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Delusion Proneness is Linked to a Reduced Usage of Prior Beliefs in Perceptual Decisions

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Predictive coding theories state an aberrant weighting of prior beliefs and present sensory information as a core computational pathology in psychosis. Specifically, it has been proposed that the influence of prior beliefs which attenuate improbable sensory information is weakened, resulting in an overweighing of this potentially misleading information. However, it is currently unclear whether this alteration is specific to perceptual processes or whether it represents a more pervasive deficit that extends to cognitive processes. Here, we carried out 2 behavioral experiments that probed the usage of priors during perceptual and cognitive processes, respectively, in 123 healthy individuals with varying degrees of delusion proneness. In an audio-visual perceptual discrimination task, participants had to judge the global motion direction of random dot kinematograms. Prior beliefs were induced by auditory cues that probabilistically predicted the global motion direction of the dot kinematograms, allowing us to measure the impact of prior beliefs on perceptual decision making. A control experiment paralleled the design of the perceptual decision making task in the domain of cognitive decision making. By fitting the participants' responses with a probabilistic decision model, we quantified the impact of prior beliefs on participants' decisions in both tasks. With growing delusion proneness, we found a decreased impact of prior beliefs on perceptual but not on cognitive decision making. Our results show that delusion proneness is linked to a specifically reduced usage of prior beliefs in perceptual decisions, thereby empirically substantiating predictive coding theories of psychosis.

Keywords: predictive coding/psychosis continuum/perception/decision making/cognitive models

Introduction

According to predictive coding theories of psychosis, delusions arise from disturbances in basic information integration processes,[1–4] particularly from an aberrant interplay between prior beliefs and present sensory information. These theories build on the idea that the brain uses prior beliefs to deal with present incoming information that is inherently ambiguous and thus allows for different interpretations.[5] Accordingly, prior beliefs are used to enforce perceptual interpretations with a higher prior probability by attenuating improbable sensory information; dysfunctions in this preference of more probable interpretations will therefore result in the tendency to place trust in implausible explanations and thus to delusion proneness.

The specific interplay between prior beliefs and sensory information has been studied in the field of visual perception, where a substantial body of research demonstrates that our perception is shaped by prior beliefs derived from experience.[6–10] Importantly, in this field, predictive coding theories of delusions imply an easily testable hypothesis: the impact of prior beliefs on decisions between alternative visual percepts should be reduced in delusions and delusion proneness, reflecting a failure to attenuate improbable sensory information. The resulting proneness towards surprising, unusual and potentially threatening percepts might then contribute to the emergence of hallucinations and delusional ideation.[2]

In the present study, we empirically tested this hypothesis using a task that requires the usage of prior beliefs induced by auditory cues for visual decision making in a large sample of healthy individuals with varying degrees of delusion proneness. We predicted that there would be a negative correlation over individuals between their delusion proneness and the influence of prior beliefs established by the predictive cue.

However, findings on relationships between delusions and the usage of prior beliefs are complex.[6,11,12] In this context, it has been proposed that prior beliefs stored at different levels of the processing hierarchy differentially affect perceptual decisions: While the impact of low-level prior beliefs that attenuate the precision (weight) of sensory evidence may be decreased, higher-level priors may be unaffected or even have a stronger effect to compensate for the attenuation failure.[1,6,11] In the present study, we therefore further aimed to determine whether the previously suggested delusion-related reduction in the impact of prior beliefs is specific to more low-level perceptual decisions or whether it also affects more high-level cognitive decisions. Hence, we carried out a control task that involved cognitive instead of perceptual decisions but otherwise mimicked the design of the perceptual decision making task. This allowed us to dissociate a specific deficit in the usage of prior beliefs for perceptual decisions from a more general deficit in the usage of prior beliefs that extends to cognitive decision making.

Methods

Participants and Experimental Setup

One hundred twenty-three healthy participants were recruited from the general population through advertising (basic demographic information is summarized in table 1). Inclusion criteria comprised normal or corrected-to-normal vision and absence of psychiatric disorders. The study was approved by the ethics committee of the Charité, Universitätsmedizin Berlin. After complete description of the study to the participants, written informed consent was obtained in accordance with the Declaration of Helsinki of 1975.

The participants' delusion proneness was quantified using the Peters Delusion Inventory (PDI).[13] The 40 items of this self-rating questionnaire cover a wide range of common delusional beliefs. As in our previous work,[14] we used the total score obtained by adding up the 3 PDI subscales. Detailed analysis regarding the factor structure of the PDI as well as the PDI subscales are provided in the supplementary material.

Perceptual Decision Making Task

To assess the impact of prior beliefs on perceptual decisions, we used a dot motion detection task (Fig. 1), in which 2 sources of information had to be integrated to make decisions about motion direction (left/right). Firstly, noisy visual information was given by dot kinematograms that contained a certain number of dots coherently moving to the left or to the right, overlaid by randomly moving dots. Secondly, prior beliefs about the motion direction were induced by a tone that was—dependent on the pitch—probabilistically associated with leftward or rightward motion.

Table 1. Sample Characteristics

Characteristic	Median (Interquartile Range)
Age	29 (15)
PDI score	45 (84)
Characteristic	Absolute numbers
Sex	Female: 67; male: 56
Smoking	Yes: 37; no: 86
Graduation	Lower secondary school: 9; higher secondary school: 30; high school: 83; missing information: 1

Note: PDI, Peters Delusions Inventory.

Our perceptual decision making task comprised 30 rounds that contained a varying number of trials, dependent on the participants' decision behavior (see next paragraph). In each round, the global motion direction remained the same (either the left or the right). However, on the first trial, it was very difficult to discriminate the global motion direction because only 2% of the dots moved coherently to the defined direction while the remaining dots moved randomly. Over the course of each round, the discrimination of the global motion direction became easier as the percentage of coherently moving dots gradually increased.

At the end of each trial, participants indicated their perceived motion direction (left or right) by moving the cursor on the horizontal response bar. Here, a placement of the cursor on the very left signified a very certain perception of the movement to the left and a placement closer to the center a more uncertain perception to the left (vice versa for the right). The cursor could not be placed at the very center of the bar, so that the participants were forced to decide for one direction. After indicating the perceived motion direction, participants were asked if they were certain enough about the motion direction to commit themselves to the given response. If participants did not commit to their response, the round continued with a new trial with the same tone and global motion direction but an increased percentage of coherently moving dots. Once participants had committed to their response, a new round began. A low-pitched tone preceded leftward motion and a high-pitched tone rightward motion each time in 80% of the cases. The tone was the same throughout one round and was repeated on every trial of the round before the onset of motion. To let participants learn the associations between tone-pitch and motion direction, we conducted a learning run with 15 rounds prior to the main experiment. The probabilities associated with the tone pitches were kept constant throughout the whole experiment and the participants were told that the tone meanings learned in the learning run would not change in the main experiment.

Please refer to the supplementary material for details on audiovisual stimulation.

Cognitive Decision Making Task

To test whether delusion proneness was associated with a more general alteration of the usage of prior belief extending to cognitive decisions, participants performed a cognitive decision making task as a non-perceptual control task. Therefore, we used an adapted version of the lake task (originally introduced by Phillips et al[15]).

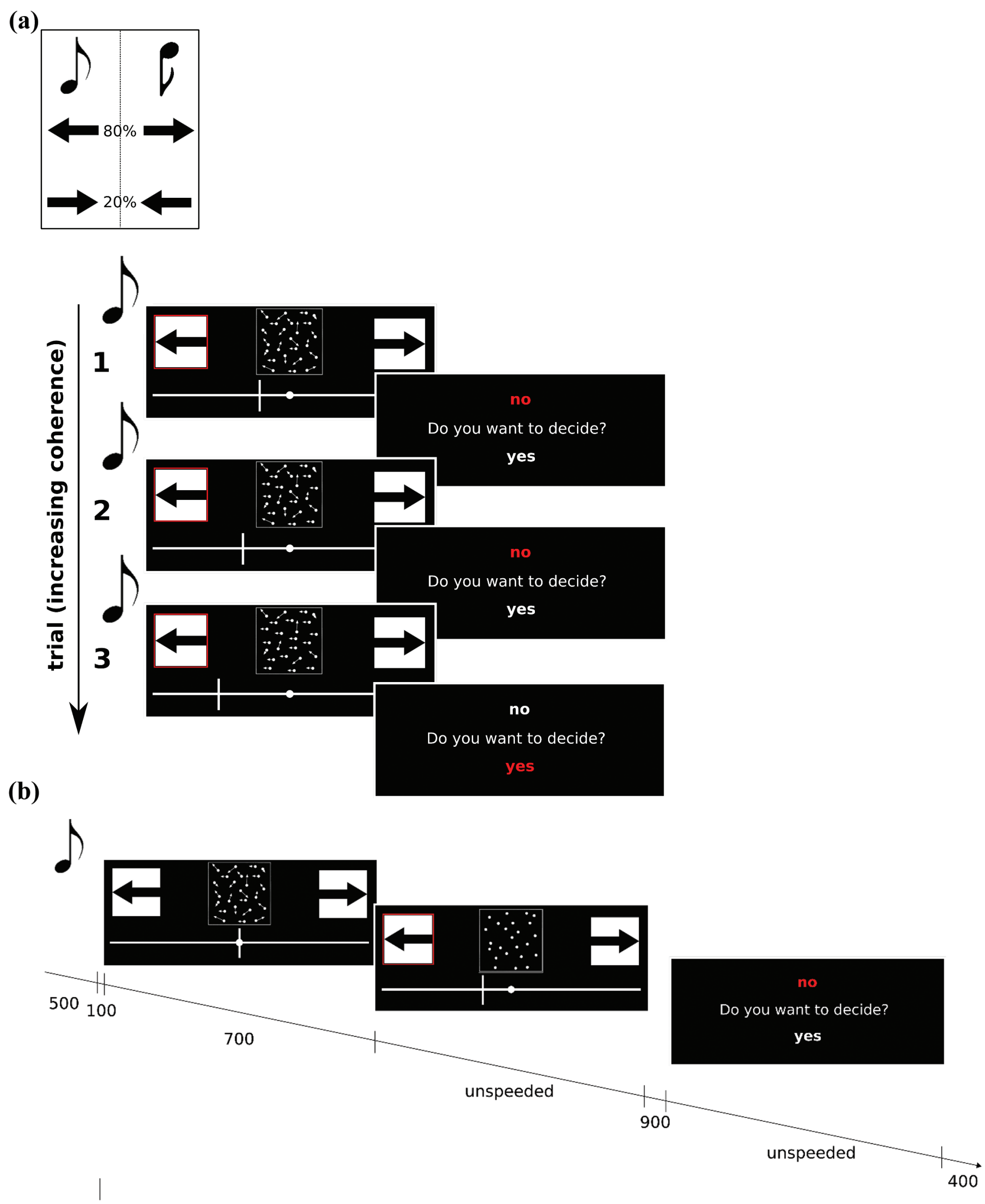

Fig. 1. Experimental design of the perceptual decision making task. (a) Sequence of a round with typical tone meaning (see panel top left) and 3 trials. (b) Sequence of one trial with timing in milliseconds.

In close analogy to the perceptual decision making task, participants had to integrate prior beliefs with sensory information in order to come to a decision about which of 2 lakes, a "carp lake" or a "trout lake," was currently being angled. The 2 lakes were home to a different proportion of carps and trouts (70% carps and 30% trouts in the carp lake and vice versa in the trout lake). Information about the currently angled lake was given by the number of carps and trouts angled so far. To minimize the perceptual component in the cognitive task, this information was provided in written form without any graphical visualization. Prior beliefs about the angled lake were induced by a tone that was—pitch-dependent—associated with the carp or the trout lake.

Like the perceptual task, the cognitive decision making task comprised 30 rounds with a varying number of trials. In each round, either the carp or the trout lake was being angled. On each trial, 1 additional fish was angled and the number of carps and trouts already angled in the current round was displayed. Hence, with only one angled fish it was very difficult to make a decision about the correct lake in the first trial and over the course of a round, this decision became easier as the number of angled fishes increased. Like in the perceptual task, participants indicated their binary choice of the lake and their confidence about their choice at the same time on a response bar and were subsequently asked if they were certain enough to commit themselves to the given response. If not, the round continued with the presentation of another angled fish from the currently angled lake. If yes, a new round began.

The cognitive task was an exact replication of the perceptual task with the only difference that the sensory information was provided in form of the number of fishes (that were probabilistically related to one of the 2 lakes) and not in form of the visual display of moving dots (that was noisily related to one of the 2 possible motion directions). Hence, both the perceptual and the cognitive task were analyzed analogously (see next paragraph).

Modeling the Impact of Prior Belief and Sensory Information

In both tasks, the impact of prior belief (induced by the tone pitch) on decision making was modeled with logistic regression, a probabilistic model for binary decisions. To this end, the binary responses were predicted using the tone pitch and the sensory information as predictors. In the perceptual task, the sensory information was given by the motion (proportion of coherently moving dots with a negative sign in case of the leftward and a positive sign in case of rightward direction). The probability P of a decision for a rightward motion was thus:

$$\ln\left(\frac{P}{1-P}\right) = \text{const} + \beta_{\text{prior}} \times \text{tone} + \beta_{\text{present}} \times \text{coherence}$$

In the cognitive task, the sensory information was the posterior probability of the carp lake given the current number of angled carps and trouts (according to Bayes rule):

$$P(\text{carplake}) = \frac{0.7^c \times 0.3^t \times \binom{c+t}{c}}{0.7^c \times 0.3^t \times \binom{c+t}{c} + 0.3^c \times 0.7^t \times \binom{c+t}{c}}$$

c = number of carps; t = number of trouts; $\binom{\text{n}}{\text{k}} = \text{binomial coefficient}$.

For both tasks, coefficient values and their P values were estimated using the glmfit routine of the Statistics and Machine Learning Toolbox for Matlab. The independent impact of prior belief and sensory information on the participants' decisions was thereby captured in the magnitude of the coefficients for prior belief (β_{prior}) and sensory information (β_{sensory}), where high values indicate a strong impact.

Assessing Relationships Between Delusion Proneness and Usage of Prior Beliefs

To test our central hypothesis of a reduced usage of prior beliefs in perceptual decisions with growing delusion proneness, we correlated PDI scores with the magnitude of the prior belief coefficient βprior from the perceptual decision making task. To test if potential alterations were specific to perceptual inferences, we repeated the same analysis for the cognitive decision making task. Because of a non-normal distribution of the PDI score values (Kolmogorov-Smirnov test with Lilliefors correction, $P < .001$), 2-sided nonparametric Spearman correlations and Spearman partial correlations were used.

Results

Task Performance is Worse When Prior Belief and Sensory Information Mismatch

To test whether prior beliefs were successfully induced by our task, we first compared task performance on congruent and incongruent trials (ie, the 80% of trials in which the tone was coupled with its typical motion direction and the 20% of trials in which the tone was coupled with the other motion direction). In the perceptual task, participants tended to make more errors on incongruent trials (34.6 [20.5]% vs 41.1 [24.1]%, mean [SD], $T = 1.91$, $P = .06$, paired t test). As expected, this effect was considerably stronger when excluding inverse learners (see next paragraph, 30.6 [16.5]% vs 46.0 [22.7]%, $T = 5.09$, $P < .001$). Similarly, in the cognitive task mean error rates were higher for incongruent trials (12.9 [10.2]% vs 29.8 [20.5]%, $T = 8.81$, $P < .001$). These results show that participants made more errors when prior belief and sensory information mismatched, which indicates that prior beliefs were integrated into inferences in both tasks. Although being correlated between both tasks ($\rho = 0.287$, $P = .001$), error rates were generally higher in the perceptual task than in the cognitive task (35.9% as compared to 16.3%), raising the possibility that the perceptual task was more difficult than the cognitive task.

Prior Beliefs and Sensory Information Predict Participants' Perceptual Decisions

Bayesian model comparison suggested that prior belief as well as sensory information were used by the participants in the perceptual task (supplementary material). The mean prediction accuracy of the model was 69.49% (SD 10.29%). Prediction accuracy was not significantly related to delusion proneness (Spearman $\rho = -0.059$, $P = .515$, $n = 123$), speaking against a differing model fit as a confound for group statistics on model parameters. Surprisingly, examination of the coefficient values revealed that a substantial number of participants ($n = 17$) significantly used prior beliefs for decision making (P value of the prior belief coefficient < .05), but in an incorrect way as indicated by negatively signed coefficient values. Hence, practically, they favored the rightward motion direction in case of the low-pitched tone and vice versa. This significant, but paradox tone usage was most likely due to a non-veridical learning of inversed tone meanings during the learning run. Because participants were instructed that the associations between tone and motion direction of the learning run did not change throughout the whole experiment, they then used the inverse associations in the main experiment, manifesting in significant, but negative coefficient values. In line with this, these 17 participants indeed showed an altered tone learning in the learning run (but no differences in PDI scores, supplementary material). We therefore quantified the usage of prior beliefs as the absolute coefficient magnitude, ie, the impact of prior beliefs independent of the direction of the learned association. However, to exclude biased results, we repeated all analyses in the sample without these 17 participants and report results that relate to delusion proneness for both the full sample (n = 123) and the reduced sample without inverse learners (n = 106).

Usage of Prior Beliefs in Perceptual Decisions is Reduced in Delusion Proneness

To assess relationships between delusion proneness and the usage of prior beliefs for perceptual decisions, we correlated the individuals' PDI scores with the magnitude of the prior belief coefficient β_{prior}. In line with our hypothesis, this analysis yielded a significant negative correlation (Fig. 2, full sample $\rho = -0.233$, $P = .009$, reduced sample $\rho = -0.243$, $P = .012$, all P values 2-sided), indicating a decreasing usage of prior beliefs with growing delusion proneness during perceptual decision making.

Detailed control analyses indicated that reduced usage of prior beliefs was not attributable to potential delusion-related confounds and did not reflect a general deficit to learn and integrate prior beliefs (supplementary material).

Usage of Prior Beliefs in Cognitive Decisions is not Related to Delusion Proneness

To investigate whether the found decreased usage of prior belief in perceptual decisions extends to cognitive decisions, we similarly quantified behavior in the cognitive task. The model also successfully predicted behavior (mean prediction accuracy 88.68%, SD 8.25%) while prediction accuracy was not significantly related to delusion proneness ($\rho = -0.038$, $P = .676$).

In contrast to the perceptual decision making task, however, the magnitude of the β_{prior} was not significantly correlated to PDI scores (full sample $\rho = 0.054$, $P = .554$, reduced sample $\rho = 0.044$, $P = .656$), indicating that in cognitive decisions, delusion proneness was not related to the usage of prior beliefs.

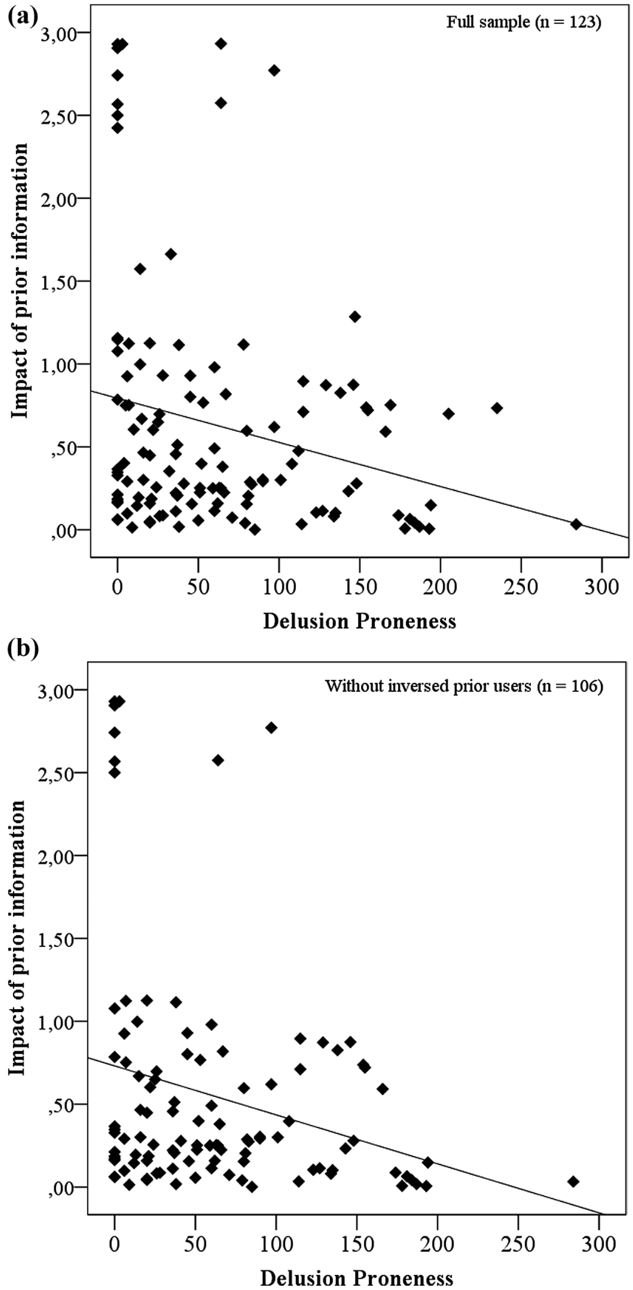

Fig. 2. Significantly decreasing impact of prior beliefs on perceptual decision making with growing delusion proneness. (a) In the full sample Spearman $\rho = -0.233$, $P = .009$, $n = 123$, (b) excluding 17 participants with inversed learning of prior beliefs, $\rho = -0.243$, $P = .012$, $n = 106$. Please note that for illustration purposes only, the values for impact of prior beliefs for 2 participants whose decisions were determined almost exclusively by the prior beliefs were cut and set to the maximal value of the remaining set (these 2 outliers with excessive usage of prior beliefs did not overly affect the results of statistical testing due to the application of nonparametric correlations).

Discussion

In the present study, we demonstrate that delusion proneness is associated with a reduced usage of prior beliefs in perceptual, but not in cognitive decision making.

An influential line of theories has proposed an impaired integration of previous experiences in inferences as a central deficit underlying delusions ("a weakening of the influences of stored memories of regularities of previous input on current perception").[16] In a Bayesian brain framework, this corresponds to a failure to attenuate the precision of (ie, trust in) sensory information, relative to prior beliefs.[1] On this basis, several studies have investigated delusion-related alterations in the impact of prior beliefs on visual perception.[6,12,17,18] Here, our result is consistent with theoretical[1,17] and empirical[6,18] work linking delusions to a reduced integration of prior beliefs in perceptual inference.

However, it should be noted that there is also evidence that suggests an increased impact of prior beliefs on perceptual decisions.[6,12,19,20] Hence, these findings seem to conflict with the current and previous findings suggesting a decreased impact of prior beliefs. We propose that this apparent discrepancy might be resolved by a distinction of different hierarchical processing levels.[6,11] According to this idea, at lower hierarchical levels prior beliefs are used to attenuate sensory precision. In psychosis, a decreased influence of such low-level prior beliefs will lead to an insufficient suppression of improbable sensory information. At the same time, at higher hierarchical levels prior beliefs are used to infer the causes of the sensory information and hence to imbue meaning to the input from lower levels. In psychosis, the influence of such higher-level priors may be increased to compensate for the increased precision of lower-level input. As a result, the insufficient suppression of improbable sensory information provided by weak lower-level priors leads to delusional interpretations afforded by strong higher-level priors. Therefore, it is plausible that a psychosis-related decrease of prior belief usage will be found in tasks in which the experimental prior beliefs can be regarded as lower-level priors. This might be the case in previously used tasks[17] as well as in our current task where implicitly learned auditory cues (eg, a tone indicating that visual motion is towards the right) were used to suppress incongruent visual information (eg, random dots moving coincidentally towards left). Conversely, in tasks in which experimental prior beliefs can be regarded as higher-level priors, psychosis is expected to be associated with unaltered or even compensatorily increased usage of prior beliefs. This could explain the previous findings indicating an increased impact of prior beliefs on visual and auditory perception.[6,12,19,20] Hence, the aforementioned findings of increased prior usage are not necessarily contradicting the computational hypothesis of a decreased usage of low-level prior beliefs in psychosis, but might rather reflect the suggested secondary increase in the precision of high-level prior beliefs that is thought to compensate for an abnormally high (unattenuated) sensory precision at lower levels.

In our results, this dissociation between low- and high-level priors might be reflected in the difference regarding the usage of prior beliefs in perceptual (assumedly low-level) as compared to cognitive (assumedly high-level) inferential processes. However, we did not find a significant relationship between the usage of priors in the cognitive task and psychosis proneness. In a previous study using the same cognitive decision making task but a different modeling approach we found that psychosis-prone individuals even showed a decreased impact of prior beliefs on tone-independent belief updates on a trial-by-trial basis.[14] As we found significantly lower error rates in the cognitive task as compared to the perceptual task, we suggest that our cognitive task might have been too easy to probe interindividual differences in the usage of sustained (tone-induced) prior beliefs but instead tapped into the mechanisms related to trial-by-trial (tone-unrelated) prior beliefs. In line with this, Jardri et al[21] used a very similar but more difficult (supplementary material) cognitive task and also found a decreased usage of priors in psychosis and psychosis proneness. These results strongly suggest that the used cognitive tasks might not be suited to measure the impact of higher-level priors and points to the fact that the distinction between low-level from high-level priors is currently based on rather soft criteria (eg, implicit vs explicit or perceptual vs cognitive). Here, future work is needed to sharpen the distinction between high-level and low-level priors and to probe the impact of varying task demands.

Taken together, our study demonstrates a diminished capacity to guide perceptual decisions by prior beliefs in delusion proneness and thereby provides evidence for predictive coding theories of psychosis.

Supplementary Material

Supplementary material is available at https://academic.oup.com/schizophreniabulletin/.

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The authors have declared that there are no conflicts of interest in relation to the subject of this study.

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