2011), or other psychiatric disorders (Toh et al., 2016), but they can also occur in those with no diagnosis at all (Powers et al., 2017; Sommer et al., 2010). Consistent with a dimensional or 'continuum' view of psychosis (van Os et al., 2000), susceptibility to hallucinatory experiences (HEs) varies across the population (Siddi et al., 2019). This has led researchers to propose the existence of a psychosis phenotype, or a continuous hallucination phenotype (Aleman & Larøi, 2008). Such HEs are assumed to share at least some phenomenological, etiological, and cognitive components with hallucinations in psychiatric disorders (though see David, 2010). Investigating associated cognitive mechanisms in the general population is crucial in that it avoids confounding variables (e.g., use of anti-psychotic medication), while allowing the development of mechanistic models that can account for both non-clinical unusual experiences and distressing experiences in psychosis, as well as being informative regarding the nature of agency and perception. However, in studies of HEs there has been little focus on reproducibility and replication, and contradictory findings are common in the field.

For example, some studies have reported that hallucinations in psychosis are associated with a bias in source monitoring – when a self-generated cognition is misattributed to an external source (e.g., Woodward et al., 2007). A number of studies have reported a similar link between source monitoring and HEs in the general population (e.g., Larøi et al., 2004), while other studies have showed no such link (Alderson-Day et al., 2019). Other studies have used auditory signal detection (SD) tasks to assess the role of top-down processing in HEs, requiring psychosis patients with hallucinations to detect short speech clips embedded in bursts of noise (Brookwell et al., 2013). A number of studies have reported an increase in false alarm responses in participants reporting more HEs (Barkus et al., 2011; Varese, Barkus, & Bentall, 2012). Nevertheless, there are inconsistent results regarding whether this is associated with a lower response threshold (the criterion for accepting the presence of a stimulus) and/or lower task accuracy, as well as suggestions of publication bias in this area (Brookwell et al., 2013).

Research into language lateralisation and attentional control using a consonant-vowel dichotic listening (DL) task has also provided evidence for links with hallucinations. In this task, participants must discriminate between conflicting speech stimuli presented simultaneously to both ears, with participants typically exhibiting a right-ear advantage (REA) (Bless et al., 2015). Meta-analytic evidence shows that psychosis patients with hallucinations do not show this

response pattern (Ocklenburg et al., 2013), though again, studies are inconsistent regarding whether this pattern is linked to HEs in the general population (Aase et al., 2018; Conn & Posey, 2000). Similarly, reduced verbal working memory (VWM) is frequently reported in schizophrenia, and may be further impaired in hallucinating patients (Gisselgård et al., 2014). Some studies have noted poorer VWM in individuals in the general population reporting more frequent psychotic-like experiences (e.g., Rossi et al., 2016), though other studies reported no such association with schizotypy (Barkus et al., 2011). Indeed, one potential reason for inconsistency may relate to variation in the scales used, including broader assessments of 'psychotic-like experiences', 'hallucination-proneness', or focuses on specific modalities of hallucination. Regarding environmental factors, the literature is more consistent in linking childhood trauma with hallucinations both in psychosis (Bailey et al., 2018) and HEs in the general population (Lataster et al., 2006).

In addition to inconsistent results, there are few standardized procedures, and sample sizes are small (a mean of 23 per group in one meta-analysis; Brookwell et al., 2013), limiting power and potentially over-estimating effect sizes (Button et al., 2013). Coupled with the lack of open research practices (Tackett et al., 2019), including a lack of preregistration, replication, and openly available data/materials, there should be serious concerns regarding the reproducibility of findings in this research area. We sought to address this, using the 'many labs' model developed by Klein et al. (2014). We collected behavioural task data and assessed participants for HEs across 11 data collection sites, as well as recruiting online. The aim was to collect a large enough sample to recruit participants across the continuum of HEs, with the ability to detect small effect sizes. Due to methodological variability in previous literature, we created a single centralised test battery used by all participating research groups. Participants completed assessments of HEs, as well as source memory, dichotic listening, verbal working memory, and auditory signal detection tasks, and an assessment of adverse childhood events. Given recent focus on the prevalence and quality of online data collection (de Boer et al., 2019; Peer et al., 2017), we also sought to investigate the quality of data gained through online collection.

Our hypotheses focused on key empirical results that have been used to support central conclusions about the cognitive mechanisms of HEs, and are presented in Table 1.

Table 1: summary of hypothesis for each measure, the construct they aim to assess, and key previous references on HEs in the general population.

	Hypothesis	Construct assessed: variables of interest	Key references
H1	Source memory: number of imagined words incorrectly recalled as heard would be positively associated with HEs.	Verbal source monitoring: number of externally misattributed words	Larøi et al. (2004); Alderson-Day et al. (2019)
H2	Dichotic listening: number of correct right (or left) ear responses in the non-forced (or forced-left) condition would be negatively associated with HEs.	Language lateralisation, attentional control: number of correctly reported right- or left-ear syllables	Conn & Posey (2000); Aase et al. (2018)
H3	Digit span (backwards): Mean digit span would be negatively associated with HEs.	Verbal working memory: mean digit span	Barkus et al. (2011); Rossi et al. (2016)
H4	Auditory signal detection: false alarms would be positively associated with HEs.	Top-down processing on speech: number of false alarms	Barkus et al. (2011); Varese et al. (2012)
H5	Adverse childhood experiences: ACE score would be positively associated with HEs.	Adverse childhood experiences: number of ACEs reported	Janssen et al. (2004); Lataster et al. (2006)
H6	For data collected online: effect size would differ for participants that failed all attention checks as compared to participants that passed at least 2/3 attention checks.	Quality of online data and success of attention checks.	Peer et al. (2017)

2. Method

2.1. Preregistration

The study protocol, hypotheses, variables of interest, exclusion criteria, and sample size were preregistered on AsPredicted.org on 27th February 2018, before data collection commenced (available here: osf.io/cyu6j). There was one deviation from the preregistration, described in Section 3.8.

2.2. Participants

Participants were recruited via two routes: 1) lab data collection (i.e., participants attended a data collection site and took part under laboratory conditions) and 2) online data collection (i.e., participants were recruited online, and completed the tasks on their own computer). Previous meta-analyses of comparable general population studies have shown large effect sizes in this research area. For example, Brookwell et al. (2013) reported $g = 0.8$ (95% CI = [0.54, 1.06]. Converting the lower confidence interval in this estimate to r would give an effect size of $r = .26$. Our main aim was to collect as large a sample as possible at as many data collection sites as possible, so decisions regarding sample size were not based purely on power analyses; we preregistered a minimum sample size of $n = 420$ in lab-based data collection (based on the anticipated number of data collection sites) and $n = 800$ in the online data collection (based on available funding). Based solely on anticipated lab-based data collection, $n = 420$ would allow power of .80 to detect a small effect size of $r = .12$ – though our aim was to collect substantially more than this number. The final sample size was 1513 (647 in the lab, 866 online), before exclusions. The sample size after exclusion criteria were applied was 1394 (see Results, and Supplemental Materials). Demographic information can be found in Table 2 and in the Results section.

2.3. Lab data collection sites

The study was advertised as part of a working group of the International Consortium for Hallucinations Research. Participating sites were required to recruit a minimum of 40 participants into the study to be eligible for inclusion in the final dataset. 12 sites were involved in data collection, situated in the UK (6 sites), France, The Netherlands, Czech Republic, Norway, Canada, and Australia (1 site per country). All sites obtained ethical clearance from their relevant institutional review board, in accordance with the Declaration of Helsinki. Participants were required to be aged 18-75 years, fluently speak the native language of the

respective country, and report no diagnosed hearing impairments. Participants were given a small reward for participation at the discretion of each participating site (e.g., a gift voucher, course credits, small payment, or prize draw entry).

2.4. Online data collection

In addition to data collection in labs at participating sites, the study was also advertised on the website Prolific Academic (prolific.ac), a recruitment website through which researchers can advertise online behavioural studies, and reward participants with small payments for task and questionnaire completion. Eligibility criteria and exclusion criteria were the same as for the lab-based data. Participants were rewarded with a payment of £4.20 for participation.

2.5. Task platform

All tasks and questionnaires were programmed in JavaScript, using the *jspsych* toolbox, and run from an internet browser (code accessible here: [osf.io/eqy76/](osf.io/eqy76/)). For the purpose of this study, all measures were translated and back-translated from English into French, Czech, and Norwegian, for use at data collection sites in countries where these were the primary language, and verbal stimuli suited to each language were used for the source memory and dichotic listening tasks.

For online data collection, participants were required to complete a task designed to ensure that they were wearing headphones, as developed by Woods et al. (2011), before gaining access to the main task platform (see Supplemental Materials, S1). Additional attention-checks are described below.

2.6. Questionnaires

Cardiff Anomalous Perceptions Scale (CAPS) (Bell et al., 2006) – the CAPS was employed as the primary assessment of HEs. It consists of 32 items (e.g., *Do you ever hear noises or sounds when there is nothing about to explain them?*), with yes/no as response options. The primary outcome variable, as specified in the preregistration, consisted of the total number of items on which the participant responded 'yes' (scored as 1, so that scores varied from 0-32), with higher values indicating higher levels of HEs. Further subscales on distress, intrusiveness, and frequency were included but not used in any preregistered analysis.

Launay-Slade Hallucination Scale - Extended (LSHS-E) (Larøi et al., 2004) – the LSHS-E was used as a secondary assessment of HEs, due to its frequent use in studies examining HEs in the general population. It consists of 16 items (e.g., *I have been troubled by hearing voices in my*

head), and participants are asked to respond on a 5-point Likert scale (0 = *Certainly does not apply to me*, 4 = *Certainly applies to me*), with the overall score calculated as the sum of the score for each item (0-64). Compared to the CAPS, the LSHS-E assesses a range of more commonly reported experiences, including intrusive thoughts and vivid daydreams, as well as multisensory and auditory-visual HEs.

Adverse Childhood Experiences (ACE) scale (Felitti et al., 1998) – the ACE scale was used as an assessment of childhood trauma. It consists of 17 items (e.g., *Did a parent or other adult in the household often or very often swear at, insult, or put you down?*), with participants responding Yes or No for each item. Total score was calculated as the sum of 'Yes' responses (0-17).

Two further scales were included not to test any specific hypotheses, but simply to characterise the sample and for potential exploratory analysis – the Schizotypal Personality Questionnaire (SPQ-BR, Davidson et al., 2016) and the Depression Anxiety and Stress Scale (DASS-21, Lovibond, 1998). No analysis was conducted using these scales in this paper. Participants also provided basic demographic information, and answered questions regarding their alcohol, nicotine, and cannabis intake.

Attention-checks – taken from Peer et al. (2017), three questions were included within the questionnaires of the task platform, which were designed to be easily answerable, and thus acted as attention-checks. Participants were excluded from all data analysis if they incorrectly answered more than one attention-check question (see Supplemental Materials, S2).

2.7. Source memory task (SMT)

The SMT 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).

In the first stage of the task, participants were presented with a series of words in the centre 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 centre of the screen, and an audio clip of that word 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 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. The primary variable of interest in this task was the number of responses on which the participant mistakenly decided that they had heard a word from the Imagine list (*Imagine-to-Hear errors*).

The task was based on previously used versions (e.g., Moseley et al., 2018), though differed from others in a number of ways to ensure consistency across data collection sites and online. For example, participants listened to recordings of a voice, rather than listening to an experimenter read the word aloud. Some previous tasks have also required participants to generate their own verbal stimuli (Larøi et al., 2004) or complete word pairs (Alderson-Day et al., 2019), whereas the task used here presented single words via recording.

2.8. Consonant-vowel dichotic listening (DL)

The DL task is designed to assess language lateralisation, with two additional 'forced attention' conditions aimed at assessing cognitive or attentional control. The task used identical stimuli to previous studies (e.g., Aase et al., 2018; Hugdahl et al., 2013). The task involves 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 350ms. In the 'non-forced attention' condition, the participant is required to select the syllable they could hear most clearly. In the 'forced right' and 'forced left' conditions, the participant is instructed to select the syllable they believe has been presented to the right or left ear, respectively. Participants provided a response with a mouse click.

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 are excluded from data analysis and are used only as a data quality check. Resulting variables were the total number of correctly identified syllables presented to the right ear (REC) (for the non-forced and forced-right conditions), or correctly identified syllables in the left ear (LEC) (forced-left condition only). Laterality index ([(REC – LEC) / (REC + LEC)] *100) was calculated for further analysis.

2.9. Backwards digit span (DS)

The DS task assessed verbal working memory performance, with each trial requiring participants to view a series of numeric digits, and then recall these digits in reverse order. Previous studies of HEs (e.g., Barkus et al., 2011) have required the participants to respond by speaking their

answer aloud; here, we used a computerised version of the task that required response via a mouse-click and adaptively increased or decreased trial length based on performance, as recommended by Woods et al. (2011). Digits (1-9) were presented on the centre of the screen, randomly sampled without replacement (until trial length of 10, when digits were resampled). Each digit was presented on-screen for 1s. Trial length started at 2 digits, and was varied according to the rules set out in Woods et al. (2011); that is, a correctly recalled digit string led to an increase in trial length by 1, whereas two consecutive incorrectly recalled digit strings decreased the trial length by 1. Participants responded using a mouse to click the digits they wished to input on an on-screen keypad. All participants completed 14 trials. Performance was assessed using the *mean span* method described by Woods et al. (2011), which estimates the trial length at which the participant performs with 50% accuracy.

2.10. Auditory signal detection (SD) (lab data collection only)

The auditory SD task required the participant to respond as to whether they believed a speech clip had been embedded in noise. The task was identical to previous studies (e.g., Barkus et al., 2011). 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, with participants who did not participate in the main study ($N = 10$ per site). This task was only administered with participants in the lab, as calibration would not have been possible with online participants.

In the main task, the participant was presented with 72 3.5s bursts of pink noise, 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 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 responded by clicking a mouse button for *Yes* or *No*. For each trial, they were also then prompted to enter a confidence rating, data from which will be analysed and reported separately. The primary outcome variable was false alarm rate (the percentage of voice-absent trials on which the participant incorrectly responded that a speech clip was present). Secondary outcome variables were hit rate, task sensitivity (d', calculated as the standardised false alarm rate subtracted from the standardised hit rate), and criterion ($\beta = e^{\left\{\frac{Z(FA)^2 - Z(H)^2}{2}\right\}}$) (aka. response bias).

2.11. 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 > 97,000 participants) (Condon & Revelle, 2014). Participants complete a 3 x 3 grid of shapes, choosing from six options, within 60s. Raw number of correct responses was used as an assessment of non-verbal reasoning ability.

2.12. Procedure

For participants tested in a lab environment, testing took place in a quiet room at a laptop or desktop computer, using over-ear headphones for tasks involving auditory stimuli. Study completion took approximately 50-60 mins. The task platform presented the dichotic listening, source memory, matrix reasoning, digit span, and auditory signal detection tasks, followed by questionnaire measures. The task platform used in online data collection was identical, with the exception being the inclusion of a headphone check task (see Supplementary Materials, S1), and exclusion of the auditory SD task, which relied on laboratory-controlled conditions.

2.13. Data analysis

Exclusions based on pre-registered criteria (e.g., poor task performance) are outlined in the Supplemental Materials (S3). Firstly, we examined associations between demographics and CAPS score, as well as measures of alcohol, cannabis, and cigarette usage, and non-verbal reasoning. These analyses were non-preregistered, and included for descriptive purposes.

To assess associations between task performance and CAPS score, as detailed in H1-H5, simple correlations (Spearman's r_s for non-normally distributed variables) were calculated, with associated 95% confidence intervals. For the preregistered analyses, where confidence intervals crossed 0 (indicating a potential null effect), equivalence testing was conducted (using the *TOSTER* R package) with upper and lower bounds of $r_s = 0.1$ and $r_s = -0.1$. These bounds were chosen as representing 'small' effect sizes, with effects significantly smaller than this likely to be of negligible relevance. When a significant *p*-value is reported for an equivalence test, this can be taken to indicate that the effect is indistinguishable from 0 (providing evidence for the null hypothesis).

As well as assessing simple correlations between task measures and CAPS score, we also constructed linear mixed models, with data collection site as a random effect, task measures as

fixed effects, and CAPS score as the dependent variable, to investigate which cognitive task variables would contribute to the highest quality model. Akaike Information Criterion (AIC), a measure which takes into account both predictive ability and number of parameters in a model (with fewer seen as better) was used to assess model quality. All data analysis was conducted in R, with code available at osf.io/eqy76/.

3. Results

3.1. Sample

In total, 1513 participants were recruited into the study. One UK-based data collection site did not meet the minimum sample size requirement, and was therefore not included in any analysis. Of the final sample, 647 (42.8%) participated in a laboratory environment, while 866 (57.2%) took part in the online version of the study. After applying preregistered exclusion criteria, the final sample consisted of 1394 participants (594 in the lab, 800 online) native to 46 countries. Further demographic information can be seen in Table 2.

Demographic	%	CAPS	95% CI
Age (*M, SD*)	29.4 (10.9)	$r_s = -.17$	[-.11, -.22]
Gender (female)	55.7	$d = 0.05$	[-0.06, 0.16]
Handedness (non-right)	10.8	$d = -0.01$	[-0.18, 0.16]
Diagnosis	16.0	$d = -0.55$	[-0.70, -0.41]
Relative diagnosis	19.5	$d = -0.28$	[-0.41, -0.15]
Cigarette usage	16.2	$r_s = .052$	[.003, .11]
Alcohol intake	56.0	$\eta_p^2 = .005$	[.00, .011]
Cannabis usage	8.6	$\eta_p^2 = .024$	[.011, .037]
Parental income	14.5	$\eta_p^2 = .006$	[.00, .012]

Table 2: demographics of sample (N = 1394), and association with CAPS score. Diagnosis = percentage reporting any form of psychiatric or neurological diagnosis; Relative diagnosis = percentage reporting first-degree relatives with any form of psychiatric or neurological diagnosis; Cigarette usage = percentage reporting smoking at least one cigarette a day; Alcohol intake = percentage reporting drinking alcohol at least twice a month; Cannabis usage = percentage reporting using cannabis at least twice a month; Parental income = percentage refers to proportion reporting less than enough money to meet their needs, during childhood. Note that confidence intervals for η_p^2 cannot cross 0 (because η_p^2 cannot be a negative value).

3.2. Assessment of hallucinatory experiences

Across the whole sample, participants endorsed a mean of 4.68 items on the CAPS scale (95% CI = [4.42, 4.93], *Mdn* = 3, range = 0-32). Internal reliability of the CAPS was good ($\alpha = 0.87$).

CAPS score was strongly positively skewed (skewness = 1.58, *SE* = 0.07) and leptokurtic (kurtosis = 3.21, *SE* = 0.13), with most participants reporting few HEs, and a smaller number of participants reporting many HEs. That said, 50 participants scored at or above the mean score of psychosis patients (e.g. Bell et al., 2006; 2011), suggesting that the sample covered a sufficient range of the hallucination continuum. Non-preregistered analysis showed that, consistent with previous findings (Bell et al., 2006; 2011), CAPS score was associated with age, having a psychiatric diagnosis, having a first-degree relative with a psychiatric diagnosis, and with cannabis usage (see Table 2). There was no association between CAPS score and non-verbal reasoning, as assessed by matrix reasoning (r_s = .02, 95% CI = [-.03, .08], *p* = .399). The LSHS-E was used as a secondary measure of HEs, with participants scoring a mean of 20.33 (95% CI = [19.71, 20.94], *Mdn* = 20, range = 0–60).

3.3. H1: Hallucinations and source memory

1375 participants' data was included for the source memory task. Overall accuracy was well above chance (*M* = 64.97%, 95% CI = [64.33, 65.60]). In terms of source judgements, participants were more likely to misattribute a heard item as imagined ('hear-to-imagine error') (*M* = 6.26, 95% CI = [6.08, 6.45]) than to misattribute an imagined item as heard ('imagine-to-hear error') (*M* = 4.04, 95% CI = [3.88, 4.19]) (*t*(1381) = 18.29, *p* < .001, *d* = 0.49).

The number of 'imagine-to-hear errors' (i.e., external misattributions) was used as the primary variable to assess source monitoring performance (H1). There was no correlation between number of imagine-to-hear errors and CAPS score (r_s = .02, df = 1376, 95% CI = [-.03, .07], *p* = .461). Equivalence testing indicated that the effect was statistically indistinguishable from 0, given equivalence bounds of -0.1 and 0.1 (*p* = .001). Similarly, further analysis indicated that there was no association between imagine-to-hear errors and score on the LSHS-E (r_s = -.005, df = 1377, 95% CI = [-.06, .05], *p* = .839).

Further, as an exploratory (non-preregistered) analysis, we calculated overall 'reality monitoring accuracy'; that is, the proportion of correctly recalled 'old' words for which the source was also correctly recalled (as in Garrison et al., 2017, calculated as follows: (Hear-Hear + Imagine-Imagine) / (Hear-Hear + Imagine-Imagine + Hear-Imagine + Imagine-Hear)*100). There was no association between reality monitoring accuracy and CAPS score (r_s = .04, *p* = .11).

3.4. H2: Hallucinations and dichotic listening

1262 participants' data was included for the dichotic listening task. Across the whole sample, a right-ear advantage was observed, with participants also successfully orienting their attention in the forced-left and forced-right conditions, as previous research has indicated (see Supplemental Materials, S5).

There was no correlation between CAPS score and performance in the non-forced condition of the dichotic listening task, as assessed by the number of right ear responses (H2) (r_s = .006, df = 1263, 95% CI = [-0.05, 0.06], p = .842), and equivalence testing indicated that the effect was statistically indistinguishable from 0 (p < .001). Similarly, there was no association between CAPS score and the number of correct left ear responses (r_s = .022, df = 1263, 95% CI = [-.03, .08], p = .435) in the forced-left condition, which was also indistinguishable from 0 (p = .003).

As a secondary analysis, total LSHS-E score also showed no association with dichotic listening task performance for all conditions (all r_s < .019, ps > .493).

3.5. H3: Hallucinations and verbal working memory

Overall mean span (M = 6.39, 95% CI = [6.31, 6.47]) was approximately equal to that reported by Woods et al. (2011). There was no association between mean digit span and CAPS score (H3) (r_s = -.02, df = 1358, 95% CI = [-.07, .04], p = .552), with equivalence testing indicating an effect indistinguishable from 0 (p < .001), though secondary analysis showed a very weak association between mean digit span and LSHS-E score (r_s = -.06, df = 1357, 95% CI = [-.11, -.0004], p = .042).

3.6. H4: Hallucinations and auditory signal detection

Auditory signal detection data was collected only from participants that took part in the lab-based version of the study (n = 594). Mean hit rate was comparable to previous studies using this task (M = 74.39%, 95% CI = [73.18, 75.59]), as was the false alarm rate (M = 23.29%, 95% CI = [21.44, 25.15]).

There was a positive association between CAPS score and false alarm rate (H5) (r_s = .14, df = 581, 95% CI = [.06, .22], p < .001). Additional analysis also showed a positive association between CAPS score and hit rate (r_s = .18, df = 581, 95% CI = [.10, .26], p < .001), and a negative association between CAPS score and β (r_s = -.17, df = 581, 95% CI = [-.25, -.09], p < .001), indicating that increased CAPS score was associated with a reduced threshold for

accepting the presence of a stimulus. There was no such association between CAPS score and d' ($r_s = -.05$, df = 581, 95% CI = [-.13, .03], $p = .238$), though equivalence testing indicated that the correlation was not statistically equivalent to 0 ($p = .110$).

Using LSHS-E as a secondary outcome, similar associations with false alarm rate ($r_s = .12$, df = 581, 95% CI = [.03, .19], $p = .005$), and β ($r_s = -.12$, df = 581, 95% CI = [-.20, -.04], $p = .005$) were observed. Unlike with the primary outcome measure, there was also a small association between LSHS-E score and d' ($r_s = -.10$, df = 581, 95% CI = [-.18, -.02], $p = .018$).

3.7. H5: Hallucinations and adverse childhood events

Mean number of ACEs reported was 1.75, although this was heavily positively skewed, with a median number of ACEs of 1. 53.9% of participants reported one or more ACE.

There was a positive correlation between CAPS total and ACE score ($r_s = .24$, df = 1365, 95% CI = [.19, .29], $p < .001$). A similar effect size was found when LSHS-E was used as a secondary outcome measure to assess hallucinations ($r_s = .24$, df = 1366, 95% CI = [.19, .29], $p < .001$).

	CAPS	SM: imagine-hear errors	DL: non-forced	DL: forced-left	DS: mean span	SD: false alarm rate	ACE: number endorsed
CAPS score	-						
SM: imagine-to-hear errors	.019 [-.03, .07]	-					
DL: non-forced	.006 [-.05, .06]	-.038 [-.09, .02]	-				
DL: forced-left	.022 [-.03, .08]	.033 [-.09, .02]	**.126 [.07, .18]**	-			
DS: mean span	-.016 [-.07, .04]	**-.065 [-.12, -.01]**	.050 [-.01, .11]	**.071 [.02, .13]**	-		
SD: false alarm rate	**.140 [.06, .22]**	.019 [-.06, .10]	.061 [-.02, .14]	.011 [-.07, .09]	.056 [-.03, .14]	-	
ACE: number endorsed	**.241 [.19, .29]**	-.006 [-.06, .05]	.006 [-.06, .05]	.008 [-.05, .06]	-.050 [-.10, .003]	.011 [-.07, .09]	-

Table 3: correlation matrix for CAPS and primary outcome variables for each measure. All correlations presented as Spearman's r_s due to non-normality of variables [95% CI]. DS mean span = backwards digit span, verbal working memory. DL (non-forced) = dichotic listening, number of correctly identified syllables presented to the right ear. DL forced-left = dichotic listening, number of correctly identified syllables presented to the left ear. SM imagine-to-hear errors = source memory, number of imagined words misremembered as heard. SD false alarm rate = signal detection task, proportion of 'voice-absent' trials on which participant responded 'yes'. CAPS = Cardiff Anomalous Perception Scale. Bolded coefficients = 95% CI does not cross 0.
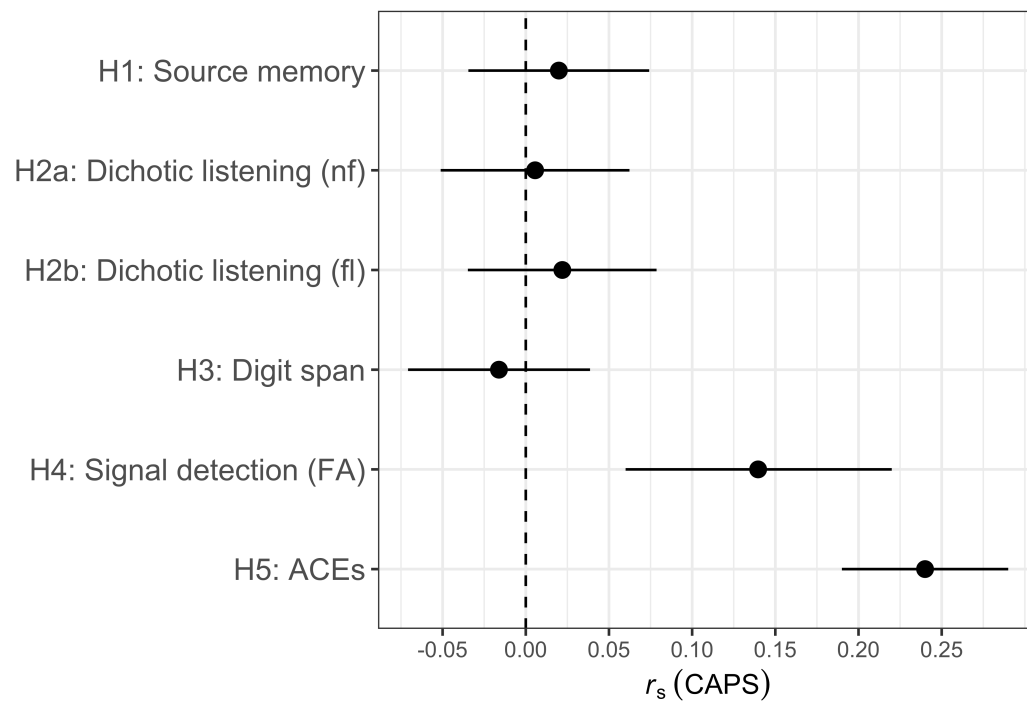
Fig. 1: correlations (Spearman's r_s) between HEs (CAPS) and primary outcome variables for each task. H1-5 correspond to the first 5 hypotheses outlined in the introduction. Error bars = 95% confidence intervals. NF = non-forced condition in the dichotic listening task. FL = Forced-left condition in the dichotic listening task. FA = false alarm rate on the signal detection task. ACEs = adverse childhood experiences.

3.8. H6: Attention-checks and data quality

Due to a low number of participants failing all attention-checks (n = 15), we diverged from our preregistered analysis plan, and compared participants who failed two or more checks, and were hence excluded from full analysis (the *failed checks* group, n = 66) to those who failed one check or fewer (the *included* group). The failed checks group scored lower on all task primary outcome variables, though confidence intervals crossed 0 in all cases other than mean digit span (U = 37728, 95% CI = [0.165, 1.004], p = .004, d = 0.34). Correlation coefficients were also computed between task variables and CAPS score for the failed checks group (n = 66) only, and compared to the coefficients gained in the main analysis. There were no differences between the two groups in correlation coefficients (all 95% CIs overlapping). For a comparison of data collected in the lab compared to online, see Supplemental Materials (S6).

3.9. Constructing a model to predict HEs from cognitive task performance

We constructed three linear mixed models (using the *lme4 r* package), each with CAPS score as the dependent variable, and including data collection site as a random effect (intercept). This analysis was conducted only on data collected in the lab, so that SD task data could be included. Predictor variables were centred and standardised. Assumptions regarding multicollinearity, homoscedasticity, homogeneity of variance, and normality of random effects were met. However, inspection of QQ plots suggested non-normality of residuals; therefore, CAPS score was log-transformed, and the models re-computed. For these models, QQ plots suggested normality of residuals; therefore, the models with a log-transformed CAPS score were used.

The first model (*baseline* model) included basic demographic information (age, gender, and parental income) as fixed effects, which significantly improved upon a model with only the random effect entered (p < .001). The second model (*signal detection*) added the SD task false alarm rate as a fixed effect, and significantly improved upon the baseline model (p = .028). The third model added the remaining task variables (dichotic listening non-forced right ear syllables, digit span mean span, source memory imagine-hear errors), and did not improve upon the signal detection model (p = .965). The Akaike Information Criterion (AIC) was also used to assess model quality. The signal detection model provided the lowest AIC (AICc = 470.5). See Table 4 for full coefficients for the model with all variables included, and Supplemental Materials (S8) for full breakdown of model comparisons.

Table 4: coefficients for linear mixed model containing variables from all task measures (dependent variables = log-transformed CAPS score, random effect = data collection site)

Fixed effect	Beta	SE	Standardized beta	Standardized beta SE	*t*	*p*
Intercept	0.68	0.071			9.42	< .001
Age	-0.07	0.018	-0.17	0.045	-3.80	< .001
Gender	0.01	0.017	0.03	0.042	0.68	.499
Parental income	-0.03	0.020	-0.07	0.043	-1.56	.120
Signal detection	0.04	0.016	0.09	0.042	2.20	.028
Dichotic listening	0.003	0.017	0.01	0.043	0.20	.842
Source memory	0.01	0.017	0.02	0.042	0.41	.679
Digit span	-0.004	0.017	-0.01	0.042	-0.23	.815

Random effect (site): variance = 0.005, SD = 0.07

Model equation: CAPS total score ~ age + gender + parental income + SDT false alarms + DL right ear responses + SMT imagine-hear + DS mean span + (1 | site)

Model df: 524 (Satterthwaite approximation)

p-values for fixed effects calculated using Satterthwaite's approximations. LMM calculated using *lme4* R package.

4. Discussion

In a general population sample of 1394 participants, we showed that HEs were associated with false perceptions and a lower response criterion on an auditory signal detection paradigm (H4), and with adverse childhood experiences (H5). However, HEs were not linked to impaired source memory, dichotic listening, or verbal working memory (H1-3). Additionally, we provided evidence that, with these cognitive tasks, data quality from online recruitment is equal to that collected in the lab (H6). Our findings raise important issues regarding i) continuities and discontinuities in HEs across the general population and in psychosis, and ii) regarding reproducibility in hallucinations research and cognitive/clinical psychology.

4.1. Continuity and discontinuity in hallucinatory experiences

Combined with previous evidence using auditory signal detection tasks (e.g., Barkus et al., 2011) and other paradigms aimed at assessing top-down influences on perception (de Boer et al., 2019; Vercammen & Aleman, 2010), this study provides strong evidence that HEs are associated with performance on the signal detection task, with a small effect size. This finding held across both primary and secondary assessments of HEs, and, in combination with previous studies, can be taken to support theoretical arguments regarding over-weighted top-down processes in HEs (Powers et al., 2016). Increased false alarm rates have been reported across a number of domains in schizophrenia (e.g., Weiss et al., 2004, recognition memory), though evidence comparing tasks across symptoms or task modality is lacking and should be a focus of further research. The evidence regarding sensitivity (ability to distinguish between speech and noise) was more equivocal; there was a very small association between HEs and d', with confidence intervals crossing 0 – yet equivalence testing did not indicate that the effect was equivalent to 0. This highlights the extent to which precise parameter estimates require large samples; to our knowledge, this is the largest study to use the signal detection task alongside assessments of HEs, yet it is still not possible to confidently rule out a small impairment in sensitivity. We also found evidence for the contribution of ACEs to HEs, consistent with previous evidence in both psychosis patients (Bailey et al. 2018) and in the general population (Lataster et al., 2006).

The findings were unequivocal, however, in showing no association between HEs and dichotic listening, source memory, and verbal working memory performance, with effects statistically indistinguishable from 0. This fails to conceptually replicate previous studies, and suggests important complexities regarding the continuum hypothesis as applied to hallucinations. It also raises the question of how to interpret clinical findings in light of these results. In the case of

dichotic listening, meta-analytic evidence supports the existence of a reduced right ear advantage (Ocklenburg et al., 2013), and poorer performance on the forced attention conditions (Hugdahl et al., 2013), in schizophrenia patients with hallucinations. A meta-analysis by Brookwell et al. (2013) reported that source monitoring errors were specifically associated with hallucinations in psychosis and HEs in the general population. This study, in contrast, provides evidence that no such association exists in the general population. These results advance our understanding of the underlying cognitive mechanisms of HEs, importantly including those that seem not to be important in the general population. One potential interpretation is that there is a discontinuity in mechanism between clinical and non-clinical hallucinations; that is, atypical language lateralisation, poor attentional control, or source monitoring biases may be markers of clinically significant hallucinations, but not less frequent or less distressing experiences. That said, clinical studies on the cognitive mechanisms of hallucinations often use small sample sizes and non-standardized methods, and direct replications are rare. It is therefore not clear how well these results would replicate if subjected to larger-scale preregistered studies in patient populations. In addition, individuals with hallucinations of similar intensity to patients but without apparent distress or disability (e.g., the 'non-clinical hallucinators' reported by Powers et al., 2017 and Sommer et al., 2010) have been an important comparison group. Further preregistered studies with larger samples in these groups are needed to clarify whether these mechanisms are continuous across non-clinical and clinically significant hallucinations.

4.2. Reproducibility in hallucinations research

In terms of reproducibility, these results may be a cause for concern in hallucinations research (and cognitive and clinical psychology more broadly). Of the five hypotheses regarding HEs, this study only supported two, despite previous evidence for all five. Poor reproducibility has been reported across psychology (Camerer et al., 2018), but as others have noted, steps such as making data, code, and materials openly available and preregistering studies are likely to improve the field (Button et al., 2013). The reproducibility crisis has not been directly addressed in this area. This study aimed to take a first step in addressing the issue.

A key part of the present study involved collecting data at sites across the world and online. We used three attention-checks, excluding participants who failed more than one (as in Peer et al., 2017). There was a negligible difference between the proportion of participants excluded due to attention-check failure in the lab-based and online data, providing evidence that online participants were equally as engaged as lab-based participants while reflecting a more diverse

demographic. There were only negligible differences in effect sizes between lab-based and online data. This study, therefore, provides support for the feasibility of collecting cognitive task data online, which is of similar quality to that collected in the lab.

4.3. Limitations and directions for future research

There are a number of limitations that should be considered when drawing conclusions from the present study. Firstly, while the co-authors of this paper collectively decided that the four cognitive tasks reported here were of highest importance, they are only a small selection of domains which may be important; other candidates for inclusion were intentional inhibition of memories (Waters et al., 2003), and meta-cognition (Varese & Bentall, 2011). Even the tasks we selected have multiple variants, for example priming participants during the signal detection task to enhance the top-down component (Vercammen & Aleman, 2010), or increasing cognitive load in a source memory task (Woodward et al., 2007). Task variation could be an important factor underlying inconsistency in the literature, as some may be closer to relevant theoretical concepts than others (e.g., variation in 'self-generation' of words in source memory). It is possible that task variations could account for null effects reported here. Further research should investigate task manipulations affecting the association between performance and HEs. Secondly, the CAPS provided skewed data, with comparatively few participants scoring very highly, potentially weakening the ability to detect associations with cognitive tasks. That said, our use of the LSHS-E as a secondary measure, which provides less skewed data and a higher prevalence of endorsed items, suggested an almost identical pattern of correlations. Thirdly, scales such as the CAPS or LSHS-E do not provide separate assessments of different modalities of HE (e.g., auditory, visual, tactile). Future research should aim to investigate these using specific assessments (or individual items) for different modalities. Finally, although we recruited participants native to 46 different countries, the data collection sites themselves were situated mainly in western European countries. Future studies could, therefore, expand to include more culturally diverse countries, and expand the multi-site approach to further cognitive domains in clinical and non-clinical populations.

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