Susceptibility to auditory hallucinations is associated with spontaneous but not directed modulation of top-down expectations for speech

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Abstract

Auditory verbal hallucinations (AVH) – or hearing voices – occur in clinical and non-clinical populations, but their mechanisms remain unclear. Predictive processing models of psychosis have proposed that hallucinations arise from an over-weighting of prior expectations in perception. It is unknown, however, whether this reflects i) a sensitivity to explicit modulation of prior knowledge, or ii) a pre-existing tendency to spontaneously use such knowledge more in ambiguous contexts. Four experiments were conducted to examine this question in healthy participants listening to ambiguous speech stimuli. In experiments 1 (*n* = 60) and 2 (*n* = 60), participants discriminated intelligible and unintelligible sine-wave speech (SWS) before and after exposure to the original language templates (i.e., a modulation of expectation). No relationship was observed between top-down modulation and two common measures of hallucination-proneness. Experiment 3 (*n* = 99) confirmed this pattern with a different stimulus – sine-vocoded speech (SVS) – that was designed to minimise ceiling effects in discrimination and more closely model previous top-down effects reported in psychosis. In Experiment 4 (*n* = 135), participants were exposed to SVS without prior knowledge that it contained speech (i.e., naïve listening). AVH-proneness significantly predicted spontaneous pre-exposure identification of speech, but was unrelated to performance on a subsequent discrimination task, post-exposure. Altogether, these findings support a pre-existing tendency to spontaneously draw upon prior knowledge in healthy people prone to AVH, rather than a sensitivity to temporary modulations of expectation. We propose a model of clinical and non-clinical hallucinations, across auditory and visual modalities, with testable predictions for future research.

Keywords: predictive coding, psychosis, speech perception, speech-in-noise, audition.

Introduction

Hallucinations have long been considered a product of top-down processes: what the mind brings to our perception of the world, not the other way round (Esquirol, 1832). Auditory verbal hallucinations (AVH), in particular, have been studied extensively because of their association with schizophrenia. They occur in 60-90% of cases (Bauer et al., 2011) and at rates that are often double those seen for other modalities (Waters et al., 2014). AVH have been variously proposed to result from internal sources such as memories, imagery, and self-talk or inner speech (Mintz & Alpert, 1972; Seal et al., 2004; Waters et al., 2003). Difficulties in distinguishing the internal from external were long framed as a problem with reality monitoring, in which a deficit in source monitoring could explain how self-generated cognitive states could become perceptual experiences (Bentall, 1990; Feinberg, 1978; Frith, 1992). Although not always framed as a "top-down" model of hallucinatory experience, this grounded much research in the meta-cognitive domain, consistent with cognitive approaches to psychosis in clinical practice (Morrison et al., 1995).

Recent interest in predictive processing approaches has reframed the putative role of top-down processes in hallucination. Under the predictive processing framework, all of perception, cognition, and action is the result of a trade-off between generative models of the world, shaped by prior expectations, and prediction error, i.e., the gap between expectation and sensory input (Clark, 2013; Hohwy, 2014) . Hallucinations have been posited as an imbalance between prior expectation and prediction error, typically in favour of the former (Fletcher & Frith, 2009; Jardri & Denève, 2013; Powers et al., 2016). Such accounts have been argued to be consistent with source-monitoring theories (Corlett et al., 2019; Griffin & Fletcher, 2017; Wilkinson, 2014), and may even reflect a generalisation of prediction mechanisms inherent in earlier theories (Pickering & Clark, 2014). Nevertheless, they arguably involve a shift in emphasis away from the metacognitive monitoring of self, focusing instead on expectation and learning as being central to hallucination.

Because of their large overlap, it can be challenging to distinguish source-monitoring and predictive approaches to hallucination behaviourally and experimentally. One of the most consistent findings in AVH research has been an association between hallucination-proneness and perceptual bias (Brookwell et al., 2013). On auditory signal detection tasks, when asked to monitor for the presence of speech, clinical participants with AVH demonstrate a bias to identify speech in white noise (reduced beta, β), alongside otherwise intact discrimination (d') (Bentall & Slade, 1985a). Similar effects are associated with hallucination-proneness in the general population (Bentall & Slade, 1985a; Moseley et al., 2020). Under source monitoring approaches, this was typically interpreted as a failure to distinguish one's own inner speech or imagery from actual perception, leading to an external signal being identified instead (Bentall, 1990). Predictive approaches, in contrast, predict not just bias, but a potential enhancement of perception given the right conditions: if prior expectations are over-weighted, this should facilitate perception where top-down knowledge is required (Fletcher, 2017).

Recent evidence to support this is provided by Teufel et al. (2015), in a study of individuals with an at-risk mental state for psychosis. Patients and healthy controls were asked to discriminate monochrome Mooney (1957) images, before and after exposure to their original templates (pictures of humans and animals). Both groups improved their discrimination after viewing the templates, reflecting an update of their prior expectations. However, clinical participants showed significantly enhanced discrimination post-exposure compared to controls, consistent with top-down information being given greater weight in their perceptual processing. No group differences were evident in bias scores. Teufel and colleagues then replicated this finding in a sample of 40 healthy participants rated for psychosis-proneness on measures of hallucination-like experiences (r = 0.42, the Cardiff Anomalous Perceptions Scale; Bell et al., 2006) and delusional traits (r = 0.33, the Peters Delusion Inventory; Peters et al., 2004), with higher scores on these scales being associated with a greater improvement in discrimination following exposure to the templates (Teufel et al., 2015).

These findings speak to visual processes – but what of voices, the most common kind of hallucination in psychosis? Analogous to Mooney images, sine-wave speech (SWS; Remez et al., 1981; Rosen et al., 2011) is a perceptually ambiguous stimulus derived from speech that allows for exploration of top-down effects on perception. SWS is not necessarily heard as intelligible speech by naive listeners; instead, it typically requires prior training to be recognised and understood. In a recent study, a sample of non-clinical voice-hearers (NCVH) – individuals with frequent AVH but no need for clinical care (Johns et al., 2014; Peters et al., 2016) – were scanned in fMRI while passively listening to SWS (Alderson-Day et al., 2017). The first scan was under naïve conditions and participants were not told that speech was present, their task being to listen out for a distinct but unintelligible target sound amidst the SWS. They were then told speech *was* present, exposed to some training examples, and scanned again. Participants who reported hearing any speech prior to training were asked to estimate when this had occurred, based on visual markers displayed during the scan. This design allowed for i) the assessment of top-down modulation following training (analogous to the effect reported by (analogous to the effect reported by Teufel et al., 2015), but also ii) any pre-existing tendency to spontaneously hear speech in ambiguous situations (not examined by Teufel and colleagues). The latter effect was observed: during naïve listening, NCVH participants reported identifying speech in SWS earlier than participants in a matched control group, but no modulation effect distinguished the two groups following training. This was supported by group differences in the neural response specifically for intelligible SWS trials, suggesting that NCVH participants were not biased to hear speech under *all* conditions, but only when there was sufficient "fit" to the incoming signal.

Both experiments provide broad support for top-down processing being linked to hallucinations, but they highlight contrasting effects: a *modulatory* effect (Teufel et al., 2015) and a *naïve listening* effect (Alderson-Day et al., 2017). While the modulatory effect offers a more unambiguous demonstration of a predictive model of hallucinations, the naïve listening effect is potentially consistent with both predictive and the kinds of perceptual biases observed previously under a source monitoring approach. Elucidating whether prior expectations differ for people with AVH, and in what way, is important not just theoretically but practically, as it may have implications for therapeutic approaches (Wilkinson et al., 2017). Expectations that will shift substantially with new information and feedback are not the same as those that may be more ingrained and established.

In this paper, we had two main aims: i) to conceptually replicate Teufel and colleagues' work with an auditory analogue of their modulatory effect, using ambiguous speech stimuli; and ii) to replicate the finding of a naïve listening effect using the same stimuli. We did this in healthy individuals rated for hallucination-proneness – as in Experiment 2 of Teufel et al. (2015) – to allow for the recruitment of larger samples in each case. In **Experiment 1** (n = 60), we followed a similar test-train-test procedure to Teufel and colleagues, and tested discrimination of the same speech stimuli as we have used previously, SWS (i.e., Rosen et al., 2011). Following Teufel et al. (2015), we included the CAPS (Bell et al., 2006) and PDI

(Peters et al., 2004) as measures of unusual perceptual experiences and delusional beliefs specifically. **Experiment 2** (*n* = 60), run partly in parallel, used an alternative measure specific to AVH-proneness, a version of the Launay-Slade Hallucination Scale-Revised (Bentall & Slade, 1985b; Morrison et al., 2000). It also included participants intentionally recruited to expand the potential range of individual differences in hallucination-proneness (specifically, people with a history of imaginary companions; Fernyhough et al., 2019), and an added condition which sought to further prime potential templates for speech. In **Experiment 3** (*n* = 99), we tested the same prediction but with a new stimulus, sine-vocoded speech (SVS). We developed this particular stimulus set with the aim of offering a tighter control on some of the potential learning effects inherent to SWS comprehension. This in turn allowed us to align the structure and difficulty of our tasks even more closely with Teufel et al. (2015). According to the **modulation** hypothesis, in experiments 1-3, improvements in discrimination following template exposure should be associated with higher hallucination-proneness.

Finally, in Experiment 4 we instead repeated the behavioural design from Alderson-Day, Lima et al. (2017) , with 134 students listening to SVS under naïve listening conditions. According to the **naïve listening** hypothesis, hallucination-proneness should be higher in those who were quicker to recognise that SVS contained hidden speech. After the naïve listening procedure, we also tested them on their post-training discrimination skills, this provided a further and final test of the role of explicit modulation. Data and code for each of the experiments are available via OSF.

Experiment 1: Modulating prior knowledge of sine-wave speech

The aim of our first experiment was to develop a modulation of expectation in the auditory modality, and to see how this related to hallucination-proneness scores. In contrast to Teufel et al. (2015), who used 12 blocks of before/after trials, we chose to play all 90 trials, train on the whole set, and then retest for all trials (a “one-shot” procedure). This was chosen based on initial piloting of the stimuli, which indicated that many participants begin to successfully identify speech and find SWS intelligible after exposure to only a handful of examples. We predicted that higher CAPS scores would be associated with greater increases in discrimination following template exposure. As in Teufel et al. (2015), we also explored this effect for delusion-proneness scores on the PDI.

Method

Participants

A convenience sample of 60 participants was recruited from a university cohort (age *M*(*SD*) = 21.22 (3.11), range 18-–32 years, 18 male)[1]. Individuals were invited to take part if they were native English speakers with no hearing impairments or any previous psychiatric or neurological diagnoses. Participants received course credit or a gift voucher in recognition of their time. For this and for the remaining experiments, written informed consent was obtained for all participants and all procedures were approved by a university ethics committee.

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[1] While a convenience sample, this number was nevertheless sufficiently powered to replicate Teufel and colleagues’ observed effect size for the CAPS (r = 0.42, 90% power, min. sample = 50).

Materials and Procedure

Sine Wave Speech (SWS) Discrimination Task.

SWS is created by tracking and modelling the formant tracks of spoken sentences using a sine-wave tone. This procedure can be used to create potentially intelligible stimuli (in which the frequency and amplitude tracks of the same original sentence are combined) – or unintelligible stimuli (combining the frequency and amplitude information of two different sentences). Both are typically perceived as unintelligible, but potentially intelligible SWS typically becomes comprehensible following training and exposure to 2-3 template sentences (Rosen et al., 2011). Experiment 1 used the same SWS stimuli as in Alderson-Day, Lima et al. (2017), which were first developed by Rosen et al. (2011)[2]. The original sentences were taken from the Bamford-Kowal-Bench sentence set (Bench et al., 1979). Participants completed the task in a quiet university room. The task was presented using Psychtoolbox in MATLAB 2016 on a Windows PC with a 17” monitor, using Sennheiser headphones for stimulus delivery. See Figure 1 for a summary of the design of this and the other reported experiments.

The SWS discrimination task used in Experiment 1 was designed to broadly mirror the one used by Teufel et al. (2015). The task was divided into two runs of 90 trials (45 intelligible SWS, 45 unintelligible SWS) occurring *before* and *after* participants heard each of the original sentences that the intelligible SWS trials were based on (“template exposure”). On each run, participants listened to 2.5s clips of SWS and were asked to decide whether speech was present or not for each trial, allowing for signal detection measures to be calculated based on hit rates (intelligible trials marked as containing speech) and false alarm rates

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[2] Rosen and colleagues’ SWS stimuli were also noise-vocoded. This step was omitted in our use of the stimuli for the present paper and in Alderson-Day, Lima et al. (2017), as noise-vocoding can induce an effect akin to whispering, and can make the underlying sinewaves cohere – both of which could potentially reveal the underlying speech signal.

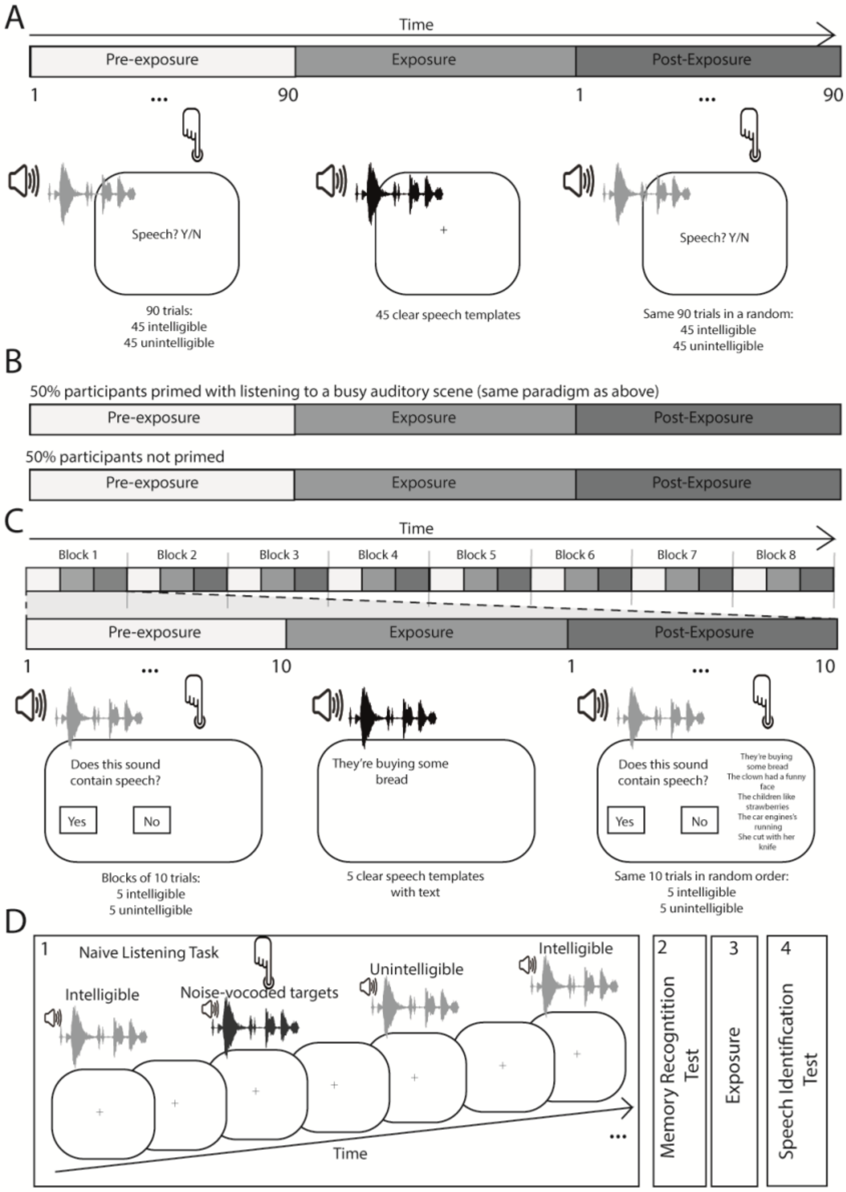
(unintelligible trials marked as containing speech). Signal detection theory (Stanislaw & Todorov, 1999) was used to calculate discrimination (d'), plus two measures of bias: criterion (C), which was the measure used by Teufel and colleagues, and beta (β), the measure most typically used in source monitoring research on hallucinations (Brookwell et al., 2013). Where hit rates and false alarms were 0 and 1, the Macmillan and Kaplan (1985) method was used (i.e., zero scores replaced with 0.5/n and 1 replaced with (n-0.5)/n).

Questionnaires

The *Cardiff Anomalous Perceptions Scale* (CAPS; Bell et al., 2006) is a commonly used scale of hallucination-proneness that assesses a range of unusual perceptual experiences – including auditory, visual, and gustatory phenomena – across 32 items. It correlates with other measures of schizotypy and hallucinations, such as the Oxford Liverpool Inventory of Feelings and Experiences (OLIFE; Mason et al., 1995) and has strong internal reliability (alpha = 0.87). Participants are asked to indicate whether they have ever had a specific experience, and if so, how distressing, how intrusive, and how frequent the experience was (on a 1-–5 scale). To assess the general tendency to experience hallucinations, here we used the total frequency as the main CAPS outcome.

The *Peters Delusion Inventory – 21 item version* (PDI; Peters et al., 2004) is a shortened adaptation of the original 40-item PDI (Peters et al., 1999). Both measures have been used extensively as a measure of proneness to unusual beliefs in the general population, have good convergent validity with other measures of schizotypy, and have strong internal reliability (e.g. alpha > 0.8). The PDI has an identical structure to the CAPS (the latter being modelled on the former). Frequency of belief was included as the main outcome. Both questionnaires were completed following the SWS discrimination task.

Figure 1. Overview of experiments. (A) Experiment 1: Participants heard 90 trials comprised of potentially intelligible and unintelligible sounds and judged whether each sound contained speech (pre-exposure). They were then exposed to the target clear speech exemplars from which the intelligible trials were made (exposure), and then asked again to judge which trials contained speech (post-exposure). (B) Experiment 2: Participants took part in the same paradigm as Experiment 1 but half the participants were primed by listening to a busy auditory scene and the other half were not. (C) Experiment 3: Participants heard blocks of 10 trials using the same pre-exposure, exposure, post-exposure cycles in Study 1. (D) Experiment 4: Participants took part in a naïve listening experiment in which they were tasked with identifying sounds with a specific acoustic quality (noise-vocoded sounds). They were not informed that some sounds contained speech. They were then asked whether they had heard any speech in the naïve listening task and took part in a memory recognition test to see if they remembered the intelligible trials. They were then exposed to the clear speech targets and tested on their identification of speech.



Our analytic approach sought to first assess changes in discrimination and bias variables following exposure phase, using paired t-tests. We then followed Teufel and colleagues by testing the main hypothesis – examining the relationship between CAPS scores and d-prime improvement – using Pearson's correlation coefficient test, along with also assessing correlations with PDI scores. Correlations with other change scores (i.e. beta and C) and relations to pre-exposure performance were included for exploratory purposes.

Results and Discussion

Table 1 shows signal detection outcomes for the SWS discrimination task. As would be expected, performance significantly improved following exposure to the original (i.e. non-masked) sentences, as indicated by an increase in *d'*. However, bias also significantly increased on both *C* and *β*, with participants being more likely to say that speech was present after template exposure (before hits *M*(*SD*)% = 67.9% (21.1%), false alarms *M*(*SD*) = 20.6% (12.3%); after hits *M*(*SD*)% = 88.6% (14.2%), false alarms = 26% (14.9%)).

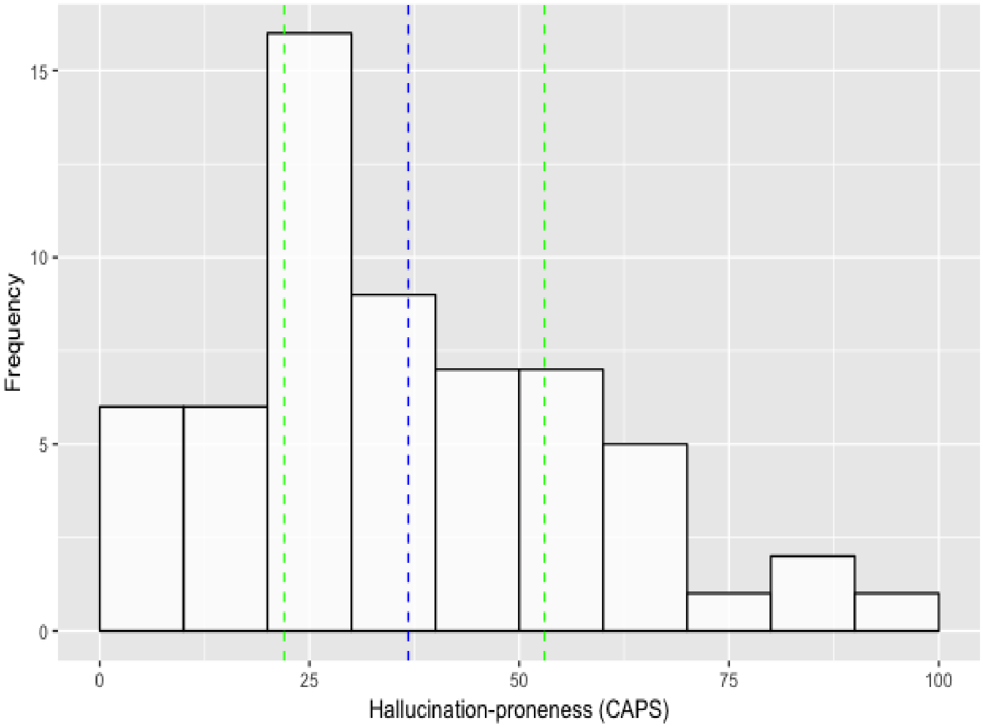
Figure 2 shows the distribution of CAPS scores for the sample and indicates that the average level of unusual experiences reported in our sample is comparable (if not higher) than the validation sample of the original CAPS, and roughly half the mean frequency seen in clinical samples (Bell et al., 2006).

Table 1. Signal detection outcomes for the SWS discrimination task

	Before		After				
	M	*SD*	*M*	*SD*	*T*	*p*	*d*
d'	1.47	0.77	2.17	0.81	-8.63	4.809e-12	-1.11
C	0.19	0.45	-0.37	0.44	8.32	1.554e-11	1.07
β	1.63	1.87	0.60	0.51	4.21	8.883e-05	0.54

Note: higher values of d' indicate increased sensitivity to detect speech. Scores below 0 for C and 1 for beta indicate bias to indicate speech is present.

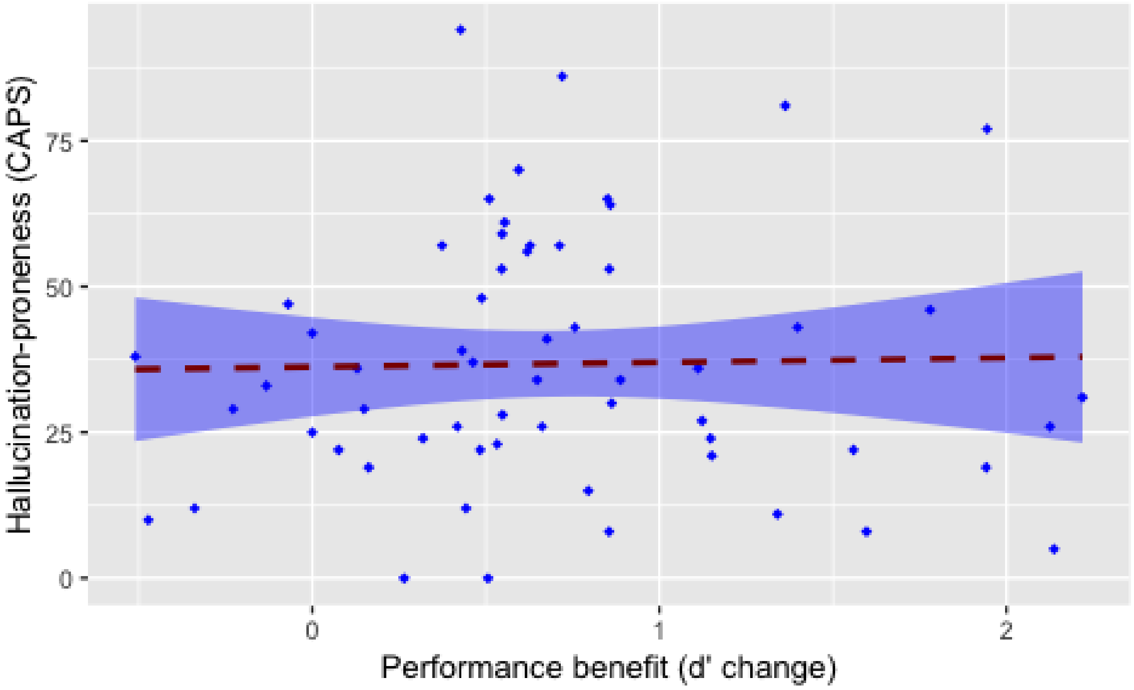
Figure 2. Distribution of hallucination-proneness scores (CAPS). Mean (blue dotted line) and interquartile range (green lines) indicated.



Despite the clear change in discrimination scores following exposure, no correlation was observed between CAPS scores and change in *d'* (Pearson's product, *r* (58) = -.02, *p* = .86, 95% CI = -0.23:0.28), contrary to the modulation hypothesis (see Figure 3). Due to the positive skew in CAPS scores (which is common for measures of hallucination-proneness, e.g. Alderson-Day et al., 2019), we ran secondary correlation tests using square-root transformed CAPS scores (*r* (58) = .01, *p* = .92, 95% CI = -.24:.27) and Spearman's Rho (*r* (58) = .04, *p* = .74), but neither indicated any relationship of interest. Finally, a one-sided Bayesian analysis (using JASP v.0.8.6 with default priors) indicated a BF of 0.19 for the experimental hypothesis and 5.39 for the null (i.e., good evidence for a lack of any effect of interest).

Following Teufel et al. (2015), we also tested for the relationship with delusions on the PDI, plus any relations between bias (C and β) and proneness to psychotic experiences. No significant correlations were observed between task and questionnaire scor (all *p* > .10). The largest relationship was between pre-exposure β scores and CAPS (*r* = .21, p = 0.11), but visual inspection indicated that this was driven by two outliers with very high β scores before exposure (both > 3 SD; see Supplementary Table 1 and Figure 2). Removal of these outliers reduced this correlation by nearly half (*r* = -.13).

Figure 3. Relationship between hallucination-proneness (CAPS) and change in discrimination performance (d') for experiment 1 (*n* = 60). Blue bands = 95% confidence intervals.



The results of Experiment 1, therefore, did not support the idea of a modulatory effect of expectation being related to hallucination-proneness. When exposed to new information via the original sentence templates, participants consistently performed better in terms of their speech vs. non-speech discrimination and increased their bias to state that speech was present (across intelligible and unintelligible SWS stimuli). None of these performance changes were related to hallucination-proneness scores on the CAPS or delusion ratings on the PDI (the two measures used by Teufel et al. (2015) in their second experiment).

Three limitations are important to consider with regard to these data. The first is that using hallucination-proneness in non-clinical analogue samples has been questioned for its ability to identify individuals with truly hallucinatory experiences (Stanghellini et al., 2012). If valid, this could lead to the concern that correlations between tasks and self-report will be very low and very hard to capture, given the low base level and minimal variation in proneness scores. The spread of CAPS scores shown in Figure 2 is comparable to prior research of this kind and not insubstantial when compared to clinical data (Bell et al., 2006). Nevertheless, directed recruitment of members of the general population with higher levels of hallucination-proneness could provide greater variation and more opportunity to examine how changes in expectation relate to unusual sensory experiences.

A second concern is that measures of hallucination-proneness can yield inconsistent results, and there is currently no “gold-standard’ for assessing such experiences in the general population. For the purposes of replication, we used the CAPS, but the Launay-Slade Hallucination Scale (Bentall & Slade, 1985b) is perhaps a more commonly-used scale in prior research on hallucinations. Moreover, the CAPS asks about hallucinations across a range of modalities, whereas prevalence rates for AVH – and the auditory nature of the SWS task – may warrant a more specific measure of auditory hallucination-proneness.

Experiment 2: Modulating prior knowledge with a wider range of hallucination-proneness.

Next, we present a second experiment that addressed each of these points in a new sample of 60 participants. With the aim of gathering a wider range of unusual experiences, we explicitly set out to recruit individuals with a history of having imaginary companions (ICs). Engaging with imaginary companions has been proposed to bear commonalities with hallucinatory experiences (Pearson et al., 2001), despite the fact that there is no good evidence that they are a developmental marker for later psychopathology (Maijer et al., 2019; Taylor, 1999). Specifically, there is evidence to suggest that having an IC as a child is associated with both elevated hallucination-proneness and bias in auditory signal detection skills as an adult (Fernyhough et al., 2019). In addition, children with ICs are more likely to hear words amidst jumbled speech, which is similar in many ways to effects seen for SWS (Fernyhough et al., 2007). As an alternative to the CAPS, we instead used a revised version of the Launay-Slade Hallucination Scale (Morrison et al., 2000), with a specific focus on auditory experiences (McCarthy-Jones & Fernyhough, 2011).

We also attempted to provide a second test of the modulation of expectation, by priming half the participants with a short listening activity (listening to a recording of a conversation in a busy room) before attempting the same task as Experiment 1, i.e., discrimination before and after exposure to the sentence templates. Reasoning that directing participants to listen for speech under suboptimal conditions should prime both the expectation of speech and top-down templates for speech, we predicted that primed participants would go on to show greater speech discrimination of SWS in the subsequent task, even prior to template exposure. If this could be demonstrated, it would represent a more naturalistic modulation of expectation, by indirectly priming generic speech templates that could assist in the disambiguation of the SWS stimuli. The design for Experiment 2 therefore mixed a between-groups approach (prime vs. no-prime) and a within-subjects approach (before vs. after template exposure). As in Experiment 1, we hypothesised that greater improvements in discrimination scores on the SWS task would be associated with greater LSHS scores. Because we could not be sure in advance how many people we would be able to recruit with a history of having an IC, this was treated as an individual differences variable, rather than being counterbalanced across the priming conditions. Its effects were therefore explored via a correlational approach alone.

Method

Participants

Sixty participants (age *M*(*SD*) = 23.22 (4.76), range 18-43 years, 14 male) were recruited from university settings, social media, and via word-of-mouth. Exclusion criteria were identical to Experiment 1. Within the 60, it was possible to recruit 22 people with a history of having imaginary companions as children, of whom 14 were able to provide parental verification of their childhood IC – a validation step considered good practice in IC research (Fernyhough et al., 2007, 2019).

Materials and Procedure

The same procedure and task structure were used for the SWS discrimination task as in Experiment 1. In addition, half of the participants completed a priming activity before the discrimination task. The CAPS and PDI were replaced with a version of the Revised Launay-Slade Hallucination Scale.

Listening prime task

Thirty participants were asked to complete the priming activity before the SWS discrimination task. Participants were given a worksheet and were asked to circle words that they heard being mentioned in a 3-minute pre-recorded conversation between five girls. The recording was layered with white noise to increase the difficulty in discerning what was being said. The remaining thirty participants were instructed to close their eyes, and count their breaths for 3 minutes in silence, as timed by the experimenter.

Questionnaires

Experiment 2 included a version of the *Revised Launay- Slade Hallucination Scale* (McCarthy-Jones & Fernyhough, 2011; Morrison et al., 2000). Since the development of the original scale by Bentall and Slade (1985b), numerous versions of the LSHS have been used to assess hallucination-proneness in the general population. Here we used a five-item version in which all of the items related specifically to auditory experiences, which participants rated for frequency on a scale from 1 (Never) to 4 (Almost Always). This version was developed by McCarthy-Jones and Fernyhough (2011) following a revision by Morrison, Wells and Nothard (2000). This version has satisfactory internal reliability (typically alpha => 0.7) and has been used to explore task-to-questionnaire relations in various studies previously (e.g. Alderson-Day et al., 2019; Garrison et al., 2017).

Results and Discussion

A 2×2 mixed ANOVA (prime group x pre/post exposure) was used to assess the effect of the priming condition on discrimination, plus any interaction it had with exposure to the sentence templates (i.e. before vs. after). As in Experiment 1, there was a clear increase in discrimination following exposure to the template sentences (*F* (1,58) = 81.31, *p* = 1.24e-12, η^2_p = .22). But despite the manipulation, no main effect of priming was observed on the discrimination task following the listening activity (*F* (1,58) = 0.98, *p* = .33, η^2_p = 0.01), nor any interaction effect between priming group and template exposure (*F* (1,58) = 0.53, *p* = .47, , η^2_p = .001). Pre-exposure *d'* scores were very similar in each group (Primed *M*(*SD*) = 1.68 (0.75); Control *M*(*SD*) = 1.45 (0.77)), as were post exposure scores (Primed *M*(*SD*) = 2.39 (0.79); Control *M*(*SD*) = 2.29 (0.66)). Comparisons of pre-exposure bias were also non-significant (all *p* > .300; see Supplementary Materials, Experiment 2).

Given the lack of differences on any task measure, we subsequently combined the priming groups to facilitate comparison with Experiment 1. Table 2 shows the SWS task outcomes. As before, there was a significant increase in discrimination following exposure. Pairwise t-tests showed that this was also the case for both measures of bias (i.e., lower scores, indicating a greater tendency to say speech is present).

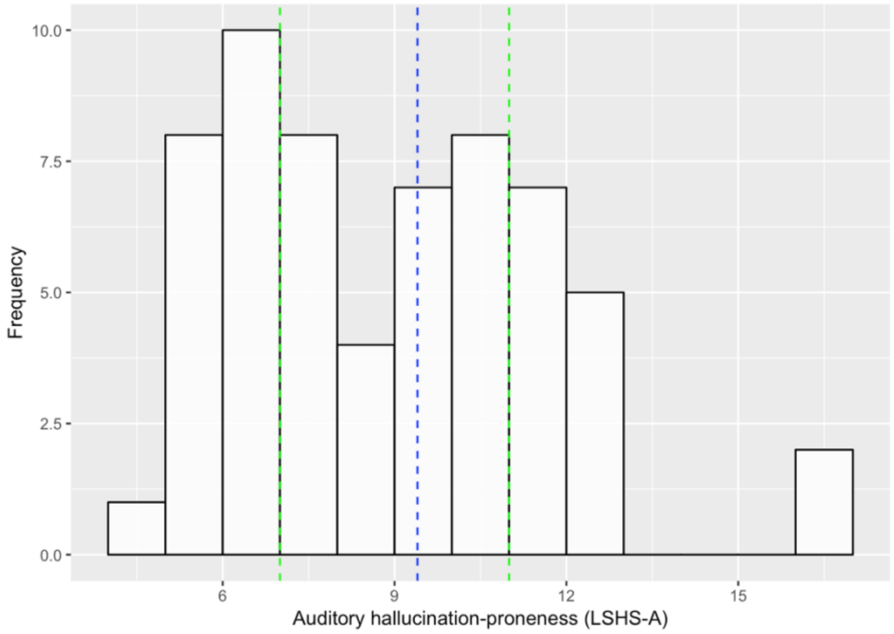
Table 2. Signal detection outcomes for the SWS discrimination task.

	Before		After				
	M	*SD*	*M*	*SD*	*t*	*p*	*d*
d'	1.56	0.76	2.34	0.72	-9.05	9.298e-13	-1.17
C	0.29	0.63	-0.42	0.52	9.65	9.59e-14	1.25
β	2.58	3.04	0.88	1.62	4.99	5.726e-06	0.64

Figure 4 shows the distribution of hallucination-proneness scores as collected by the LSHS-A. The mean score of 9.40 places this sample as having a mean level of hallucination-proneness comparable to other samples with childhood histories of ICs, and slightly higher than large samples without any IC history (M = 8.76; Fernyhough et al., 2019). As would be expected, participants with an IC in the present sample had significantly higher LSHS-A scores (IC *M*(*SD*) = 10.55 (2.89); No IC *M*(*SD*) = 8.74 (2.41); $t = -2.48$, $df = 37.86$, $p = .02$, $d = 0.66$).

However, even with higher rates of hallucination-proneness in the sample, few relations between SWS task outcomes and self-report scores were observed. A stronger relationship was evident between the improvement in d' and LSHS-A scores ($r = .19$), but this was still non-significant, both with a Pearson's test ($p = .15$)[3], Spearman's Rho ($r = .22$, $p = .09$), and with Bayesian analysis offering no evidence for any effect (one-sided $BF_{10} = 0.81$). Similarly, correlations with bias metrics (C and β) were non-significant (all $r < .19$, all $p > .14$). Pre-exposure discrimination actually *negatively* correlated with LSHS scores ($r = -.34$, $p = .01$, uncorrected), suggesting more hallucination-prone people were worse at discriminating speech than controls before hearing the sentence templates.

Figure 4. Auditory hallucination-proneness in sample 2. Mean (blue dotted line) and interquartile range (green lines) indicated.



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[3] As in Experiment 1, this was also tested with LSHS-A square-root transformed to account for the positive skew in hallucination-proneness scores. This yielded almost identical results ($r = .18$, $t(58) = 1.43$, $p = .16$).

While introducing variation in LSHS-A scores, the inclusion of people with an IC history also raises the concern that we were effectively sampling across two different populations. This was reflected in the distribution of LSHS-A scores in Figure 4, which showed significant bimodality (Hartigan’s dip test, D = 0.075, *p* = .01). To address this, we reran our analyses as a regression accounting for IC status, LSHS-A, and their interaction in their prediction of d’ change. An initial model containing Age (stan. b = -0.01, *p* = .958), Gender (stan. b = -0.19, *p* = .153), and IC status (stan. b = 0.36, *p* = .007) significantly predicted d’ change (R^2 = .13, *F* (3,56) = 2.81, *p* = .048), indicating that participants with an IC showed greater d’ improvement (*M*(*SD*) = 1.05 (0.54)) than those with no IC (*M*(*SD*) = 0.62 (0.69)). However, the addition of LSHS-A (stan. b = 0.11, *p* = .41) and the interaction of LSHS-A and IC status (stan. b = 0.02, *p* = .21) did not significantly improve the fit for models 2 and 3, while IC status remained significant throughout (see Supplementary Materials, Experiment 2). This suggested that d’ change and hallucination-proneness were nevertheless unrelated, despite the effect of IC status.

The results of Experiment 2 therefore provided a further test of the modulation hypothesis in the auditory domain, but again could not support it: improved discrimination following template exposure did not significantly relate to hallucination-proneness. In addition, priming expectation for speech with a further manipulation yielded no difference in discrimination performance. Taken together, the results of experiments 1 and 2 highlight a failure to replicate Teufel et al.’s (2015) modulation effect in the auditory domain across two independent samples, using two different common measures of hallucination (including one tailored for auditory experiences), and including healthy individuals who may be expected to be particularly hallucination-prone. Of note, though, is that individuals with a history of having an imaginary companion do appear to benefit more from the updating of prior knowledge, leaving open the possibility that some kinds of unusual or quasi-hallucinatory experiences may be linked to momentary changes to expectation. This is consistent with adults with a history of imaginary companions also showing speech biases on standard auditory signal detection tasks (Fernyhough et al., 2019).

Our findings suggest that a sensitivity to momentary modulation of expectation for speech is not part of the putative mechanism underlying hallucinations, raising problems for a “strong priors” account of the phenomenon (Corlett et al., 2019). However, the findings may still reflect unusual properties of SWS itself. For example, SWS comprehension following exposure and training can show something akin to a “pop-out” effect, where suddenly new stimuli can be easily understood. In addition, they offer potentially different opportunities for learning: compared to Mooney images (Mooney, 1957), where the level of visual noise is high compared to the level of repeated signal across trials, SWS arguably provides more opportunity to improve trial-by-trial, due to intertrial consistency in speech-like cadence and prosody. When one considers that even pre-exposure, participants in Experiment 1 achieved high hit rates, it may be that the speech vs. non-speech discrimination was simply too easy for participants (compared to the harder challenge of actually understanding the underlying speech). This in turn could have limited the opportunity to highlight association with individual differences in hallucination-proneness.

Experiment 3: Modulating prior knowledge of sine-vocoded speech with varying levels of difficulty.

Adapting and extending the SWS developed by Rosen et al. (2011) is challenging, as the stimuli were originally hand-edited to closely map the formant contours of speech. To address the factors described above, we deployed a different auditory stimulus in Experiment 3 – sine-vocoded speech (SVS) – and mixed it with unintelligible SVS to add a source of auditory noise. This provided: (i) a way to automate the generation of a degraded speech stimulus (rather than using hand-crafted SWS), allowing the use of a larger number of spoken sentences, and (ii) greater control over manipulating task difficulty. We tested pre- and post-exposure identification of degraded speech in a larger sample (*n* = 99) and its association with hallucination-proneness at increased level of difficulty compared to the previous experiments. To attempt greater parity with Teufel et al. (2015), the task was administered in prior knowledge exposure cycles of ten trials, rather than using a one-shot exposure approach.

Method

Participants

A sample of 99 participants were recruited from university settings, social media, and via word-of-mouth (age *M*(*SD*) = 21.58 (3.34), range 18-34 years, 45 male). Exclusion criteria were identical to the previous experiments. All participants provided informed consent in accordance with the approval of the relevant ethics committee. Due to experimenter error, the questionnaire data were not complete for 12 participants: one participant did not have PDI data and 11 did not have CAPS data. Participants received course credit for taking part.

Materials and Procedure

Auditory stimuli

Sine-vocoded speech (SVS; Souza & Rosen, 2009) is similar to SWS. However, rather than tracking only the first three formants of speech, the sinewaves are synthesised at the centre frequency of a logarithmically spaced bank of filters spanning a broad frequency range (up to 5 KHz). Like SWS, SVS sentences can be rendered intelligible and recognisable as speech when participants are aware that it is a speech stimulus (Souza & Rosen, 2009). SVS can also be rendered unintelligible by flipping the frequency mapping of the original sentence (e.g., pushing energy in high frequency bands into low bands and vice versa), providing an ideal control stimulus, with similar complexity and acoustic structure.

The BKB sentences (Bench et al., 1979) were recorded by a male speaker at a sample rate of 22.05KHz. Each sentence was digitally filtered using either 8 or 16 bands, with sixth-order Butterworth IIR filters in MATLAB. Filter spacing was based on equal basilar membrane distance (Greenwood, 1990) across a frequency range of 100–5000 Hz. Next, the output of each band was half-wave rectified and low-pass filtered (fourth-order Butterworth) at 30 Hz to extract the amplitude envelope. The envelope was then multiplied by a tone carrier at the band centre frequency for each filter. The resulting signal (envelope × carrier) was filtered using the same bandpass filter as for the first filtering stage. RMS level was adjusted at the output of the filter to match the original analysis, and the signal was summed across bands. When a larger numbers of filter bands (e.g. 16 vs. 8) are used to synthesise a spoken sentence this increases the spectral information in the signal with a resulting increase in intelligibility (Souza & Rosen, 2009).

Sine-vocoding was used to make two types of stimulus: an intelligible and unintelligible SVS condition. For the Intelligible SVS condition, intelligible SVS sentences were mixed with an unintelligible sine-vocoded sentence that acted as a competing noise source. This was designed to make stimulus identification more difficult reducing learning in the pre-exposure phase and ensuring greater dynamic range in the prior knowledge advantage provided by hearing clear speech templates. The RMS level of the intelligible sentence was rendered at different levels of intensity relative to the unintelligible sentence before mixing them together (e.g. a differing signal to noise ratio, SNR, was used). This, alongside manipulating the number of vocoding bands, provided a way to manipulate the difficulty of speech identification.

For the Unintelligible SVS condition, two sentences were sine-vocoded and frequency flipped and mixed together in an equivalent SNR as the Intelligible SVS condition, with one unintelligible sentence arbitrarily assigned to be of greater intensity than the other. This ensured that the Intelligible SVS and Unintelligible SVS condition were of equivalent complexity and overall intensity. A set of stimuli were synthesised from +6dB to -6dB in 3dB steps using 8 and 16 bands. The sentences composing the intelligible and unintelligible conditions were mutually exclusive. We have made this full set of stimulus materials available here (even those conditions not used in this article) to facilitate future research: https://osf.io/yrn9j/.

Auditory task

Participants attended to sounds presented using MATLAB on a laptop using Sennheiser HD 206 headphones. They were randomly assigned to five groups which each received two different sets of auditory stimuli (approximately 20 participants in each group). These two sets differed in either SNR and/or number of bands. Informal piloting indicated that the 8 band +6dB condition provided an appropriately challenging listening level, such that accuracy would be above chance, but not at ceiling. Each group was tested on this common 8 band +6dB condition, plus one other condition. This common condition was included with the purpose of pooling the data across groups to test for the relationship between signal detection measures and questionnaire responses. The second condition had a different signal to noise ratio and/or number of vocoding bands and was included to scope how speech detection accuracy was influenced by the SNR and number of bands.

Data from these conditions indicated that the SNR level and number of bands had a significant effect on participant performance and confirmed the observation that the 8 band +6dB condition provided an appropriately difficult listening experience (see Supplementary Materials, Experiment 3). The specific set of sentences used in each condition and order of the conditions was counterbalanced across participants to ensure that participants did not hear repetitions of any sentences across the experimental session and to reduce order effects.

Testing in each auditory condition took around 20 minutes (40 minutes total). Prior to each condition participants received a short training session in which they were introduced to the intelligible and unintelligible stimuli. They were informed that they would hear a 50:50 ratio of intelligible to unintelligible trials in the forthcoming experiment and needed to judge whether each trial contained speech or not.

In the experiment, sounds were presented in blocks of ten in a randomised order (5 intelligible trials and 5 unintelligible trials). In the pre-exposure phase, on each trial participants indicated whether the sentence contained speech or not. They then received exposure to prior knowledge: they heard each target sentence presented in the original clear speech and saw the written transcript of the sentence. In the post-exposure phase, they heard the intelligible and unintelligible sentences that they heard in the pre-exposure phase in a different randomised order and were again asked to indicate which sentences contained speech. The five transcribed target sentences remained on right hand side of the screen during the post to reduce memory demands and to maximise the prior knowledge benefit. This cycle repeated 8 times, each time with a different set of 10 sentences, such that 80 trials were presented in each condition (40 intelligible; 40 unintelligible) and 160 trials were presented in total across the experiment.

Following administration of the auditory tasks, total frequency scores were collected for the CAPS (Bell et al., 2006) and the PDI (Peters et al., 2004). Signal detection measures were calculated as in the previous experiments. Total testing time was around 50 minutes.

Results and Discussion

A one-way independent ANOVA with group as a factor showed that there was no evidence of a difference in d’ between the five data collection groups, so data were pooled for the common 8 band +6dB condition (F (4, 94) = 1.83, p = .130, η^2 = .07). Speech identification accuracy in this condition was above chance before prior knowledge exposure (t(98) = 10.96, p = 9.952e-19, d = 1.10), but crucially was significantly increased after prior knowledge exposure (t(98) = 9.34, p = 3.217e-15, d = 0.94, see Figure 5A and Table 3).

A 2 x 8 repeated measures ANOVA with factors prior knowledge exposure (pre/post) and block (1-8) was conducted to understand how d’ changed across the experiment. This indicated a significant exposure x block interaction (F (6.07, 595.19) = 2.23, p = 0.030, η^2=

.02, see Figure 5B). Follow-up repeated measure one-way ANOVAs indicated a change in d' across blocks before exposure to prior knowledge (*F*(6.23, 610.46) = 3.33, $p = 0.003$, $\eta^2 = 0.03$) but not after it (*F*(6.18, 605.54) = 0.86, $p = 0.542$, $\eta^2 = 0.01$). In the pre-exposure phase the change in accuracy increased linearly with block progression (*F*(1, 98) = 14.83, $p = 2.100e\text{-}4$, $\eta^2 = 0.13$). There was also a main effect of block such that accuracy in general increased across blocks (*F* (5.94, 582.36) = 2.17, $p = 0.045$) and from pre- to post-exposure (*F* (1,98) = 64.69, $p = 2.054e\text{-}12$). Hence, even with these more challenging stimuli, participants continued to improve in their ability to detect speech in SVS in the pre-exposure phase, demonstrating the learning opportunity inherent to SWS/SVS.

As in the previous studies, there was no evidence of a significant relationship between change in d' and the CAPS (*r* (88) = -0.06, $p = 0.574$) or the PDI (*r* (98) = -0.19, $p = 0.060$, see Figure 5C and see Supplementary Materials, Experiment 3). For this latter measure there was a trend towards a negative relationship, the opposite direction predicted by the modulation hypothesis. One-sided Bayesian correlations assessing a positive association between d' and the questionnaire measures were used to assess the relative evidence for the null as compared to the experimental hypothesis. These tests provided strong evidence for the null hypothesis (both one-sided $BF_{01} > 11$). We also tested to see if change in d' correlated with either the CAPS or PDI on the additional acoustic conditions (e.g., those differing in number of bands and SNR level), but this was not the case (see Supplementary Materials, Experiment 3). Hence, we did not find evidence in support of the modulation hypothesis, even when using a task more closely aligned to Teufel et al. (2015).

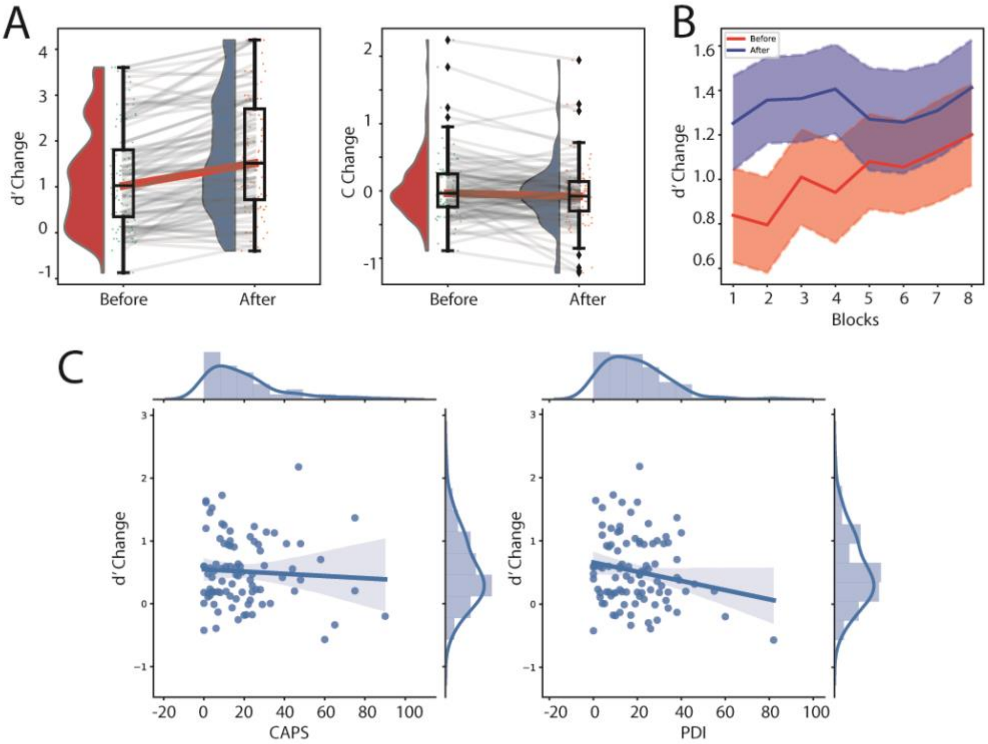
Finally, we examined associations with bias. There was evidence of a decrease in C after prior knowledge exposure reflecting an increased bias to report the presence of speech (C (*t*

(98) = 2.99, *p* = .004, d = 0.30). However, C did not differ significantly from zero either before or after prior knowledge exposure (both *p*'s > 0.193). A non-parametric Wilcoxon test – to account for a deviation in normality – also indicated that beta values did not change significantly (*w* = 2020.5, *z* = 1.59, *p* = 0.113). These findings suggest that the SVS stimuli provide a more controlled modulation of discrimination, while holding bias relatively more constant. Beta and C change did not correlate with either the CAPS or PDI frequency measures (all *p*s > 0.172).

Table 3. Signal detection outcomes for the SVS speech detection task for the 8 band, +6 dB condition

	Before		After				
	M	*SD*	*M*	*SD*	*statistic*	*p*	*d*
d'	1.20	1.09	1.72	1.24	t = 9.34	3.217e-15	0.94
C	0.04	0.48	-0.06	0.45	t = 2.99	0.007	0.30
β	1.28	1.23	1.14	0.98	z=1.59	0.113	0.16

Figure 5. (A) d' and C change with prior knowledge exposure, **(B)** d' change over time in the common 8 band, +6dB condition. Note that the grand mean for d' values for the by block analyses differs to the main analysis because the adjustment for extreme values was conducted by block in this instance rather than across the whole experiment (Macmillan & Kaplan, 1985), **(C)** showing the lack of evidence in support of a relationship between d' change and the CAPS and PDI measures.



Experiment 4: Replicating and extending the naïve listening effect

The aim of the final experiment was to replicate and extend the "naïve listening" effect observed in our prior study with non-clinical voice-hearers (Alderson-Day et al., 2017). In that study, participants with frequent experience of hearing voices reported recognising speech in SWS earlier than control participants, despite not being informed that speech was hidden in the stimulus. Surprisingly, those who reported tuning in to SWS earlier also reported significantly greater levels of AVH in the preceding week, as measured on the "physical characteristics" subscale of the PSYRATS (Haddock et al., 1999).

To reproduce this, we reran the naïve listening procedure (this time using SVS rather than SWS) and collected hallucination-proneness measures on the LSHS-A (*n* = 134) in a larger, healthy sample of individuals. Moreover, we added an additional procedure to reduce our reliance on participant self-report: a memory test that could only be successfully completed if participants had actually been understanding words in the SVS prior to the "reveal" that speech was present. This, therefore, would extend our initial finding by providing more objective evidence of early SVS comprehension. Using this procedure, we predicted i) that people higher in auditory hallucination-proneness would report recognising speech in the SVS earlier than others, and ii) that those who reported recognising speech earlier would also be able to remember significantly more words hidden in the SVS task.

Method

Participants

We recruited 134 participants (age *M*(*SD*)= 21.45 (5.79), range 18-59 years, 46 male/2 other) via university departments, social media, and word of mouth. Exclusion criteria were the same as for the previous experiments. Participants were invited to take part in a “study of auditory perception” that involved listening to some “unusual sounds”, but no mention of voices or speech was included in the study materials. This allowed us to test for naïve listening effects in a way that wasn’t possible under the procedure used by Teufel et al. (2015) and in experiments 1-3.

Materials and Procedure

The procedure for experiment 4 closely followed Alderson-Day, Lima et al. (2017). The measures used are reported here in the order they were attempted by participants.

National Adult Reading Test (NART; Nelson, 1982)

The NART is a measure of vocabulary and reading ability which has been used extensively in research on psychosis as an indicator of premorbid IQ (e.g., Broome et al., 2012) and was included in Alderson-Day, Lima et al. (2017) for group matching. We retained it here to follow that procedure, but also to provide control material for the memory task. By including a small selection of words from the NART (plus similar words matched for unusual spelling), we could control for general memory differences between those who did and did not recognise speech in the SVS.

Sine-vocoded speech (SVS) naïve listening procedure

Intelligible and unintelligible SVS stimuli were drawn from the same set as Experiment 3. In Experiment 4, the 16-band, +6db stimuli were used, as these appeared to be the most similar to SWS in terms of their level of difficulty. Participants were told that they would be listening out for a scratchy target sound that sounded “different” from the other sounds, and began the procedure by listening to three examples of the target sound randomly presented along with five examples of unintelligible SVS[4]. The target sound was used to maintain attention and to provide an incidental task which would discourage participants guessing at the purpose, i.e. the potential intelligibility of distractors, hidden in the SVS. As in Alderson-Day, Lima et al. (2017), the "scratchy" sounds were examples of unintelligible SWS (i.e. the frequency and amplitude tracks of two separate original sentences combined), that had been further noise-vocoded, giving them a different timbre and sound quality. Once participants could discriminate the two kinds of sound, they attempted the main listening task, which contained six blocks of 15 SVS stimuli (45 intelligible, 45 unintelligible) and three target lures per block. At the start of each block, a visual stimulus appeared announcing the start of the block (i.e. block 1, block 2, etc). Stimuli were presented in a predefined pseudo-random order with no more than two of the same kind of stimuli consecutively.

Once the participants had listened to all six blocks, they were asked by the experimenter i) if they noticed anything unusual about the words, ii) if they noticed any words and sentences, and crucially iii) if they knew which round they started noticing them (using the visual block markers as means of marking out time). Participants' estimates for the third question were used as the main task outcome, defined as their "recognition point". They were then told that in fact there were words present in the stimuli, and asked to complete the memory task for words contained in the SVS. The memory test consisted of a list of 46 words, including 18 words included in the SVS (3 per block), 18 words matched for length and complexity that did not feature in the SVS, five words from the NART, and five non-target words matched to the NART words for their irregular spelling. Following recognition memory methodology

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[4] Specifically, participants were told: *"Your task is to listen out for a target sound and press the space bar every time you hear it. It might sound "scratchy" compared to the others. Have a listen to these examples, and press the space bar if you think you hear the unusual sound."*

(Tulving, 1985), participants were asked to indicate for each word whether they remembered the word (R), knew they had seen the word (K), or didn't recognise it (N).

SVS training and accuracy task

To allow for comparison with prior applications of SWS/SVS, participants were then trained to understand SVS by listening to six new sentences and receiving visual feedback as their underlying meaning. Following Alderson-Day, Lima et al. (2017), they were then tested for their speech/non-speech discrimination and keyword comprehension for 50 SVS trials (25 intelligible, 25 unintelligible). To check genuine comprehension rather than simply repetition effects, this included five new intelligible sentences that did not feature earlier in the experiment. Signal detection outcomes were again calculated to assess d' and beta scores, post-training.

Questionnaires

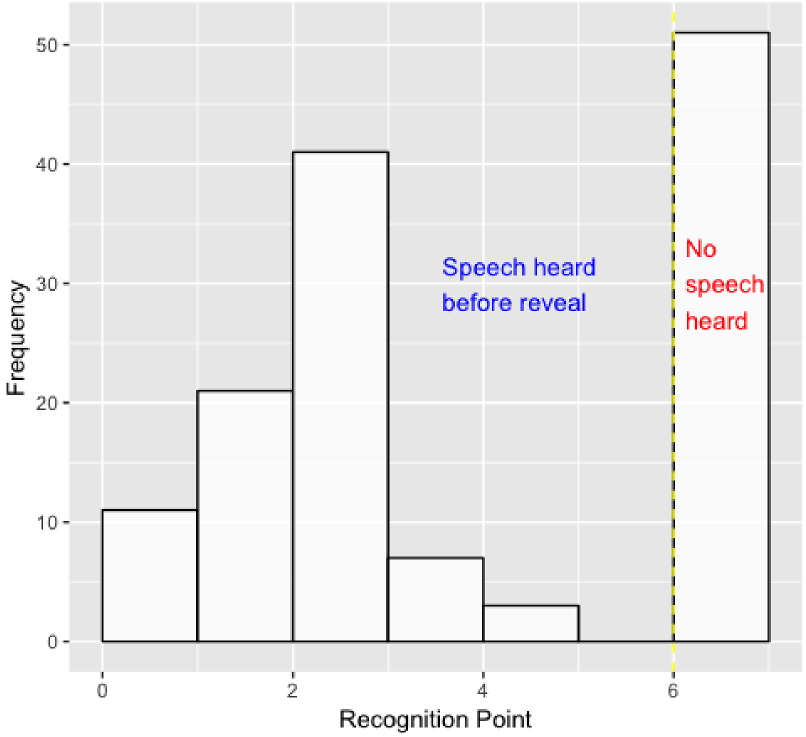
Following the tasks, participants completed the LSHS-A (as in Experiment 2), but also two further measures: the four corresponding visual questions from the LSHS (i.e. the LSHS-V) and the brief version of the Oxford Liverpool Inventory of Feelings and Experiences (OLIFE; Fernyhough et al., 2008; Mason & Claridge, 2006). This allowed for specificity testing by comparing auditory hallucination-proneness with visual experiences and general proneness to schizotypal experiences.

Results and Discussion

No participants guessed the purpose of the experiment before testing. Overall, 83 out of 134 participants (62%) recognised speech being present in the SVS, of which 72 (54%) could understand and repeat some of the words encoded in the stimuli. Figure 6 shows the frequency of recognition points for participants recognising speech in the SVS, which showed a surprisingly bimodal distribution: 83 participants reported recognising speech in one of the first six blocks, while 51 did not notice any speech until after listening (marked with a score of 7). A number of participants reported recognising speech on one trial in particular in block 3: "*the boy is running away*". As the distribution was significantly bimodal (D = 0.17463, $p = 2.2e-16$), logistic regression was used to assess how well LSHS-A scores predicted those who recognised the speech early (i.e. *before* training) vs. those who did not. A model containing age, gender, and LSHS-A scores significantly predicted recognition group (X(4) = 11.46, $p = 0.02$), with only LSHS-A scores acting as a significant predictor (Z = 2.061, $p = .04$, OR = 1.19, CI = 1.02-1.43). Specificity analysis swapping LSHS-A for visual items of the Launay-Slade (LSHS-V) or a measure of general schizotypy (the OLIFE) did not result in significant models (see Supplementary Materials, Experiment 4). However, adding NART scores to the model yielded a significant improvement in fit (X(2) = 13.24, $p < .001$), with higher reading scores being associated with identifying speech early (Z = 34.12, $p < .001$, OR = 1.15, CI = 1.06 - 1.25). Under this model, the coefficient for LSHS-A scores was reduced and non-significant (Z = 1.83, $p = .07$, OR = 1.17, CI = 0.99 – 1.141).

Following the reveal that speech was present, participants were tested on their memory for the hidden words, trained on some SVS examples, and tested on 50 trials of speech/non-speech discrimination. In support of their self-reported performance, the early-recognition group correctly recalled more words (either explicitly remembered, that they knew they had heard at some point) (see Table 4); in contrast, there were no differences for words recalled from the NART. Those who recognised SVS as speech also recognised more words during training and during the accuracy task, and they differed on signal detection performance – showing greater discrimination, but also a bias to say speech was present. However, no significant correlations were evident between LSHS-A scores and performance on the accuracy task, once all participants had been exposed to SVS training (all $p > .10$, $r < .10$).

Figure 6. Distribution of participant recognition points for listening blocks 1-6 (n = 83) and participants who did not identify speech in SVS (n = 51).



The results of Experiment 4, therefore, demonstrated that a naïve listening effect could be replicated: people higher in hallucination-proneness were more likely to notice speech in SVS, even when not told that speech was present. This supported the original findings of Alderson-Day, Lima et al. (2017), but added to it by providing a more objective test of participants being able to recognise speech early – namely, actual improved recall for words hidden in the SVS. This was specific to auditory hallucination-proneness – not visual hallucination-proneness, or general schizotypy – but also potentially mediated by verbal IQ (using NART as a proxy). Performance on SVS following training (in terms of discrimination and comprehension) was better for those who tuned in to SVS early, but this was unrelated to their hallucination-proneness.

Table 4. Memory test, training, and SVS accuracy performance by those who recognised SVS early vs late.

	Early (n = 83)		Late (n = 51)				
	M	*SD*	*M*	*SD*	*t*	*p*	*d*
Memory test							
Recognised	5.43	3.16	3.76	1.49	4.13	6.65e-05	0.73
Knew	4.82	3.95	2.90	3.59	2.89	.005	0.51
New	16.19	5.10	16.94	5.93	-0.75	.457	-0.13
NART words	4.16	1.42	4.41	1.02	-1.21	.230	-0.22
Training	11.31	6.63	3.18	3.79	9.03	1.85e-15	1.61
Accuracy task							
D'	2.72	0.89	1.60	1.22	5.73	1.596e-07	1.02
C	-0.21	0.52	0.02	0.49	-2.62	.010	-0.47
Beta*	1.23	1.64	1.41	1.29	(W = 1517.5)	.006	0.24
Keywords	39.65	17.03	15.04	14.70	8.85	1.036e-14	1.57

*Wilcoxon test used due to non-normal data.

General Discussion

Our aim in the present paper was to align and reconcile two findings of enhanced top-down perceptual processing in people prone to hallucinations. Across four experiments, we were only partially successful in this aim. Our findings in experiments 1–3 could not provide evidence for a modulation hypothesis, i.e., that people who are more prone to hallucinations draw upon prior expectation more in their perception when their expectations are explicitly updated. Instead, in Experiment 4 we provided further evidence for a naïve listening effect: healthy people who are prone to hallucinations are more able than others to identify speech in SVS prior to template exposure and without knowing that speech is present, suggesting a *spontaneous*, rather than directed, use of top-down resources.

Some limitations of our general approach must be noted before considering the implications of these results. First, we have tested exclusively university and general population-based samples, rather than including either a patient sample or a group of non-clinical voice-hearers (i.e., those with very regular hallucination-like experiences; Johns et al., 2014). We therefore cannot rule out that participants with more frequent experiences would not show a pattern of responses to these stimuli more consistent with those reported by Teufel et al. (2015), although such effects have not previously been claimed to only be present in those with a clinical status. That is, predictive approaches to hallucinations are often explicitly framed as models of both clinical and non-clinical phenomena, with the former resulting from an accentuation of mechanisms underlying normal, veridical perception (rather than there being a clinically-specific profile that produces symptoms). Second, we used SVS to more closely control for learning effects across trials, but our data from Experiment 3 showed that, even with increasing difficulty, sine-based speech stimuli appear to afford inter-trial learning opportunities which may not be readily available when using visual stimuli. Further direct comparison of auditory and visual analogues in the same experiment is required to elucidate modality-general and modality-specific effects, while controlling for potential differences in learning and discrimination difficulty. Finally, none of our experiments deployed basic tests of auditory processing or hearing ability, which could contribute to low-level differences in how SWS/SVS are recognised and processed by people prone to hallucinations: there is emerging evidence that subtle differences in hearing ability can be associated with hallucinations for some people (Linszen et al., 2016). Participants with a self-declared hearing difficulty were not recruited to the study, and tests of speech intelligibility do not pose the same challenges to hearing as other tasks used in hallucination research (such as auditory signal detection), but closer control of these factors would have been to test hearing skills in all participants.

Notwithstanding these considerations, our findings have substantial implications for top-down processing in hallucinations and the predictive approach to understanding them. The results of experiments 1-3 highlight that a modulatory effect in the auditory domain cannot be demonstrated despite variation in stimuli (SWS vs. SVS), difficulty, and both levels and measures of hallucination-proneness. This implies that either i) the top-down effects observed by Teufel and colleagues do not extend to the auditory domain or ii) that directed top-down effects (i.e. explicit modulation) at least require further examination. Conversely, it appears that Alderson-Day, Lima et al.'s (2017) finding *can* be replicated in healthy individuals rated for hallucination-proneness, and this can be verified using a more objective measure of when participants started to hear speech in the SVS (i.e. via their memory performance).

How to explain this discrepancy in findings? Crucial to note is that any advantage that some participants have with SWS/SVS appears to be modest and short-lived. Here and in Alderson-Day, Lima et al. (2017), post-training performance for discriminating speech was no better for people who are hallucination-prone: only early detection under naïve conditions showed a difference. This implies the existence of a "default" mode of interpretation when in ambiguous conditions, rather than a strongly held bias that endures or is amplified with the addition of new knowledge. It may be that healthy individuals who have unusual experiences have very slight biases that facilitate this kind of top-down advantage, akin to the concept of encoding style for internal over external meanings[5] (Valérie et al., 2011). Conversely, individuals with clinical hallucinations may be more fixed in their expectations of finding

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[5] Kristiina Kompus (U. Bergen) is thanked for this comparison.

signal in noise, leading to non-veridical experiences more generally. In such a situation, a slight bias might yield an advantage – especially if it can be applied selectively – whereas a strong bias would lead to false positives (i.e. hearing speech in unintelligible SWS/SVS). Supporting this, a recent, small-scale study by Kafadar and colleagues (2020) – using the structure of Experiment 1 here, but the same stimuli as experiment 3 and 4 – found that people at clinical high risk of psychosis are marked more by their pre-exposure *bias* to hear speech, rather than discrimination. Moreover, they found no differences in post-exposure discrimination, suggesting again that the explicit modulation of expectation was less relevant to understanding how they perceived SVS.

This would also imply, however, that healthy people prone to unusual experiences are not necessarily suffering from momentary suggestibility or demand characteristics – both of which could be prompted by explicit modulation – but something potentially more ingrained. In predictive processing terms, this could constitute a higher-order belief about the world (e.g., “the universe is full of hidden meanings”) which directs the individual response in ambiguous situations to explore potentially important signals despite the instruction to listen for the target sound.

Alternatively, the constraint could be at a different level in the processing hierarchy and be expressed in how auditory stimuli are modelled as objects. A recent reframing of the predictive approach by Teufel and Fletcher (2020) has proposed to separate long-term, context invariant “constraints” on perception from context-specific, temporary “expectations” that shape immediate, moment-to-moment sensation. Our data point towards a long-term constraint for some individuals in how they recognise auditory objects when faced with ambiguous and potentially speech-like stimuli, rather than sensitivity to changes in situationally-specific expectations. Support for this argument comes from recent work on the actual templates that people use to make judgements about speech. By creating “speechiness” kernels for individual participants, Erb and colleagues (2020) have demonstrated that people high in hallucination-proneness utilise qualitatively different speech templates when discriminating speech sounds, such that lower frequencies typical of speech are attended to less, compared to higher frequency auditory information. If so, this suggests a fundamental long-term alteration to how speech is recognised and processed in those prone to hallucinatory and illusory experiences – rather than a dynamic, moment-to-moment volatility in how expectations are managed (as can be seen, for example, in suggestibility effects). Variation of naïve listening effects with SVS tailored to different speech kernels could be used to explore this further.

It is also important to consider the potential differences between information provided in the auditory and visual domains. As already noted, SWS/SVS appeared to allow for learning across blocks and trials even pre-exposure: it is possible that more generic and isomorphic templates are available for listening vs. viewing under such ambiguous conditions. Alternatively, hallucination-proneness itself could involve differing expectation of auditory compared to visual signals: it is notable that rates of auditory hallucinations in schizophrenia, for example, are often reported to be 2-3 times higher than rates of visual hallucination (Waters et al., 2014). Reasons why this is the case are debated (and may reflect clinical inquiry and reporting practices), but it is not implausible that expectations for linguistically meaningful communicative signals will be higher in one domain over another. Auditory signals are often fleeting and evolve over time, which can make them more vulnerable to degradation. Indeed, we encounter degraded speech signals frequently in daily life, such as when listening in noisy cafeterias and over public address systems. By contrast, situations involving ambiguous visual scenes occur much less frequently. We speculate that the greater relative experience with auditory ambiguity may lead to expectations for speech that are simply *stronger* than for other kinds of stimuli and are more readily invoked in ambiguous situations. In future studies, it would be possible to parametrically vary the perceptibility of hidden speech in SVS by adapting the signal to noise ratio and reducing the number of vocoding channels to dampen such effects and to demonstrate modulatory effects that are comparable to those seen in the visual domain.

Finally, such effects are also likely to be shaped by a considerable number of other individual differences, including auditory experience and cognitive factors such as IQ (Gwilliams & Wallisch, 2020). Our finding that NART scores better explained recognition point performance than LSHS scores highlights how considerably cognitive skills can influence ambiguous speech perception, and we cannot rule out other unmeasured factors playing a similar role. The range of variables guiding individual comprehension skills for degraded speech, noise-vocoded speech, and speech-in-noise are vast, complex, and yet to be clearly pinpointed (McGettigan et al., 2012).

In conclusion, the experiments that we present here refine our understanding of how top-down expectations shape speech perception for people prone to auditory hallucinations. Directly updating expectation does not appear to confer an advantage for people higher in hallucination-proneness, but they do spontaneously respond to ambiguous speech stimuli in a differential way, facilitating speech identification. This implicates longer term and potentially lower level constraints on how speech is recognised in such populations, rather than a temporary sensitivity to expectation.

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