Aus der Klinik für Psychiatrie und Psychotherapie
der Medizinischen Fakultät Charité – Universitätsmedizin Berlin

---

DISSERTATION

"Sensory processing in psychosis: Evidence for aberrant low-level information processing from multiple modalities and experiments"

"Sensorische Verarbeitung unter Psychose: Evidenz für aberrante Verarbeitung niedrig-hierarchischer Informationen aus multiplen Modalitäten und Experimenten."

---

zur Erlangung des akademischen Grades
Doctor of Philosophy (Ph.D.)

vorgelegt der Medizinischen Fakultät
Charité – Universitätsmedizin Berlin

von

ANNA-LENA ECKERT, M.SC.

aus Bad Segeberg

Berlin

Erstbetreuung: Prof. Dr. med. Philipp Sterzer

Datum der Promotion: 30.06.2024

Table of contents

List of tables

List of figures

List of abbreviations

ANOVA	**An**alysis **O**f **V**ariance
CAPS	**C**ardiff **A**nomalous **P**erceptions **S**cale
CI	**C**onfidence **I**nterval
fMRI	**F**unctional **M**agnetic **R**esonance **I**maging
HC	**H**ealthy **C**ontrols
IFC	**I**nferior **F**rontal **C**ortex
ITI	**I**nter-**T**rial-**I**nterval
mm	**M**ill**i**metre
ms	**M**illi**s**econds
NMDA	***N*-m**ethyl-**D**-**A**spartate
OFC	**O**rbito**f**rontal **C**ortex
PANSS	**P**ositive **A**nd **N**egative **S**ymptoms **S**cale
PDI	**P**eters et al. **D**elusions **I**nventory
PMF	**P**sycho**m**etric **F**unction
PPS	**P**sychosis **P**roneness **S**core
PSE	**P**oint of **S**ubjective **E**quality
RDK	**R**andom **D**ot **K**inematogram
s	**S**econds
SCZ	**Sc**hi**z**ophrenia
SSD	**S**chizophrenia **S**pectrum **D**isorders
TMS	**T**ranscranial **M**agnetic **S**timulation

Abstract

***Introduction*.** Psychosis is a debilitating mental state characterized by hallucinations and delusions. Recent developments in computational and cognitive neuroscience may help to elucidate the mechanisms underlying this complex disorder. The Bayesian Brain theory views the brain as actively generating perception from the combination of prior predictions (priors) and sensory data (likelihoods). In psychosis, this normative process may be altered so that perception is biased towards sensory data on lower levels of the cortical hierarchy. This lack of low-level constraint may be compensated by overly precise prior predictions on more abstract, cognitive levels. While conceptually successful, direct empirical tests of Bayesian accounts of psychosis remain sparse, a research gap which I aimed to address with my thesis work.

Methods. *Study I* consisted of two psychophysics paradigms, designed to study the effects of low- vs. high-level prior information on auditory- and visual perceptual decision-making, respectively. We investigated the associations between individual psychosis proneness score (PPS) in the general population and the weighting of differential types of prior information. In *Study II*, we assessed the reliance on prior information vs. sensory data in a bistable perception paradigm. Patients with paranoid schizophrenia and healthy controls viewed bistable stimuli with graded amounts of disambiguating sensory information.

Results. *Study I* showed that the influence of low-level prior information reduced with increasing psychosis proneness in the general population across modalities. In agreement with *Study I*, results of *Study II* suggest an increased reliance on sensory data and a shift away from prior information in patients with paranoid schizophrenia compared to healthy controls.

Conclusions. In conclusion, we observed reduced reliance on low-level prior information relative to the sensory evidence in both patients with paranoid schizophrenia and psychosis prone individuals in the general population. This finding replicated across different stimuli, task modalities, experimental settings, and study populations. It thus provides empirical support for recent conceptual- and computational models of psychosis. To bridge the gap to patient care, future experimental- and interventional research is needed to understand the neural correlates of reduced low-level priors in psychosis, with inferior frontal cortex as a candidate region for aberrations of conscious experience.

Zusammenfassung

Einleitung. Psychose ist ein Überbegriff für psychische Störungen, die durch Wahnvorstellungen und Halluzinationen charakterisiert sind. Interdisziplinäre Forschung aus dem Bereich der *Computational Psychiatry* könnte helfen, das mechanistische Verständnis dieses heterogenen Störungsbildes zu verbessern. Die *Bayesian Brain* Theorie besagt, dass Wahrnehmung aus der optimalen Kombination von Vorannahmen (*Priors*) und aktuellen sensorischen Informationen (*Likelihoods*) aktiv konstruiert wird. In diesem Rahmen wird angenommen, dass Psychosen aus einem Ungleichgewicht zwischen Vorannahmen und sensorischen Informationen entlang der kortikalen Hierarchie entstehen. Diese Dissertation befasst sich mit der empirischen Überprüfung der Vorhersagen der *Bayesianischen* Perspektive auf Psychosen.

Methoden. *Studie I* bestand aus zwei Psychophysik-Experimenten, die zur Untersuchung von verschiedenen Arten von *Priors* in der auditorischen- und visuellen Wahrnehmung optimiert waren. Wir untersuchten dies im Kontext individueller Psychoseneigung in der Allgemeinbevölkerung. In *Studie II* erhoben wir die Gewichtung von *Prior* vs. *Likelihoods* in einem bistabilen Wahrnehmungsparadigma. Patient:innen mit paranoider Schizophrenie und gesunde Kontrollproband:innen betrachteten bistabile Stimuli mit variierenden Stufen an sensorischer, desambiguierender Information.

Ergebnisse. *Studie I* zeigte reduzierte niedrig-hierarchische *Priors* mit zunehmender Psychoseneigung in der Allgemeinbevölkerung. Damit übereinstimmend zeigte *Studie II* eine erhöhte Gewichtung von sensorischen Daten und eine Untergewichtung von *Priors* in einer Stichprobe aus Patienten und Patientinnen mit diagnostizierter paranoider Schizophrenie.

Fazit. Zusammenfassend unterstützen die Ergebnisse beider Studien die Grundannahmen der *Bayesian Brain* Theorie der Psychose: Eine relativ zu den sensorischen Informationen reduzierte Gewichtung sensorischer Vorannahmen scheint ein Kernmerkmal der Psychose zu sein, dass in verschiedenen Wahrnehmungsaufgaben, Stimulusmodalitäten, experimentellen Kontexten und Studienpopulationen repliziert werden kann. Die Brücke zur Behandlung von Psychoseerkrankten könnte durch ein verbessertes Verständnis der neuronalen Grundlage von abweichender, bewusster Wahrnehmung legen. Der inferiore Frontallappen könnte als Grundlage bewusster Wahrnehmung ein geeigneter Ausgangspunkt für zukünftige Untersuchungen darstellen.

1 Introduction

In this dissertation, I begin by describing the symptomatology and epidemiology of psychosis and schizophrenia, followed by a summary of modern computational accounts thereof. Specifically, predictive processing and the Bayesian brain theory are introduced and discussed. I will then derive my research questions and a study rationale, followed by the summary and discussion of two empirical studies that were conducted as part of this dissertation.

1.1 Psychosis and schizophrenia spectrum disorders

"*Maybe each human being lives in a unique world, a private world different from those inhabited and experienced by all other humans… If reality differs from person to person, can we speak of a singular reality, or shouldn't we really be talking about plural realities? And if there are plural realities, are some more true (more real) than others?*
What about the world of a schizophrenic? Maybe it's as real as our world. Maybe we cannot say that we are in touch with reality and he is not, but should instead say, His reality is so different from ours that he can't explain his to us, and we can't explain ours to him.[...]"

Philip K. Dick, Science-fiction writer

Psychosis is a complex, disruptive and very heterogeneous mental condition that can detach the affected individual from external reality (Arciniegas, 2015). It is a defining feature of primary psychotic disorders such as Schizophrenia Spectrum Disorders (SSD, or schizophrenia). The World Health Organization defines schizophrenia as a condition marked by "significant impairments in reality testing" (World Health Organization, 2019), with the presence of psychotic symptoms such as hallucinations and/ or persistent delusions. The lifetime risk of developing a form of schizophrenia is estimated around 0.7%, with approximately 15 in 100,000 individuals diagnosed annually (annual incidence, Tandon et al., 2008) and 4.5 in 1,000 people affected by it currently (point prevalence, Tandon et al., 2008).

Delusions are false beliefs that persist despite contradicting information and reside outside of normative cultural ideas (VandenBos, 2007; World Health Organization, 2019). Delusions represent the most common psychotic symptom in schizophrenia, with 80-90% of patients reporting delusional ideation in acute stages of the disorder (Ziegler & Lincoln, 2012). The themes and contents of delusional ideation vary, but ideas surrounding the

themes of persecution, grandiosity or religion are most characteristic (Berking & Rief, 2011). Delusions are typically associated with the misinterpretation of sensory experiences. For example, patients may see their initials on a license plate and infer that the car's owner is watching them (Ziegler & Lincoln, 2012).

Hallucinations are sensory percepts that do not correspond to physical reality. Hallucinations are reported by approximately 60% of patients with acute psychosis (VandenBos, 2007; Ziegler & Lincoln, 2012). While hallucinations can occur within any sensory modality, auditory hallucinations are among the most common. Frequently, patients report hearing voices that comment on their own experiences. These voices can also be hostile, threatening, or demanding in nature. Hallucinatory voices are usually perceived as distressing and affect the patient's quality of life (Ziegler & Lincoln, 2012).

The symptoms of schizophrenia are highly heterogeneous. They are usually classified as either "positive" or "negative" symptoms (Berking & Rief, 2011; Ziegler & Lincoln, 2012). Delusions and hallucinations are positive symptoms of schizophrenia. Other positive symptoms include disorganized thinking and behavior, neologisms, derailment, and ego-disturbances (Arciniegas, 2015; Gaebel et al., 2013). Negative symptoms, such as flattened affect or apathy (lack of emotion or concern), anhedonia (lack of motivation or the ability to feel pleasure), alogia (reduced or lacking speech), avolition (lack of initiative) as well as reduced psychomotor behavior including catatonia (bizarre movements and/ or immobility) are frequent co-occurring symptoms (World Health Organization, 2019).

The genesis of schizophrenia is complex and multi-factorial, with both *genetic* and *non-genetic* risk factors for disease onset (McCutcheon et al., 2020; McGrath, 2007). While a genetic basis of schizophrenia has first been suggested a century ago (Kallmann, 1938), a complete understanding of all genetic loci and pathways involved in the development of schizophrenia is still lacking today. Genome Wide Linkage Studies (GWLS) have resulted in suggestive evidence, as expected in this complex psychiatric phenotype (Ng et al., 2009; Trubetskoy et al., 2022).

Non-genetic risk factors include maternal viral infections (Patterson, 2002) or malnutrition (Susser et al., 2008), maternal adverse life events or complications during delivery (Byrne et al., 2007; Khashan et al., 2008; Tandon et al., 2008), winter births (G. Davies et al., 2003), and paternal age above 35 years (Tandon et al., 2008). Among multitude of additional factors, male gender, adolescent cannabis use, urbanicity and migration emerged as the most robust factors from meta-analyses (McGrath, 2007; McLoughlin et al., 2014).

With not one particular risk factor necessary and sufficient for the development of schizophrenia, most studies acknowledge the necessity for further research to better understand the mechanisms underlying the emergence of schizophrenia (Gage et al., 2013; McGrath, 2007).

Different pathophysiological models have focused on disruptions in neurotransmitter systems in schizophrenia. Most prominently, the *dopamine hypothesis* (Dao-Castellana et al., 1997; Laruelle, 2013; Laruelle et al., 1996; Lindström et al., 1999; Meltzer & Stahl, 1976; Toda & Abi-Dargham, 2007; Yang & Tsai, 2017) has offered important pathophysiological insights. Originally, hyperdopaminergic transmission was suggested as the basis for schizophrenia (Reith et al., 1994; van Rossum, 1966). In a refined version of the theory, the *dopamine imbalance model* (Guillin et al., 2007; Toda & Abi-Dargham, 2007) was developed, suggesting hyperdopaminergic transmission in subcortical regions underlies positive symptoms, whereas the hypostimulation of neocortical D_1 receptors leads to negative symptoms. Dopamine antagonists are among the most effective treatments for psychotic symptoms and psychotic disorders available today, providing ongoing support for an important etiological role (Maia & Frank, 2017). Other factors such as glutamatergic and GABAergic transmission have emerged as potentially relevant mechanisms in schizophrenia more recently (Hu et al., 2015; Laruelle et al., 2003). Building on this, the more general suggestion of a disturbed balance of excitatory and inhibitory modulations (*E/I imbalance hypothesis*) in psychosis has been put forward (Denève & Jardri, 2016; Jardri & Denève, 2013). An important concept that originally developed from the dopamine hypothesis of schizophrenia is that of *aberrant salience* (Kapur, 2003; Katthagen et al., 2018; Pankow et al., 2016), suggesting that psychosis is marked by a bias of selectivity in information-processing. Irrelevant stimuli are assigned a larger-than-typical significance, which can lead to psychotic symptoms (Heinz & Schlagenhauf, 2010).

Vulnerability-stress(-inflammation) models are influential in schizophrenia research to this day (Davis et al., 2016; Müller, 2018). They posit that a combination of environmental factors operates towards crossing a hypothetical threshold for disease onset, which may be lowered in genetically predisposed individuals (Davis et al., 2016). However, there now is consensus among most researchers and clinicians that psychotic symptoms are not dichotomously present or absent in clinical and general populations, respectively. This idea contradicts the assumption of a more-or-less clear threshold of vulnerability-stress models. According to the *continuum hypothesis* (Strauss, 1969; Ziegler & Lincoln, 2012),

psychotic experiences and symptoms are normally distributed in the population. Quotidian experiences such as minor auditory hallucinations (e.g., hearing one's phone ring when it did not) reside on the mild end of the continuum. Meanwhile, paranoid schizophrenia (ICD-10: F20.0) resides on the severe end of the continuum.

A complete explanatory framework of schizophrenia needs the flexibility to incorporate a multitude of factors and pathophysiological processes (Maia & Frank, 2017; Sterzer et al., 2018). Predictive processing is a unifying explanatory framework for psychosis, linking neurobiological findings with insights from cognitive and computational neuroscience (Heinz et al., 2019; Sterzer et al., 2018). In the following, I will introduce predictive processing and its application to psychosis.

1.2. The Bayesian Brain Hypothesis and Predictive Processing

To successfully interact with the world, we need to form precise, unequivocal, and accurate representations of our surroundings. How is this accomplished in the face of the vast amounts of noisy, ambiguous, and uncertain sensory information that arrives at our sensory epithelia each second? Over the past decades, prediction has emerged as a core strategy of the brain to achieve this goal (Clark, 2013; Hohwy, 2013; Rao & Ballard, 1999). Within a normative process, the brain actively generates beliefs about the external causes of sensory information (Hohwy, 2013). For this, the brain appears to combine different sources of stochastic information, following Bayes' rule:

$$\mathrm{P}(Model|Data) = \frac{P(Data|Model) \times P(Model)}{P(Data)} \quad \text{(eq. 1)}$$

The *prior* ($\mathrm{P}(Model)$) represents the a-priori probability of some hypothesis about the world being true, or in other words, the prior probability of a *generative model* of how sensory inputs were caused by the external world. It is formed over past experiences and constantly updated by incoming sensory data. The *likelihood* ($\mathrm{P}(Data|Model)$) marks the probability of an observation given a specific model. The *posterior* ($\mathrm{P}(Model|Data)$) probability is highest for the most likely hypothesis about the real-world cause of any information arriving at the senses, given prior and likelihood. Prior, likelihood and posterior are represented as probability distributions, described by their mean and variance. While the distribution's mean represents the currently estimated belief (or model/ prior) or sensory information, the variance quantifies the uncertainty associated with this belief (Adams et al., 2013; Friston, 2005b). When combining them according to Bayes' rule, all sources of probabilistic information are weighted by their precision, or inverse variance. In effect, more precise distributions contribute to the resulting posterior to a larger extent than imprecise ones. Perception is determined by the winning hypothesis of this implicit inferential process. Considering the strong reliance on prior beliefs, it has been argued that conscious perception is a "controlled hallucination" (A. Seth, 2021).

Predictive Processing, or *predictive coding* offers a biologically plausible algorithmic framework of how precisely the brain implements Bayesian inference (Clark, 2013; Hohwy, 2013; Rao & Ballard, 1999). Predictive processing is a very flexible and general

algorithm that has been applied to several problems in information processing (Haarsma, Kok, et al., 2020; Rao & Ballard, 1999). Two notions are central to predictive processing: the brain's *hierarchical organization* and the transduction of *prediction errors* between the levels of the cortical hierarchy (Ballard, 2015; Hohwy, 2013; Rao & Ballard, 1999; M. Spratling, 2017). The cortical hierarchy is marked by increasing levels of abstraction (Ballard, 2015), with lower hierarchical levels encoding basic sensory features, such as shade, contrast, lighting conditions etc. Higher hierarchical levels entertaining more cognitive beliefs such as e.g., learned causal relationships between contexts and events. All levels work in unison to maximize the probability of the brain's generative model given incoming sensory information (Ballard, 2015; M. W. Spratling, 2017). Information progresses throughout the hierarchy in feedforward- and feedback waves. Higher hierarchical levels are dependent on information being feedforward to higher hierarchical levels. In contrast, signals from higher-hierarchical levels are sent down to adjacent lower-hierarchical levels as predictions. *Prediction errors* result when a predictive signal and sensory information from adjacent lower hierarchical levels mismatch. This error is fed back up the hierarchy and leveraged to update and refine higher-level generative models.

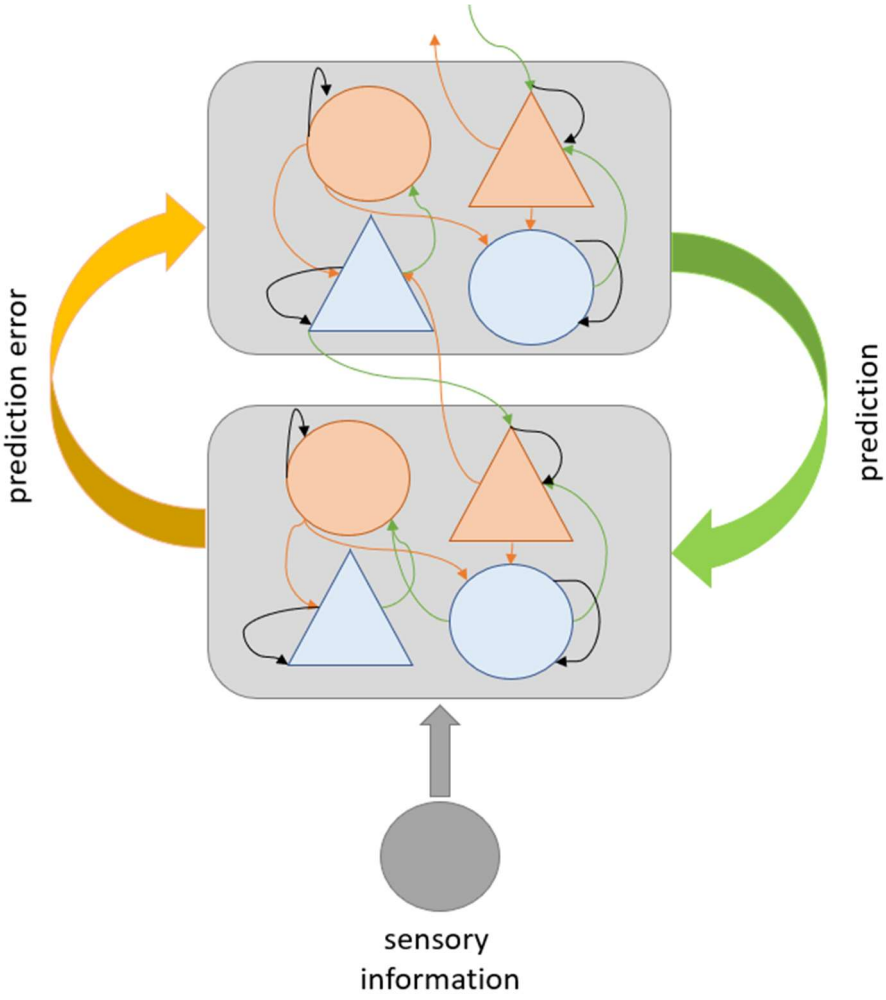


Figure 1: Schematic illustration of hierarchical predictive processing

Predictions (feedforward signals) and prediction errors (feedback signals) are transmitted among two hierarchical levels (Own representation synthesized from Seth et al., 2012; Sterzer et al., 2018).

Its laminar organization and the presence of sophisticated feedforward- and feedback connections between layers equip the neocortex to perform integrations of prior beliefs and sensory information as suggested by predictive processing (Haarsma, Kok, et al., 2020).

In conclusion, Bayesian accounts of perception suggest that the brain leverages predictions, learned over time, to infer the world around them based on uncertain sensory input. Predictive processing offers a biologically feasible and computationally tractable framework of how precisely Bayesian inference could be implemented in the brain.

1.3. Predictive Processing Accounts of Psychosis

A disrupted relative weighting of prior predictions, sensory information and/ or prediction errors have been suggested as core mechanistic factors in psychosis (Adams et al., 2013; Fletcher & Frith, 2009; Sterzer et al., 2018).

In its first iterations, predictive processing accounts of psychosis were centred around the notion of overly precise, or strong, priors, potentially resulting from disruptions in cholinergic transmission (Friston, 2005a; Haarsma, Kok, et al., 2020; Stephan et al., 2006). A prior is considered "strong" when it is more precise than sensory inputs and hence has to be considered in relation to the precision of the sensory evidence (Corlett et al., 2019). The strong-priors hypothesis suggests that given noisy sensory signals, hallucinations arise when an individual relies on overly strong top-down beliefs and suppresses prediction errors (Friston, 2005a). Indeed, empirical work has demonstrated that individuals with psychotic disorders show an enhanced influence of prior beliefs during perceptual inference (D. J. Davies et al., 2018; Haarsma, Knolle, et al., 2020; Powers et al., 2017; Schmack et al., 2013; Teufel et al., 2015).

Theoretical accounts of psychosis were further developed by the notion of hierarchical predictive processing (Fletcher & Frith, 2009). Here, both delusions and hallucinations are assumed to arise from *imprecise* priors that are insufficiently constrained by incoming sensory information. Sensory information is assigned higher precision than prior beliefs and causes large prediction-error weighted updates. Delusional ideation may result from inappropriate model updates (Fletcher & Frith, 2009; Haarsma, Kok, et al., 2020). Among others (Adams et al., 2012; Kirihara et al., 2020), empirical work in support of the imprecise-priors-account relies on perceptual illusions (Dima et al., 2009; Hohwy, 2013; King et al., 2017; Notredame et al., 2014). For example, patients with schizophrenia appear to be less susceptible to the hollow-mask illusion (Dima et al., 2009; Notredame et al., 2014). When viewing a rotating mask, this illusion causes observers to perceive a "pop-out effect" so that the mask appears convex, even when its concave "inside" should be seen. The effect has been related to the precise prior belief that faces are convex. However, this effect is reduced in individuals with psychosis (Dima et al., 2009).

The two accounts introduced above stand in direct contrast to one another, requiring refinement of the theory and its application to psychosis. Resolving this contradiction, Sterzer and colleagues (2018) suggested that psychosis results from differential modulations of prior-and-likelihood ratios across the cortical hierarchy. Specifically, prior beliefs at

lower hierarchical levels may be imprecise, as suggested, e.g., by patients' resistance to visual illusions. To compensate for the unconstrained prediction error at lower levels of the hierarchy, the brain may form overly precise beliefs at higher levels of the cortical hierarchy (Sterzer et al., 2018). A study by Davies and colleagues provides support for a differential bias in inference across hierarchical levels (Davies et al., 2018). When investigating participant's reliance on local vs. global priors in image perception, the authors found correlations between hallucination proneness and the reliance on both global and local priors. Meanwhile, individual proneness to delusional ideation correlated negatively with the reliance on local priors, supporting the notion of hierarchically different aberrations underlying hallucinations and delusions, respectively.

In conclusion, Bayesian accounts suggest that an aberrant relative weighting of prior beliefs and likelihood lies at the core of psychosis. In the hierarchical predictive processing framework, hallucinations and delusions are proposed to emerge from imprecise prior beliefs at lower hierarchical levels (e.g., in sensory areas) and compensatory increases in prior precision at higher hierarchical levels (Corlett et al., 2019; Sterzer et al., 2018). It is the aim of this thesis to empirically test the notion of aberrant prior-to-likelihood ratios in psychosis, as proposed by predictive processing theory.

1.3.1. Experimental operationalizations

Empirical tests of predictive processing accounts of psychosis require the operationalization and/ or experimental manipulation of prior beliefs and likelihoods. I will focus on two relevant avenues towards studying the effects of prior beliefs and sensory information in this thesis: 1) *Choice history biases* and 2) *bistable stimuli*.

Choice history biases. Our sensory environment is marked by auto-correlations: over time, most of our visual surroundings remain stable (Cicchini et al., 2018; van Bergen & Jehee, 2019). When predicting future sensory input, it is hence an adaptive strategy to rely on percepts from the recent past. During artificial viewing conditions, for example in a laboratory, this perceptual strategy results in choice history biases, or serial dependence (Fischer & Whitney, 2014; Fründ et al., 2014). Serial dependence occurs when an observer's current perception is biased towards events in the past (Fründ et al., 2014). Serial dependence is reported for a wide range of stimuli across perceptual domains, for example, Gabor patches (Fischer & Whitney, 2014), random dot kinematograms (Braun et al., 2018; Urai et al., 2017), pitch and loudness (Arzounian et al., 2017), numerosity (Fornaciai & Park, 2018, 2020), abstract shapes (Ghirardo et al., 2020; Suárez-Pinilla et

al., 2018), statistical mean and variability (Manassi et al., 2017), face identity and attractiveness (Kok et al., 2017; Taubert & Alais, 2016; van der Burg et al., 2019; Xia et al., 2016), tactile stimuli (Hachen et al., 2021) and more. Cicchini, Mikellidou and Burr (2017) proposed that choice history biases are caused by the summation of short-term, repulsive adaptation effects on the one hand, and attractive biases caused by inert decisional templates on the other hand. Its generality and assumed functionality as stabilizing perception in light of noisy information make choice history biases reminiscent of Bayesian priors (Fischer & Whitney, 2014; Kalm & Norris, 2018).

Bistable perception. Ambiguous stimuli (see Figure 2) can be perceived in two (or multiple) mutually exclusive ways. When viewing an ambiguous stimulus, observers report spontaneous switches between perceptual interpretations. Bistable perception occurs when perception spontaneously alternates between two mutually exclusive interpretations (Brascamp et al., 2018; Weilnhammer et al., 2020). Remarkably, the experience evoked by ambiguous stimuli is unambiguous and stable, which further strengthens the idea that perception is an active process (Hohwy, 2013; Weilnhammer et al., 2017). An example for ambiguous stimuli are *structure-from-motion* (SFM) animations (for example, rotating Lissajous figures; Weilnhammer et al., 2020). SFM animations leverage motion cues to induce the illusion of a three-dimensional, rotating object (i.e., the kinetic depth effect) and are composed of moving dots which are perceived as a three-dimensional figure. When the dots are presented orthographically, their depth order is ambiguous, allowing for two mutually exclusive perceptual states (e.g., clockwise vs. counter-clockwise rotation).

Hohwy and colleagues (2008) offer a theoretical framework for bistable perception under predictive processing, summarized in the following. In bistability, the brain is faced with an ambiguous likelihood term that offers evidence for two different perceptual solutions (Weilnhammer et al., 2017). According to Bayesian accounts of perception, the posterior probability of one interpretation over the other determines the present perceptual decision. Past interpretations also function as a prior towards future perceptual decisions, thus stabilizing perception. However, the likelihood term still contains evidence for the percept currently suppressed, which contributes to prediction error (Hohwy et al., 2008). Over time, the prediction error caused by the unexplained sensory evidence inflates and escalates into a perceptual shift towards the previously suppressed percept. These as-

sumptions were implemented within a Bayesian model of bistable perception by Weilnhammer et al. (2017). They showed that a Bayesian model of bistable perception captures the behavior of human observers and key temporal characteristics of perception in bistable viewing conditions (Weilnhammer et al., 2017).

In line with this notion, Doscher and colleagues (1986) found that when adding additional visual information to an SFM-stimulus, perception is more likely to be consistent with the direction indicated by the additional, disambiguating sensory information. Bistable perception further seems to be influenced by physical principles (Gilroy & Blake, 2004), behavioral context (Maruya et al., 2007; Sundareswara & Schrater, 2007), prior exposure to the bistable stimulus (Leopold et al., 2002; Orbach et al., 1963; Pearson & Brascamp, 2008), and learned implicit or explicit expectations (Schmack et al., 2013, 2016; Sterzer et al., 2008).

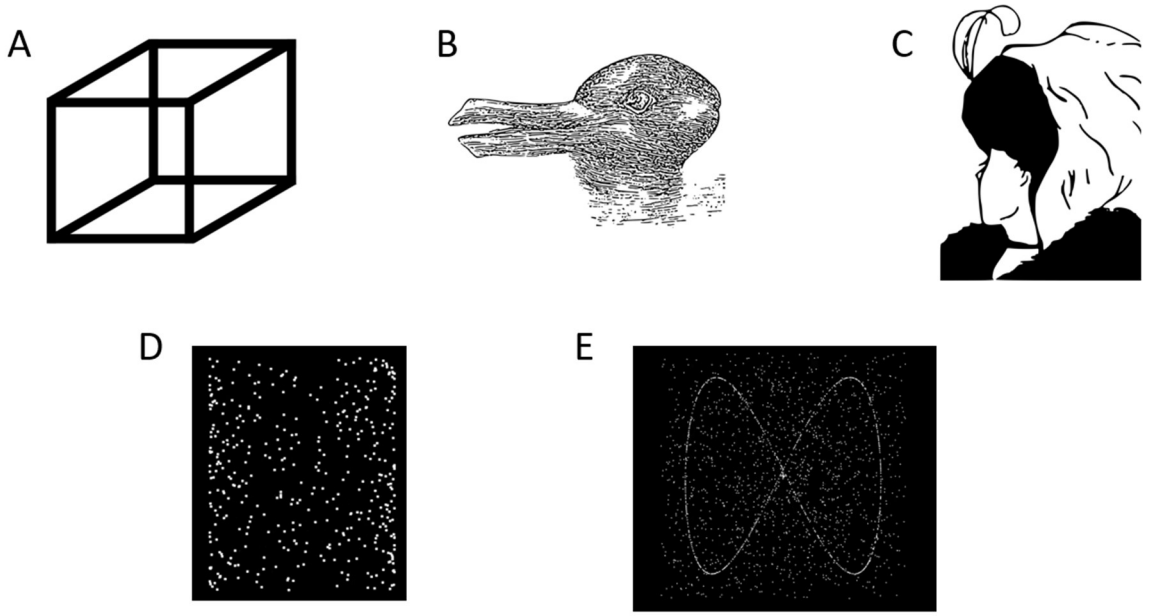


Figure 2. Examples for bistable stimuli.

A. The Necker cube. Both the lower left and the upper right square can be perceived as its front side. ***B.*** The duck/ rabbit illusion. The drawing shows either a left-facing duck's head or a right-facing rabbit's head. ***C.*** This drawing shows both a young woman facing away from the observer or an older woman in profile. ***D.*** A rotating sphere that can be perceived as rotating either left- or rightward (from public YouTube channel @mariusthart) ***E.*** Rotating Lissajous figure that can be seen as rotating both clockwise and counter-clockwise (Weilnhammer et al., 2020). Own synthesis, figures *A-C* taken from https://freesvg.org.

In this thesis, I report the methodology and results of two behavioral studies. In *Study I*, a series of behavioral experiments investigated choice history biases as proxies for low-level prior beliefs (Eckert et al., 2022). Their association with psychosis proneness in the general population was studied (*Study I*). In a second behavioral study, we investigated susceptibility to sensory information in patients with schizophrenia and healthy controls (*Study II*). The following objectives and empirical hypotheses were derived from predictive processing accounts of psychosis:

1.4. Objectives

1. ***Study I.*** To assess and compare the reliance on differential types of prior information in the visual- and auditory modality along the psychosis continuum in the general population. *Hypotheses:*
    a. Psychosis proneness is associated with reduced weighting of lower-level prior information, as operationalized by choice history biases.
    b. To compensate for the lack of constraint at lower hierarchical levels, psychosis prone individuals may show higher reliance on explicit, higher-level prior information.
    c. Increasing the adaptivity, i.e., behavioural relevance of choice history biases, will lead to smaller adaptation in more psychosis prone individuals.
2. ***Study II.*** To compare the balancing between prior beliefs and sensory information in patients with paranoid schizophrenia vs. neurotypical controls. *Hypotheses*:
    a. Patients diagnosed with an SSD are more sensitive to subtle changes in sensory evidence. This increased sensitivity would suggest a more precise likelihood term in patients compared to controls.
    b. Sensitivity to sensory information increases with symptom severity in patients with SSD.

2 Methods

This section contains descriptions of the psychophysical operationalizations and paradigms used in this dissertation (for an overview, see Figure 3). The original publications and their supplementary materials provide more detailed descriptions of each study's materials and methods (Weilnhammer et al., 2020, Eckert et al., 2022).

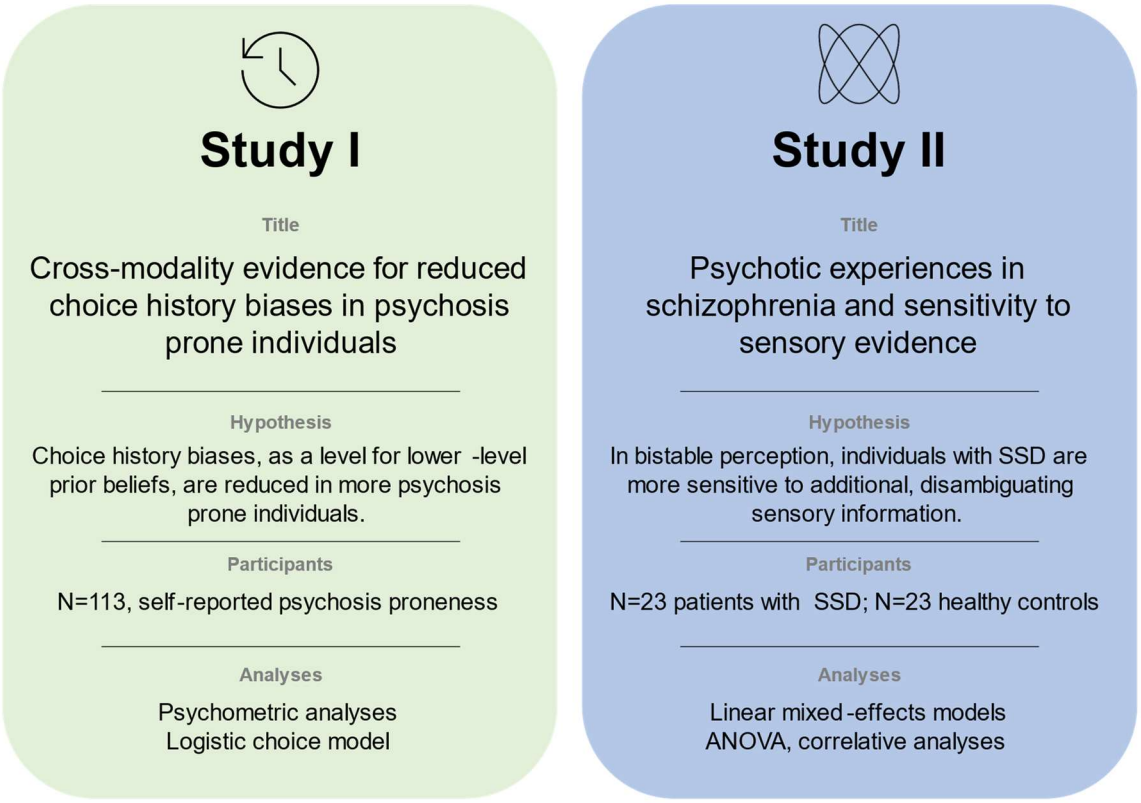


Figure 3. Methods overview

Own visual representation for the purpose of thesis.

2.1. Summary: study design

Study I. A total of N=156 healthy participants performed perceptual decision-making tasks in the laboratory (*visual task*) and online (*auditory task,* see Figure 4). Their behavioural responses to uncertain sensory information were recorded. All participants responded to two well-validated self-report measures of psychosis proneness and were scored along the psychosis continuum.

Study II. In this laboratory-based behavioural study, N=23 patients and N=23 healthy controls viewed bistable rotating spheres with graded levels of disambiguating sensory evidence and reported their subjective percept thereof. All participants subsequently rated themselves with respect to aspects of quotidian psychotic experiences using two well-validated measures.

2.2. Materials and Methods

Study I.

General procedure. The first study consisted of two behavioural experiments on perceptual decision-making. Both experiments followed a similar rationale and structure but differed in the stimulus modality to probe predictions derived from predictive processing accounts hold across modalities. Implicit choice history biases were leveraged to approximate lower-level prior beliefs. In contrast, higher-level prior beliefs were manipulated using explicit, cross-modal cues. Both experiments were pre-registered (asPredicted.org, *Experiment 1:* #50562, *Experiment 2:* #71785) and approved by the ethics commission of the Charité – Universitätsmedizin Berlin (*Experiment 1:* #EA1/134/20; *Experiment 2:* #EA1/198/19). All participants gave written informed consent prior to study participation. After completing the behavioural tasks, two well-validated questionnaires on self-reported delusional and hallucinatory tendencies were administered (Peters et al. Delusions Inventory; PDI, Peters et al., 1999, and the Cardiff Anomalous Perceptions Scale, CAPS, Bell et al., 2006). Given that both measures are usually highly correlated (Davies et al., 2018), a compound psychosis proneness score was computed, consisting of the sum of the two z-transformed sum scores. For both experiments, exclusion criteria were a history of neurological or psychiatric disorders and uncorrected visual or hearing problems. Further, we excluded participants based on performance to make sure our data allows for meaningful analyses of choice history effects (between 60 and 90% correct responses).

Experiment 1*.* A gamified, 2-alternative-forced-choice (2AFC) auditory decision-making task was implemented as an online experiment. A total number of forty click sounds was presented, separated on the participant's left and right ear, respectively. The participant's task was to determine on which ear they perceived a larger number of clicks (henceforth, the "dominant ear"). The trial's difficulty was contingent on the absolute difference in click

sounds between the left and right ear. There were six levels of difficulty which were counterbalanced across the left and right auditory channel. 2AFC responses were not timed but limited to 2000 seconds to ensure swift task completion. The position of the “left”- and “right” response options was randomized to avoid motor artifacts. Participants completed eight blocks of 48 trials (384 total, ~50 minutes). The experiment was designed using the online behavioural task builder *Gorilla* (Anwyl-Irvine et al., 2020). All participants complected a headphone check (Woods et al., 2017) and eight practise trials. Further, there were 26 attention checks placed randomly in the eight blocks. Participants were required to pass at least 20 out of 26 attention checks. The experiment was gamified in order to increase task engagement. To induce higher-level beliefs, participants viewed visual cues that were part of the cover story. Participants were instructed that the visual cue “usually” predicts the dominant ear. The cue predicted the dominant ear correctly in 75% of trials. Lower-level prior beliefs were operationalized by means of choice history biases, i.e., the effect of the preceding trial’s choice on choices in the present. Choice history biases are shown to increase with the environmental stability, or auto-correlation (Braun et al., 2018). For this reason, we introduced a block-wise manipulation of the stimulus sequence to be either repetitive or randomized. In repetitive blocks, the previous trial’s dominant ear was repeated with an 80% probability. The frequency of left- vs. right ear dominance was counterbalanced across trials. Repetitive (R-type) and neutral (N-type) blocks were pseudo-randomized, and participants were randomized to the block sequences RNNRNRRN or NRRNRNNR.

Participants. Sample size estimations yielded that when assuming a small effect size (R^2 = 0.10) in a regression model with four parameters, a power of β=0.8 can be achieved with N=110. We recruited 150 participants via the online recruitment platform Prolifc (Palan & Schitter, 2018), where we expected to exclude a minimum of 30 participants based on either performance-related exclusion criteria or technical difficulties. Of the 150 participants who accessed the experiment, six participants did not complete the experiment before the time limit of 1,5h was reached. Twenty-nine participants were excluded based on their task performance. Fifteen participants performed at ceiling levels (more than 90% correct responses), and fourteen participants showed poor performance (less than 60% correct responses). Two datasets were lost due to technical problems. This leaves a total sample size of 113 participants who were included in the final analyses.

Experiment 2. A laboratory-based behavioural task was developed to investigate differential impacts of high- vs. lower-level prior beliefs on visual perception. Participants were instructed to report the motion direction of random dot kinematograms (RDK) on the central, horizontal axis. An auditory cue was presented to induce high-level beliefs about the upcoming RDK. The cue was a female, computerized voice saying the words “Left” or “Right”, indicating the motion direction of next trial’s RDK. In 75% of trials, the auditory cue accurately predicted the RDK’s global motion direction. RDKs were presented for 750 ms and consisted of 200 white, moving dots on a grey background (dot size: 3 pixels, dot speed 0.07 pixels/frame, dot lifetime: 15 frames). After RDK presentation, the response screen appeared for a maximum of 2000ms or until a response was recorded. It consisted of two arrows, arranged centrally above and below the fixation cross (switching position randomly), pointing either to the left or the right, and the prompt “Direction?”. Participants completed 8 blocks of 96 trials each (768 total). Analogous to *Experiment 1,* there were repetitive and neutral blocks. In repetitive blocks, the previous trial’s global motion direction was repeated in 80% of current trials, whereas in random blocks, the motion direction was determined randomly. Participants were randomized to block sequences RNNRNRRN and NRRNRNNR, respectively.

Participants. Based on previous studies and an a-priori sample size estimation, we recruited 50 participants for *Experiment 2*. A sample size of 50 would discover a small effect of $R^2 = 0.2$ ($\alpha=0.05$) at a power of $\beta=0.8$. Recruitment was done via a public online marketplace, institutional mailing lists and local university-based recruitment systems. Two participants were excluded because their performance was below 60% correct responses. Further, five participants gave incomplete responses to the survey, leaving a final sample size of 43.

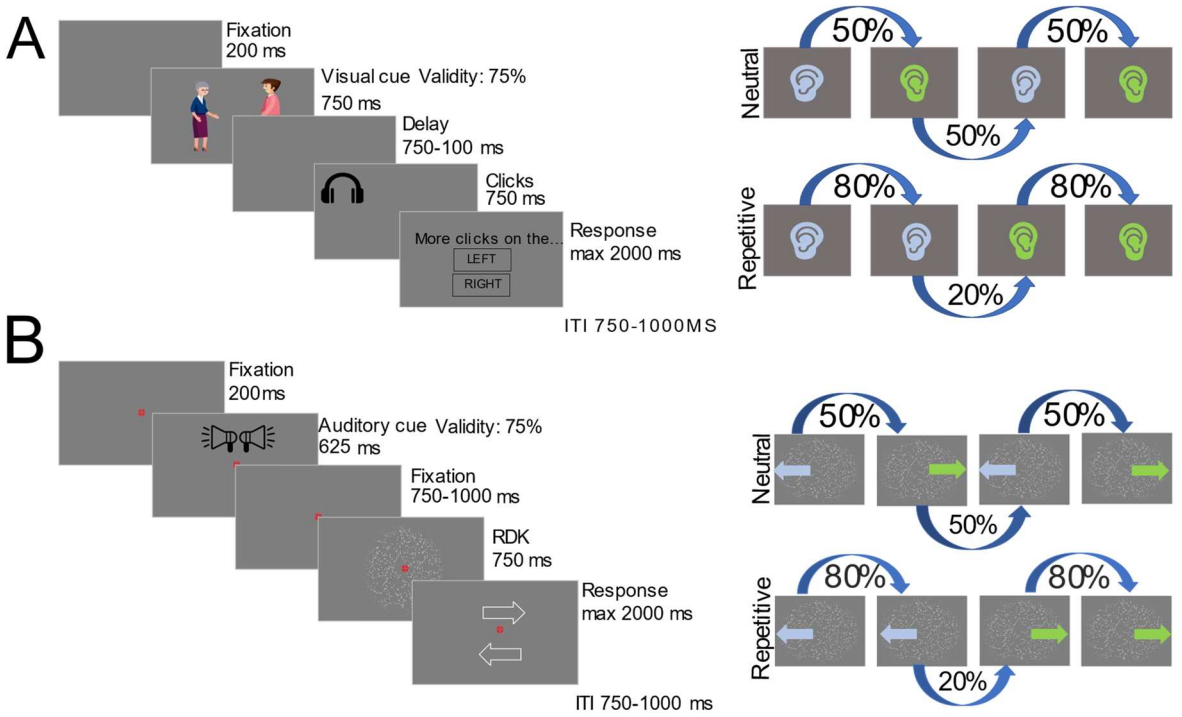


Figure 4. Schematic overview of trial events for Study I experiments.

Experiment 1 (**A**) was a gamified auditory perceptual decision-making task, where participants reported the dominant ear of a train of click sounds after viewing an explicit, visual cue. *Experiment 2* (**B**) was a visual perceptual decision-making task, where participants judged the global motion direction of random dot kinematograms after hearing an explicit auditory cue.

Statistical analyses. Data from both experiments was analysed using a mixed logistic choice model implemented in R (v.1.1-27.1). Optimization was done using maximum likelihood and the nlimb method (optimx package for R, v.2021-10.12). Explained variance R^2 was calculated with the help of the MuMIn package (v.1.43.17), and the car library (v.3.0-12) was used for computing variance inflation factors (VIF). All variables were z-transformed.

The response r on trial *t* was modelled as a combination of the presented stimulus s_t (0=right, 1=left), the previous trial's stimulus s_{t-1}, the current trial's discriminability d_t (Δclicks between channels in *Experiment 1;* coherence level in *Experiment 2,* 1-6), the previous trial's choice r_{t-1} in interaction with individual psychosis proneness score *PPS*, as well as the current trial's cue c_t (0=right, 1=left) in interaction with block type b_t and individual psychosis proneness score:

$$r_t = s_t \cdot d_t + s_{t-1} \cdot d_{t-1} + r_{t-1} \cdot PPS \cdot b_t + c_t \cdot PPS \cdot b_t + (1|subject) + (1|b:subject)$$

(eq. 1)

To further elucidate the relationship between choice history biases, block statistics and psychosis proneness, we fit psychometric functions of the shape

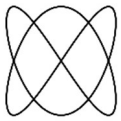
$$p(r = 1) = \frac{1}{1 + exp\left(\frac{\pi(x - \delta)}{\sqrt{3}\sigma}\right)}$$

(eq. 2)

to the data. Noise was assumed to be following a logistic distribution with variance $\sigma^2 = \frac{\sigma^2\pi^2}{3}$. Decision noise is captured by σ, δ is a systematic, individual bias and x is the stimulus intensity. Separate psychometric functions were fitted for trials that were preceded by “left” vs. “right” choices, and for different levels of psychosis proneness as determined by a median split.

Finally, we computed an individual score for repetition probability and correlated it with psychosis proneness.

Study II.



General procedure. Study II consisted of a laboratory-based, behavioural experiment, where participants viewed a bistable Lissajous figure under stereoscopic viewing conditions. A new paradigm of *graded ambiguity* was developed, where additional sensory information is presented alongside the bistable figure (Weilnhammer et al., 2020). The sensitivity to disambiguating sensory evidence approximates the likelihood term of the underlying inferential processes, whereas the phase duration (i.e., the time during which the perceptual state remains stable) acts as a proxy for the prior belief.
The study was pre-registered and authorized by the local ethics committee of the Charité – Universitätsmedizin Berlin. All participants were required to give written informed consent and have normal or corrected-to-normal vision.

Main experiment. Participants reported the rotation direction of a bistable Lissajous figure using the right, left (right- or leftwards rotation) and down (unclear) keys of a standard computer keyboard. They were instructed to place their head on a chinrest fixed at 59.50cm distance from a 98PDF-CRT-Monitor of 1042 x 768 pixels (refresh rate 60Hz). All stimuli were presented using a mirror stereoscope that allowed the presentation of separate stimulus videos to the left- and right eye, respectively. Participants completed three runs of viewing seven pairs of rotating Lissajous figures which were either fully ambiguous or partially disambiguated. Each run was divided into blocks of 40.08 seconds, followed by a 5 second fixation period. Lissajous figures consisted of 300 dots placed randomly and non-overlappingly on sinusoidal waveforms. Rotation speed of the figure was 6.80s per revolution. The figures were presented on a black background including white, randomly moving dots and a white fixation cross. *Ambiguous blocks* were characterized by two identical Lissajous figures presented to the left- and right eye. During *disambiguated blocks,* a proportion of stimulus dots was shifted in one direction between the channels. The more the two channels are shifted against each other, the higher the amount of available disambiguating evidence. There were seven levels of disambiguating stimulus evidence (D1-D7), determined by the percentage of disambiguated dots (1.25%, 3.75%, 8.75%, 16.25%, 26.25%, 50%, 100%).

After completing the experimental part, all participants completed two validated measures of delusional tendencies (the Peters et al. delusions inventory, PDI; Peters et al., 1999) and hallucinatory propensity (the Cardiff Anomalous Perceptions Scale, CAPS; Bell et al., 2006). Patients' clinical symptom severity was further rated on the Positive and Negative Syndrome Scale (PANSS, Kay et al., 1989).

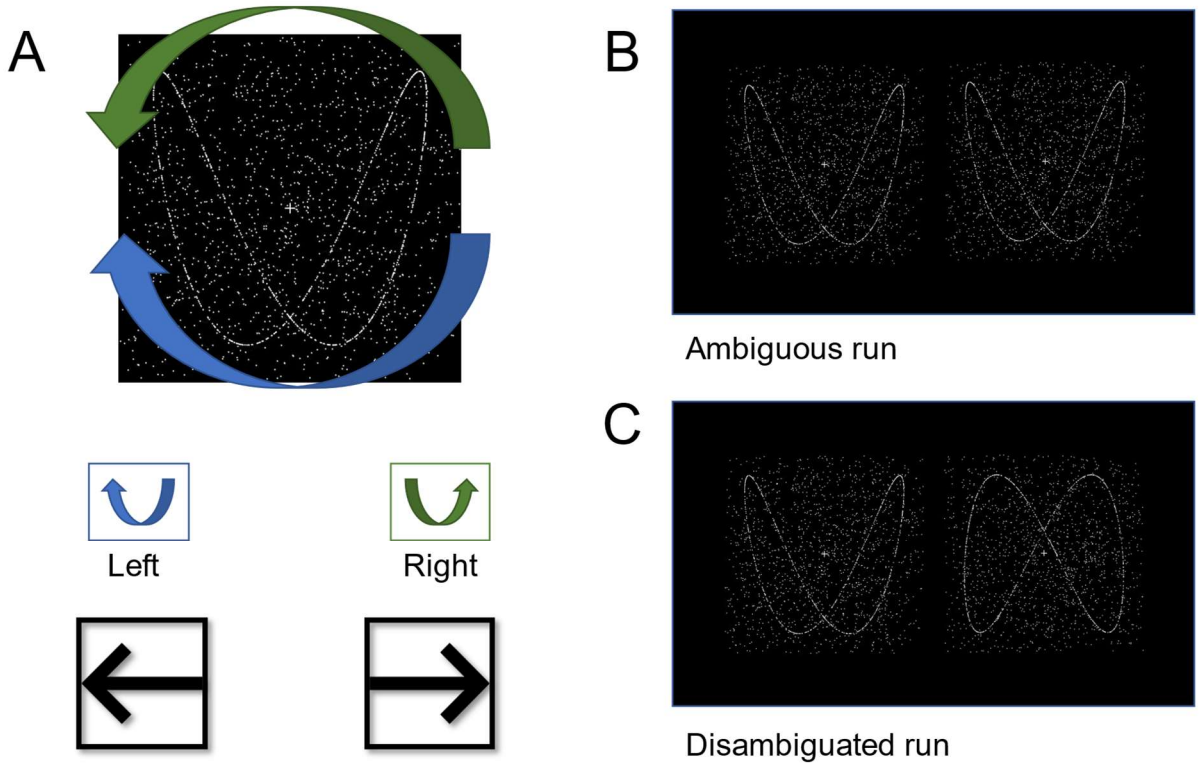


Figure 5. Schematic overview of Study II experiment.

Participants viewed Lissajous figures with varying degrees of disambiguating stimulus evidence and reported their current perception by holding down the left vs. right keys of a standard PC keyboard (**A**). In ambiguous runs, there are no or minimal differences in the proportion of dots shifted against each other (**B**). In disambiguated runs, a part of the Lissajous figure presented to one eye is shifted against the one presented to the other eye (**C**) *Own representation*

Participants. Patients were in- or outpatients at the local psychiatric clinic at Charité – Universitätsmedizin Berlin that were recruited via their attending physicians. Controls were matched for gender, age, and handedness. One control participant was excluded because they showed deficient stereovision. Three further controls showed scores in either CAPS or PDI that were 3 SD above the group's mean and were excluded. In total, 23 patients and 23 healthy controls were included in the experiment.

Statistical analyses. The main variable of interest was the time-point of transitions (switches) between the two perceptual states. Since transitions could only occur when the figure's two sides overlapped, reported timings were corrected to match the time of overlap. Further, the proportion of congruent perceptual states was computed for all levels of disambiguating sensory information (D1-D7). This proportion was considered an estimate for the prior's weighting in contrast to the likelihood. Perceptual stability was approximated using the average phase duration, i.e., the length of periods in which the reported perceptual state remained stable. All analyses were controlled for unclear perceptual states and individual biases during the ambiguous blocks.

A mixed ANOVA with within-subject factor "evidence level" (D1-D7) and between-subject factor "group" was performed. Further, a linear mixed effects model (R, nlme package) with fixed effects "group" and "evidence level (D1-D7)" and a random effect for each subject was performed. Finally, psychometric analyses included fitting linear and sigmoid functions to the proportion of congruent perceptual reports across evidence. From the best-fitting (R^2) exponential fit, growth rates were derived as approximations to individual sensory sensitivity. To estimate confidence intervals for group differences in growth rates, a bootstrapping procedure (R-dabestr) was used.

We further investigated whether participants' scores in self-report measures (PDI and CAPS) correlated with average phase duration and sensitivity to sensory evidence. In the patient sample, we further tested for correlations with the PANSS items P1 (delusional ideation) and P3 (hallucinatory experiences). Standard Spearman correlations were computed due to a lack of normality (Kolmogorov-Smirnov tests $P<0.0001$ for all variables). Partial correlations were computed, controlling age, stereoacuity, and duration of illness and chlorpromazine equivalents in patients. To ensure correlative specificity, we controlled the questionnaire scores for the alternative questionnaire.

3. Results

3.1. Study I: Reduced low-level prior-to-likelihood ratios in psychosis proneness

3.1.1. Sample characteristics and general task performance

Demographic characteristics for both experiments as well as average questionnaire scores are summarized in Table **2**. The final sample sizes after exclusions were N=113 in *Experiment 1*, and N=43 in *Experiment 2.*

In *Experiment 1,* task performance was at 80.1% (±7.1 SD, range 61.2%-89.8%) correct responses. Time-outs were at low levels (2.1%) and were excluded in the final analysis.

Experiment 2 task performance was at 71.9% (±5.1 SD, range 65.5%-79.3%) average accuracy. Less than 1% of trials timed out.

Mean PDI score in *Experiment 1* was 6.6 (±3.1 SD, range 0-17), mean CAPS score was 6.5 (±5.2, range 0-28). In *Experiment 2,* mean PDI score was 7.3 (±6.9 SD, range 0-35) and mean CAPS score was 5.0 (±5.2 SD, range 0-20). All values are within the expected ranges of a non-clinical sample.

Table 1. Sample characteristics Study I

	Age	Performance	PDI	CAPS
Experiment 1	24.79 ± 7.34	80.1% ± 7.1	6.6 ± 3.1 (range 0-17)	6.5 ± 5.2 (range 0-28)
Experiment 2	31.00 ± 10.6	71.9% ± 5.0	7.3 ± 6.9 (range 0-35)	5.0 ± 5.2 (range 0-20)

**From Eckert et al., 2022.*

3.1.2. Psychometric and correlative results

Psychometric functions were fit to the data of trials preceded by a “left” choice and those preceded by a “right” choice, respectively. Further, separate functions were fit for data of participants with high vs. low psychosis proneness.

Psychometric function fits revealed a horizontal shift between functions conditioned on previous choice, with a higher probability of a “left” choice in trials that were preceded by “left” choices. This relationship held across experiments and block types (see Figure 6). This increased probability was more pronounced in individuals who reported low psychosis proneness compared to those more prone to psychotic experiences (see Figure 6).

When computing the difference in point of subjective equality (ΔPSE) between “left” vs. “right” separately, we find slightly more negative ΔPSE in the lowest PPS quartile, and ΔPSE that are either zero (*Experiment 2*) or slightly positive (*Experiment 1*) in the highest PPS quartile (see Figure 7).

When looking at individual repetition probability in relation to psychosis proneness, we find a reduced probability of repeating a previous choice with increasing psychosis proneness. This relationship held across both experiments and block types (see **Figure 7**).

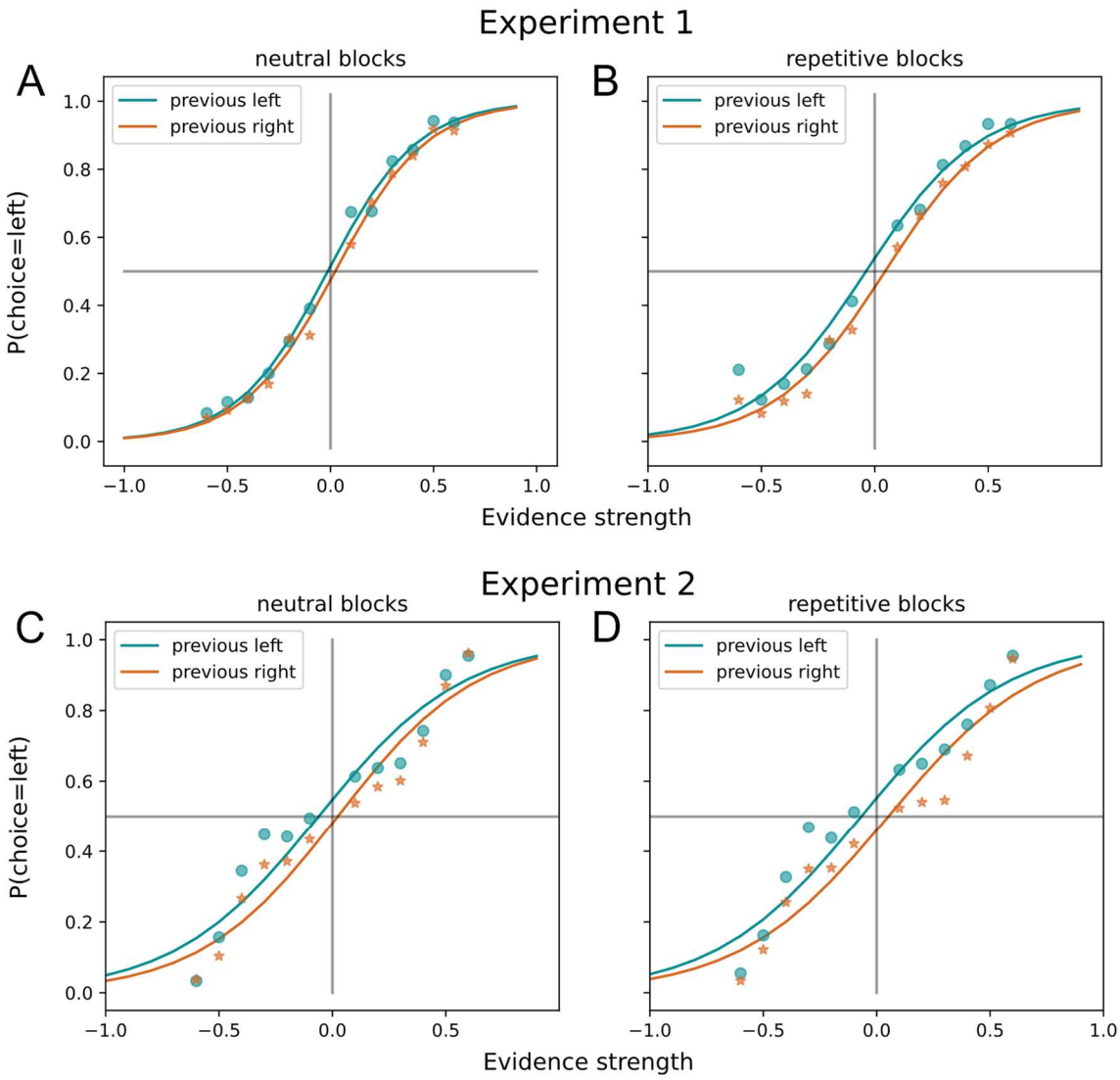


Figure 6. **Psychometric function fits per experiment and block type**

Modified from Eckert et al., 2022

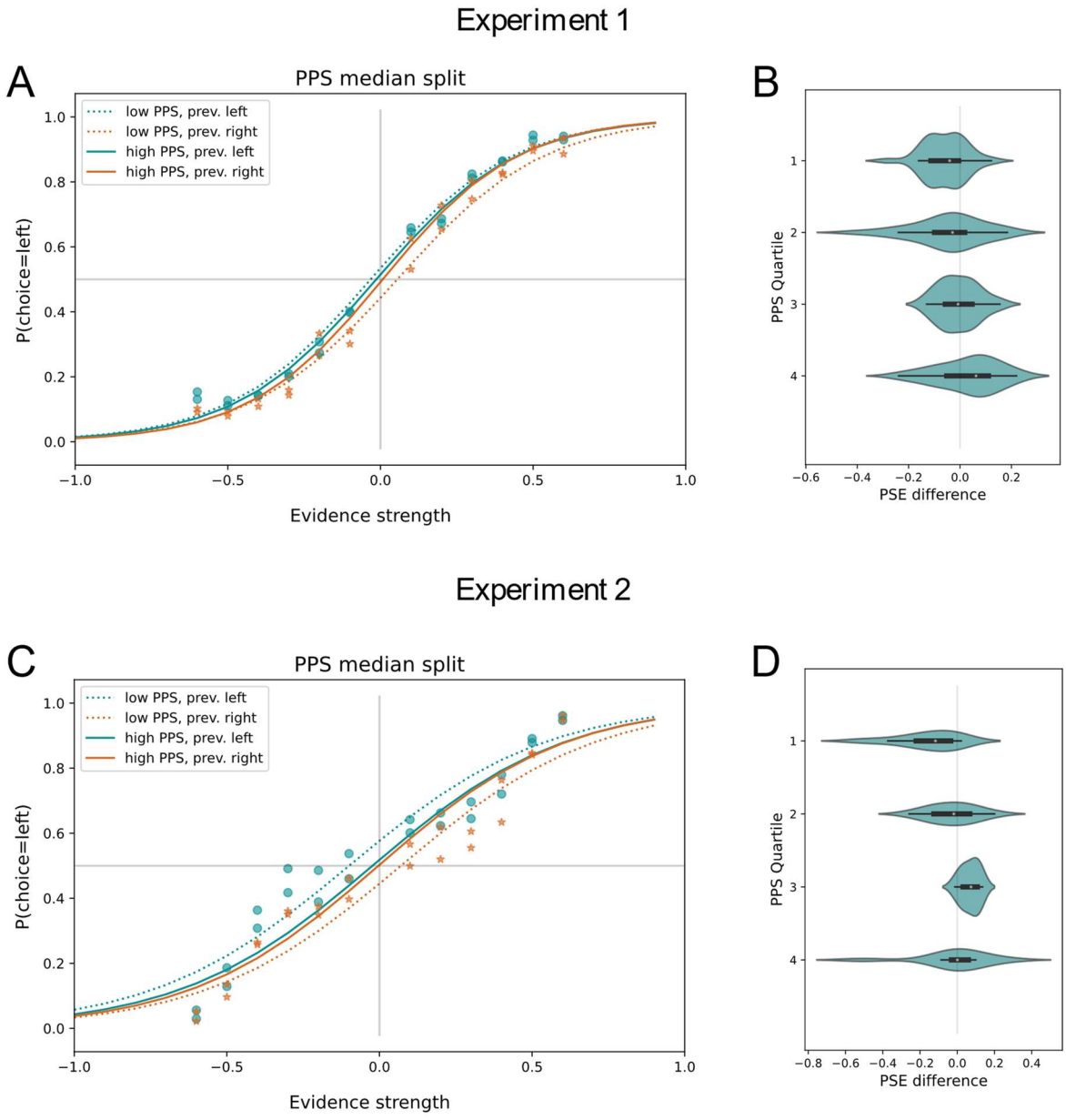


Figure 7. Psychometric functions on psychosis proneness score median split

Modified from Eckert et al., 2022

3.1.3. Results of logistic choice model

Separate trial-by-trial logistic choice models were fit to the datasets of the two experiments to estimate the influence of stimulus characteristics, cue and events in trial history and their respective interaction with PPS on current choice. All results are summarized in Table 2. Residuals were normally distributed in both *Experiment 1* (min=-6.67, max=6.12, 1Q=-0.50, 3Q=0.47; number of observations=42,601) and *Experiment 2* (min=-11.38, max=15.75, 1Q=-0.63, 3Q=0.61, number of observations=31,087). Marginal corrected R^2 values for both models were R^2=0.49 for *Experiment 1* and R^2=0.55 for *Experiment 2.* Since model predictors such as stimulus, cue and history events are likely correlated, we assessed the collinearity of model predictors. VIF scores for both datasets indicated no significant problems with collinearity [*Experiment 1:* VIF=1.33 (s_{t-1} predictor) and *Experiment 2:* VIF=1.67 (s_{t-1} predictor)].

Choice history biases. There was a significant main effect of previous choice across both experiments (*Experiment 1:* β=0.15 ± 0.001, p<0.001; *Experiment 2:* β=0.13 ± 0.02, p<0.001). Choice history effects also express themselves in horizontal shifts between psychometric functions conditioned on either preceding “left” or preceding “right” choices (Figure 6). There were meaningful effects of block structure across both experiments, with a significant previous choice x block type interaction (*Experiment 1:* β=-0.04 ± 0.01, p = <0.05; *Experiment 2:* β=-0.05 ± 0.01, p = <0.05). This indicates an adaptation of choice history biases to block statistics, with stronger choice history biases in repetitive blocks.

Psychosis proneness. A significant PPS x previous choice interaction was found across experiments, in line with our main hypothesis (*Experiment 1:* β=-0.06 ± 0.01, p<0.001; *Experiment 2:* β=-0.09 ± 0.001, p<0.001). Regression weights are negative across experiments, indicating decreasing choice history biases with increasing psychosis proneness. This relationship held across both neutral and repetitive blocks (see supplementary materials *S3* of the main paper). The adaptation of choice history biases to block statistics was significantly modulated by psychosis proneness in *Experiment 2* (β = 0.02 ± 0.01, p=0.09), but not in *Experiment 1* (β = 0.02 ± 0.01; p=0.63), which indicates that the negative choice history x PPS interaction was more pronounced in repetitive blocks in *Experiment 2*.

Cue effects. A significant main effect of cue on current perceptual choices was found across experiments (*Experiment 1:* β=0.22 ± 0.01, p<0.001; *Experiment 2:* β=0.54 ± 0.01, p<0.001). However, the cue x PPS interaction was inconsistent across experiments, with a negative weight in *Experiment 1* (β=-0.05 ± 0.01, p<0.001) and a positive weight in *Experiment 2* (β=0.11 ± 0.01, p<0.001). This indicates a reduced weighting of cue information with increasing psychosis proneness in *Experiment 1;* and an increased reliance on cue with increased psychosis proneness in *Experiment 2.* Considering PDI and CAPS separately showed inconsistent interactions with cue weights as well (supplementary analysis **5**). In short, regarding the modulation of cue reliance by psychosis proneness, results are inconsistent across experiments and measures.

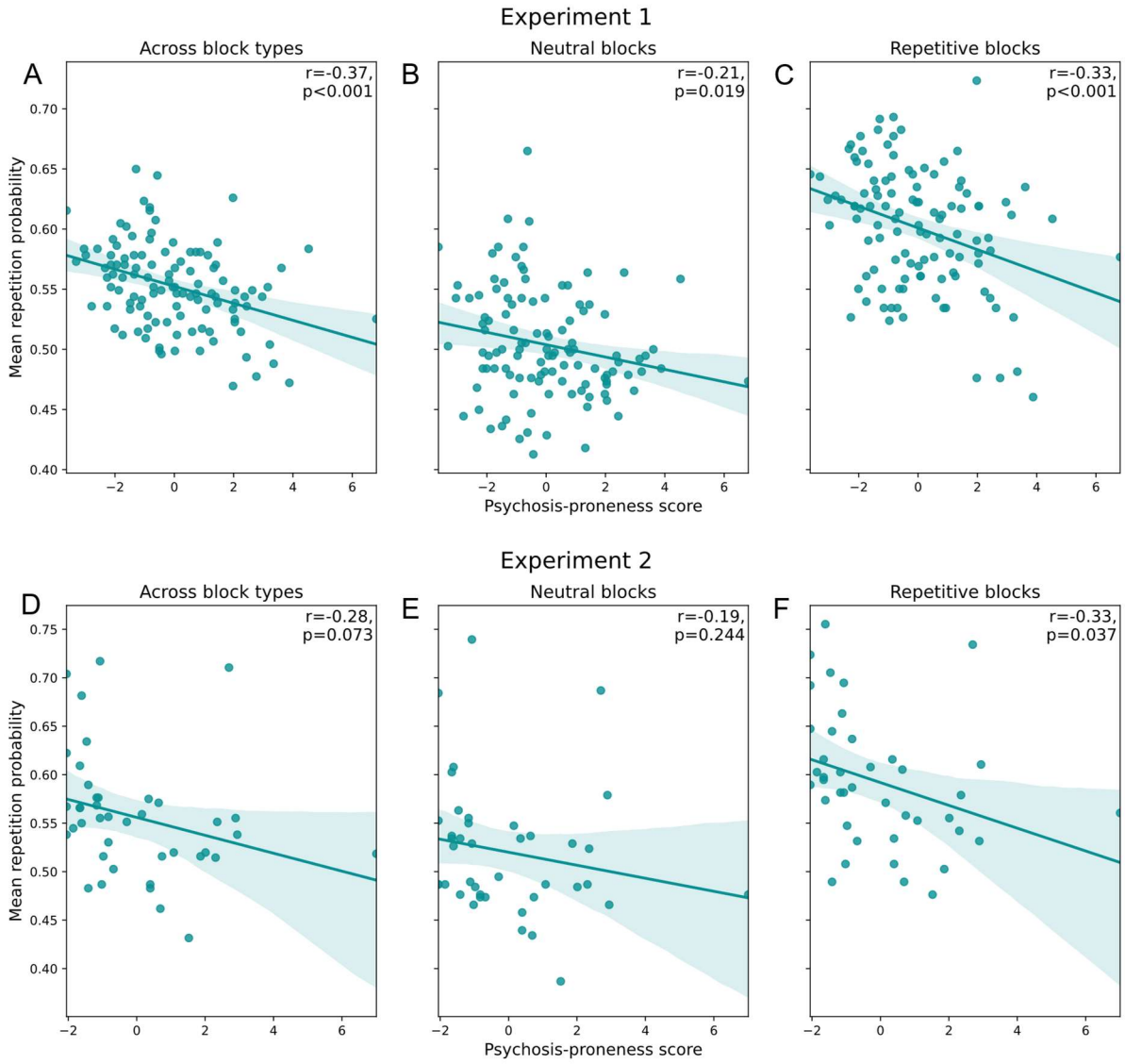


Figure 8. Correlation between repetition probability and psychosis proneness score.

A-C. Correlations between repetition probability and psychosis proneness score in *Experiment 1* across block types (A), in neutral blocks (B) and in repetitive blocks (C).

D-F. Correlations between repetition probability and psychosis proneness score in *Experiment 2* across block types (D), in neutral blocks (E) and in repetitive blocks (F).

Re-printed from open-access article Eckert et al., 2022.

Table 2. Results of the logistic model.

	Experiment 1					*Experiment 2*				
Variable	β	SE	*z*	*p*	sig.	β	SE	*z*	*p*	sig.
Intercept	0.01	0.04	0.40	0.69		0.03	0.08	0.36	0.72	
Stimulus	1.48	0.02	93.16	< 0.001	***	1.10	0.02	55.81	< 0.001	***
Discriminability	0.09	0.01	6.21	0.00	***	-0.07	0.03	-2.77	0.01	**
Previous stimulus	-0.08	0.02	-5.05	0.00	***	-0.07	0.02	-4.11	0.00	***
Previous discriminability	0.01	0.01	0.85	0.39		-0.02	0.01	-1.14	0.25	
Previous choice	0.15	0.02	8.57	< 0.001	***	0.13	0.02	7.72	0.00	***
PPS	0.01	0.03	0.35	0.73		0.01	0.08	0.09	0.93	
Block type	0.00	0.01	0.20	0.84		0.01	0.02	0.44	0.66	
Cue	0.22	0.01	15.42	< 0.001	***	0.54	0.02	34.45	< 0.001	***
Stimulus * discriminability	0.70	0.01	50.13	< 0.001	***	1.26	0.03	46.76	< 0.001	***
Previous stimulus * previous discriminability	-0.07	0.01	-5.03	0.00	***	-0.10	0.01	-6.44	0.00	***
PPS * previous choice	-0.06	0.01	-5.06	0.00	***	-0.09	0.01	-6.14	0.00	***
Block type * previous choice	-0.04	0.01	-3.13	0.00	**	-0.05	0.01	-3.20	0.00	**
PPS * block type	0.00	0.01	-0.10	0.92		0.03	0.02	1.33	0.18	
PPS * cue	-0.05	0.01	-3.93	<0.001	***	0.11	0.01	7.53	0.00	***
Block type * cue	0.02	0.01	1.23	0.22		-0.01	0.01	-0.72	0.47	
Previous choice * PPS * block type	0.01	0.01	0.49	0.63		0.02	0.01	1.63	0.10	
Cue * PPS * block type	0.01	0.01	1.01	0.32		0.00	0.01	-0.07	0.95	

Experiment 1 (Corrected R2 = 0.404, Number of observations = 42,601), and Experiment 2 (corrected R2 = 0.32, Number of observations = 31,087). SE: standard error of estimate. PPS: psychosis proneness score. *Adapted from Eckert et al., 2022*

3.2. Study II: Sensory Sensitivity in bistable perception

3.2.1. Sample characteristics

23 patients with paranoid schizophrenia (5 female, mean age 33.6 ± 8.4 SD) and 23 healthy controls (matched for age, gender, and handedness, 6 female, mean age 37.1 ± 11.6 SD) were included in the final sample. Controls reported average PDI scores of 22 (±28 SD) and average CAPS scores of 6.7 (±9.2 SD). Patients reported average PDI scores of 139 (±80 SD) and average CAPS scores of 65.0 (±50.1 SD). Patients were further rated on the PANSS. Average scores on the PANSS-*Positive* subscale were 18.5 (±6.3 SD), for the PANSS-*Negative* subscale they were 19.4 (±8.2 SD). Mean *General* score was 33 (±10 SD).

Table 3. Sample characteristics Study II

	N	Age	PDI	CAPS	PANSS:P	PANSS:N	PANSS:G	CPZe
Controls	23 (6F*)	33.6 ± 8.4	22 ± 28	6.7 ± 9.2	*N/A*	*N/A*	*N/A*	*N/A*
Patients	23 (5F)	37.1 ± 11.6	139 ± 80	65.0 ± 50.1	18.4 ± 6.3	19.4 ±8.2	33 ±10	190 ±172

* F= female, PDI: Peters et al. Delusions Inventory, CAPS: Cardiff Anomalous Perceptions Scale, PANSS:P/:N: Positive and Negative Symptoms Scale; G: General; CPZe: Chlorpromazine equivalents, *adapted from Weilnhammer et al., 2020*

3.2.2. Results from regression analyses

The regression model showed a significant main effect of the level of disambiguating stimulus evidence on the proportion of congruent perceptual states ($F(6) = 15.16$, $P=6.44*10^{-15}$). There was no main effect of group ($F(1)=0.02$, $P=.88$). A significant group x disambiguating stimulus evidence interaction was found ($F(6)=2.52$, $P=0.2$, see Figure 9). Model fitting to the proportion of congruent perceptual states revealed a superior fit of exponential functions (vs. linear or sigmoid functions). The growth rate of the exponential function, which was used as a proxy for the sensitivity to sensory evidence, differed among groups (patients: 0.06±0.01, controls: 0.02±0.02). Bootstrapping analyses revealed this as a borderline significant effect (95% CI = 0.004 to -0.08).

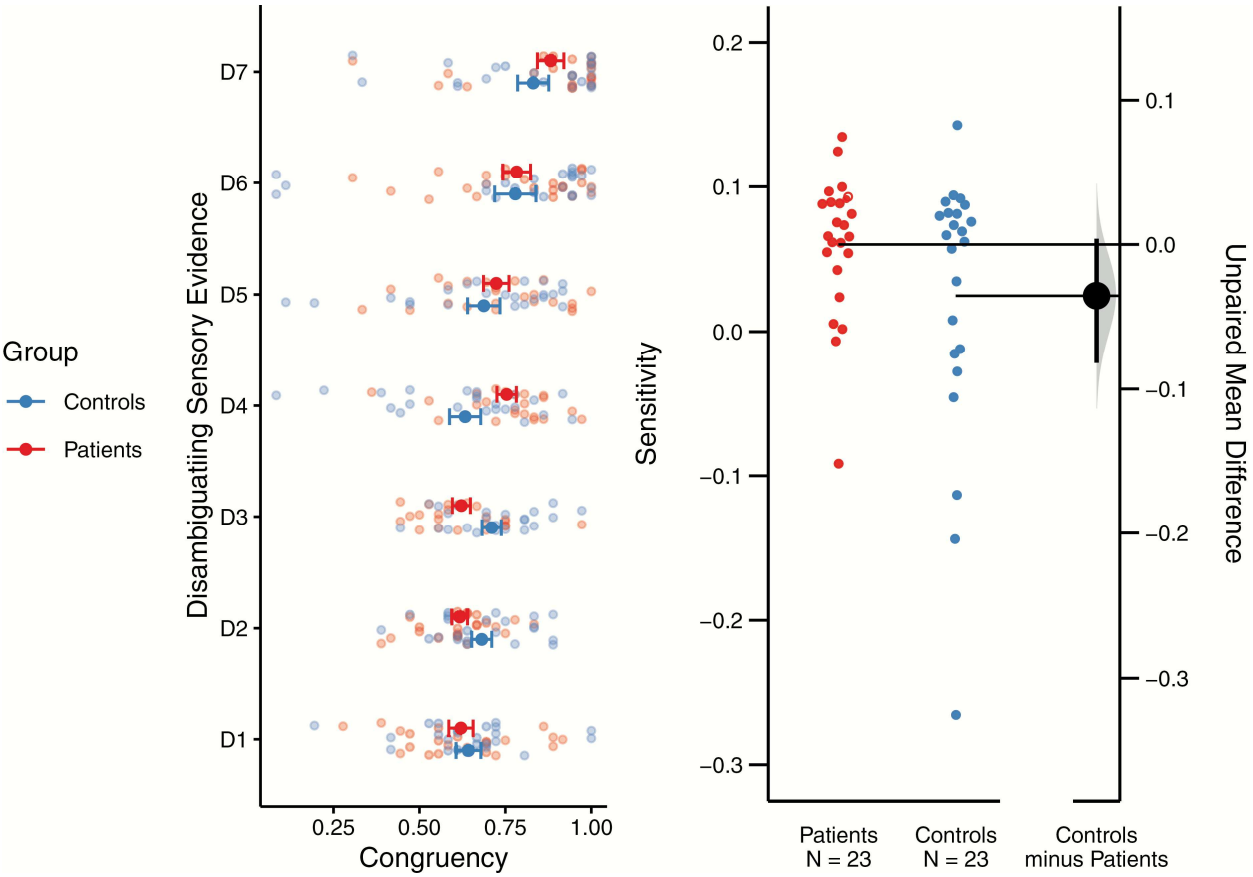


Figure 9. Sensitivity to disambiguating stimulus evidence across groups.

The left panel depicts the proportion of congruent perceptual states across the seven levels of disambiguating stimulus evidence (filled dot: mean, error bars: Standard Error). At low levels of disambiguating stimulus evidence (D1-D3), controls show a marginally stronger reliance on disambiguating stimulus evidence. At higher levels (D4-D7), congruent percepts were more frequent in patients. The right panel shows the growth rate of the exponential fits across groups. Growth rates were used as a proxy for the individual sensitivity to disambiguating stimulus evidence. Re-printed from (Weilnhammer et al., 2020) with permission from *Schizophrenia Bulletin, Oxford University Press.*

3.2.3. Correlative results

The sensitivity to disambiguating stimulus evidence was correlated with CAPS (R=0.51, p=0.02) and the PANSS-P3 item (R=0.52, P=0.1) in the patient group (see Figure 10). There was further a significant negative correlation between average phase duration and CAPS (R=-0.54, P=0.1). Correlations between the phase duration parameter and the PDI or other PANSS items did not reach significance. Neither questionnaire scores or PANSS

subitems correlated with any other perceptual biases, stereo-disparity thresholds, chlorpromazine equivalents or duration of illness.

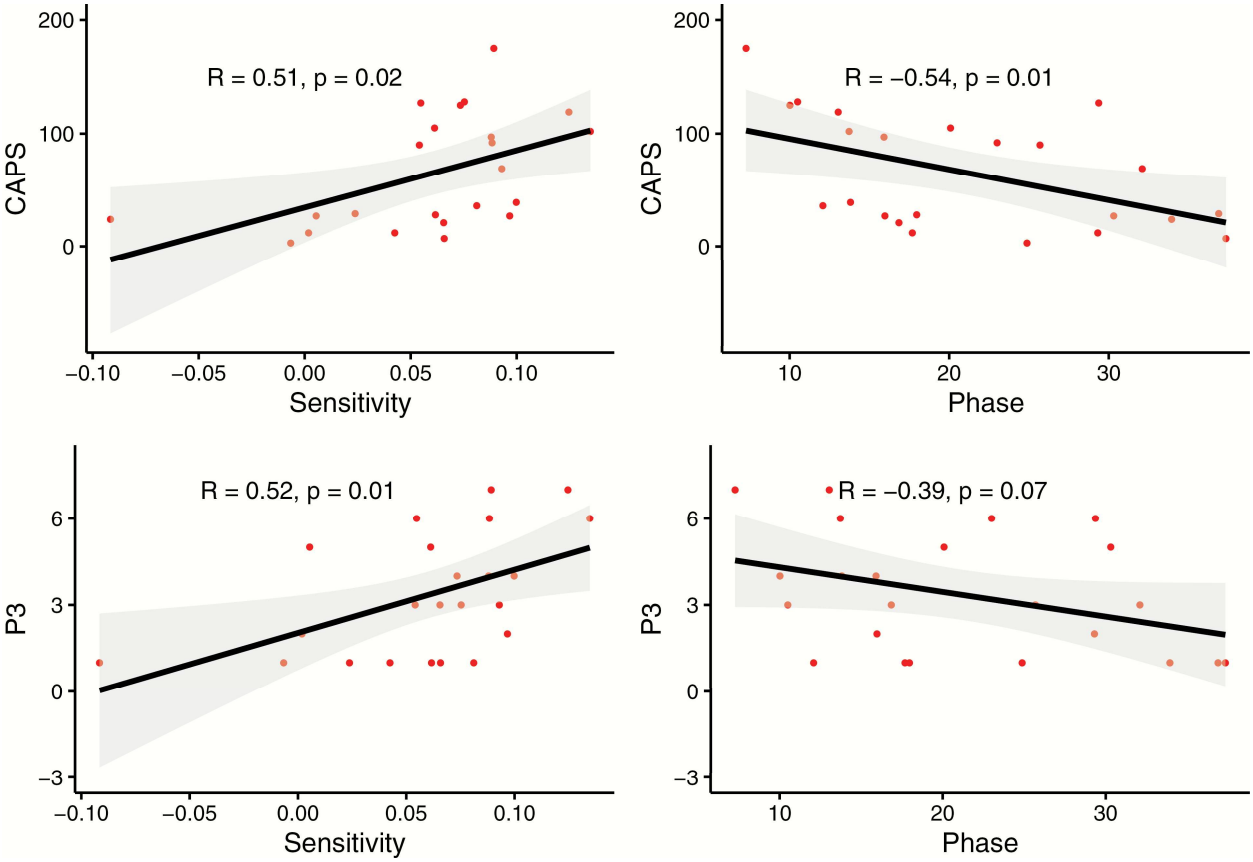


Figure 10. Correlations of sensitivity and phase duration with symptom severity

The sensitivity to stimulus evidence (left panels) and phase duration (right panel) were correlated with the individual CAPS score (top row) and hallucinations (P3 – bottom row). Shaded area represent the 95% CI of the black regression line.

Re-printed from open access article (Weilnhammer et al., 2020) *with permission from Schizophrenia Bulletin, Oxford University Press.*

4. Discussion

4.1. Summary

A visual overview of all results can be found in Figure 11.

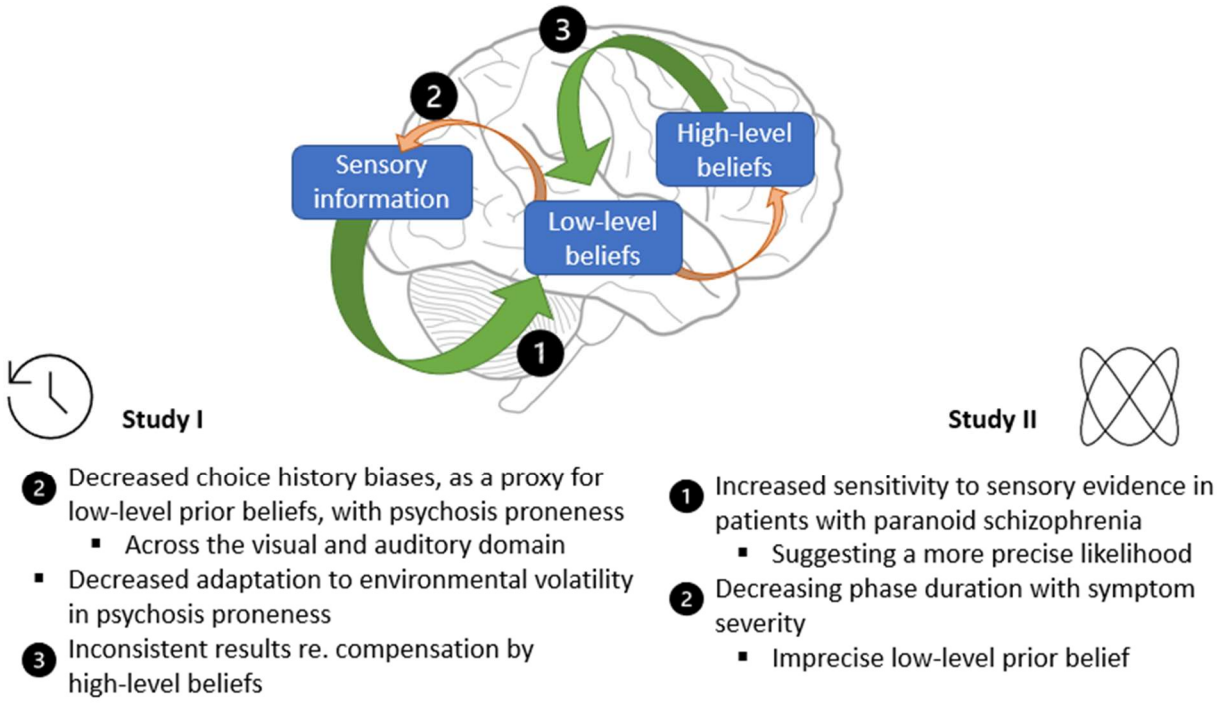


Figure 11. Graphical overview of all results

Graphical representation my own; inspired by (Heinz et al., 2019).

In *Study I*, two perceptual decision-making experiments for the visual- and auditory modality were developed. We investigated to what extent choice history biases and the reliance on an explicit cue were modulated by psychosis proneness in the general population. With this, our aim was to investigate the differential weighting of prior information at different levels of a cortical hierarchy assumed under predictive processing.

We showed that general psychosis proneness was associated with reduced choice history biases (*Hypothesis 1a*). This finding was robust across sensory modalities (auditory and visual), environmental statistics (random and repetitive) and study context (online and laboratory-based). There was inconsistent evidence for a compensatory mechanism between low- and higher-level prior information, in which more psychosis prone individu-

als are assumed to rely on explicit, higher-level information to an increased extent (*Hypothesis 1b*). Finally, there was only partial evidence that psychosis proneness modulates the adaptation of choice history biases to environmental regularities (*Hypothesis 1c*).
Study II consisted of a laboratory-based perceptual task using bistable stimuli. The sample consisted of patients with paranoid schizophrenia and healthy controls matched in age, gender, and handedness. The sensitivity to disambiguating sensory evidence was assessed as a proxy for the likelihood parameter in an assumed underlying inferential process, whereas the phase duration, or temporal stability of one perceptual state, was used to estimate a sensory-level prior belief.
Patients with psychosis showed increased sensitivity to disambiguating sensory evidence compared to healthy controls, suggesting an increased precision of the likelihood term (*Hypothesis 2a*). Further, sensitivity increased with symptom severity, whereas phase duration decreased with symptom severity in the patient group, suggesting decreased precision of prior beliefs at sensory levels of the processing hierarchy (*Hypothesis 2b*).

4.2. Interpretation and contextualization

4.2.1. Low-level priors

Converging lines of evidence from *Study I* and *Study II* suggest a decreased weighting of prior information on lower, sensory levels of a processing hierarchy assumed under predictive processing. *Study I* used implicit choice history effects, and *Study II* used phase duration to approximate lower-level prior beliefs. Results from both studies converge and suggest a decreased weighting of sensory-level prior beliefs relative to the sensory evidence. This remarkable generalizability points towards imprecise perceptual prior beliefs as a hallmark of perceptual inference in psychosis.
These empirical findings are in line with theoretical predictions of the predictive processing account of psychosis (Heinz et al., 2019; Sterzer et al., 2018). Here, psychosis is assumed to result from an aberrant balancing of likelihood and prior beliefs during perceptual inference. Specifically, sensory information at lower levels of the processing hierarchy is not sufficiently constrained by the generative model. When the resulting aberrant prediction errors are propagated up the processing hierarchy, the unconstrained information from lower levels is met with overly precise beliefs at higher levels in an attempt to constrain the incoming information. In line with aberrant precision-weighting of prior

and sensory information, Seymour and colleagues found a decreased contextual modulation of visual processing in early visual areas (Seymour et al., 2013). Further, consistent with the weak-sensory-priors account of psychosis is a study by Valton and colleagues (2019). They employed a statistical learning task, where participants estimated the global motion direction of RDKs ("*estimation task"*) and were furthermore asked to indicate whether a stimulus was presented or not (*"detection task"*). Two global motion directions were more frequently presented. Patients with chronic schizophrenia showed no deficit in statistical learning compared to controls. However, they reported significantly fewer "induced hallucinations", i.e., false-positive hallucinations of the most frequent motion directions in the detection task. The authors suggest that this may be the consequence of less precise prior expectations (Valton et al., 2019). The notion of weaker sensory-level priors is supported by studies on visual illusions (Dima et al., 2009; King et al., 2017; Notredame et al., 2014), where the relative immunity of patients with SSD can be interpreted as a weakening of sensory-level priors (Dima et al., 2009). Finally, in the sensorimotor domain, a failure to accurately predict the sensory consequences of their own actions in psychosis (*corollary discharge*, Crapse & Sommer, 2008; Shergill et al., 2005; Synofzik & Voss, 2010) has been related to imprecise, low-level proprioceptive beliefs (Teufel et al., 2010).

An important caveat is that the present studies cannot fully disentangle the effects of prior beliefs and sensory information. Our results support the notion of an aberrant prior-to-likelihood ratio at lower hierarchical levels in psychosis, in other words, an aberrant relative weighting of perceptual priors and sensory evidence in psychosis. The notion of "reduced low-level priors" hence needs to be understood in relative terms. To disentangle the effects of prior beliefs and sensory evidence, future studies may rely on learned prior beliefs rather than implicit ones; and leverage high-resolution neuroimaging techniques such as EEG to disentangle bottom-up and top-down streams of information.

Regarding the more specific finding of reduced choice history biases in psychosis proneness from *Study I*, the present work replicates and extends recent findings by Stein, Barbosa, and colleagues (2020). In a spatial working memory task, they showed decreased serial dependencies in patients with SSD and anti-NMDA-encephalitis[1] compared to controls. Interestingly, serial effects normalized with recovery in acute, encephalitis-induced

[1] Anti-NMDA-receptor-encephalitis is a severe autoimmune neurological disorder, in which a destruction of NMDA-receptors is associated with sudden-onset psychotic symptoms. These symptoms are often misdiagnosed as SSD (Wandinger et al., 2011).

psychosis. This work suggests an important role of NMDA for both the mediation of perceptual-level prior information such as history effects and psychosis (Stein et al., 2020). Some *contradictory* findings suggest an increased reliance on perceptual prior beliefs in psychosis (Corlett et al., 2019; Powers et al., 2017). When conditioning the occurrence of an auditory stimulus with the presentation of a visual stimulus, individuals who experience hallucinations appear to perceive more “conditioned hallucinations” (Powers et al., 2017), i.e., they report the presence of an auditory tone when there was none. The authors relate this to an overweighting of perceptual priors in hallucinating individuals. Similarly, individuals at high risk of psychosis showed a greater advantage of previously learned image characteristics for a recognition task in degraded images than controls (Teufel et al., 2015). These contradicting findings may be reconciled by considering the hierarchical organization of sensory processing. Unlike implicit choice history biases (*Study I*) or phase duration in bistable perception (*Study II*), previous knowledge about stimulus associations as in Powers et al., as well as previous experience with visual scenes as in Teufel et al. is a learned, and hence more explicit form of prior belief. When embedding these findings in a hierarchical predictive processing framework, they may be the expression of relatively stronger priors at higher, explicit hierarchical levels.

4.2.2. High-level priors

Besides studying choice history biases as an approximation of lower-level prior beliefs, *Study I* also investigated the potential compensation by an increased reliance on higher-level priors in psychosis proneness. Empirical results on this question were inconsistent across the two experiments in *Study I*, precluding definite conclusions on a compensatory mechanism. In the auditory modality, we found evidence for a decreased reliance on cue information (as a proxy for higher-level beliefs), whereas in the visual modality, we observed an increased weighting of cue information with psychosis proneness, in line with theoretical considerations. There are multiple studies suggesting an increased reliance on higher-level prior beliefs in psychosis. For example, Schmack and colleagues (2013) showed that psychosis prone individuals were more susceptible to a placebo-like, learned manipulation of higher-level beliefs. In their study, participants learned associations between rotational directions of a bistable rotating sphere and “polarizing” viewing glasses. The viewing glasses were made of simple glass and hence unfit to bias perception in any way. However, more psychosis prone individuals reported more percepts congruent with the learned rotational direction (Schmack et al., 2013).

Another study has investigated the reliance on low- vs. high-level priors in different disease stages (Haarsma, Knolle, et al., 2020). Participants were asked to decipher an ambiguous auditory phoneme while either viewing accompanying lip movements (sensory-level priors) or written word-sound associations (cognitive-level priors). In patients in initial stages of psychosis, results suggested a decrease in sensory-level prior precision compared to later-stage patients and healthy controls. In contrast, cognitive priors were more precise in later-stage SSD patients compared to initial-stage patients and healthy controls. The authors conclude that both the hierarchical origin and the disease stage play an important role for the specificities of the inferential process. Compensatory mechanisms between hierarchical levels may only develop while the individual progresses through later disease stages (Haarsma, Knolle, et al., 2020), which may explain the inconsistent finding in the psychosis prone sample of *Study I.*

4.4. Strengths and weaknesses of the studies

Both *Study I* and *Study II* make important empirical contributions to furthering the mechanistic understanding of psychosis from a predictive processing perspective. Indeed, the theoretical prediction of aberrant weighting of perceptual-level prior and likelihood in psychosis generalized across stimulus- and task formats, experimental context, study populations and perceptual modalities. This remarkable generalizability suggests that the aberrant weighting of prior beliefs and sensory evidence are a hallmark factor predisposing for psychotic experiences. All studies were conducted under the principles of open and reproducible science. The experimental design, research questions, hypotheses and statistical procedures of all experiments were pre-registered. All anonymized data, code and the published manuscripts are publicly accessible, increasing the probability of replication by other researchers.

Study I suggests a very robust modulatory effect of psychosis proneness on choice history biases. This effect suggests an abnormal weighting of perceptual history as a trait marker of psychosis. A compensatory increase in cue reliance was expected from theoretical considerations. However, this effect was not found consistently across experiments. Besides a potential influence of disease stage (see section 4.3), the fact that the experiment was conducted in an online environment may play a role for this inconsistency. Despite thorough controls of the participant’s technical setup and task engage-

ment, differences in attentional resources between online vs. laboratory-based experiments cannot be completely ruled out. Such attentional effects may have contributed to the finding of reduced cue reliance on psychosis proneness, since more psychosis prone individuals may have had more problems retaining cue information in memory during stimulus presentation. A further factor limiting the interpretation of this inconsistent finding may be the fact that the cues differed between the two experiments (visual cue in the auditory decision-making task, auditory cue in the visual decision-making task). While parallelizing the design as much as possible between experiments, full parallelization was not feasible due to our cross-modality hypotheses.

Finally, our operationalization of choice history biases as a form of perceptual-level prior belief can be criticized. Some researchers relate choice history biases to decisional templates (Bosch et al., 2020) rather than modulations of perceptual-level sensory processing. History biases also appear to require conscious awareness (Kim et al., 2020), which suggests that they do not (exclusively) reside on sensory levels of the cortical hierarchy (but see Cicchini et al., 2017, 2021). Our operationalization of choice history biases as a type “low-level” beliefs therefore needs to be understood in relative terms and is limited to the present study**.**

In *Study II***,** we found strong correlations between sensory sensitivity and perceptual stability with hallucinations and perceptual abnormalities. We did, however, not find any associations between these parameters and delusional ideation, in contradiction with previous work (Schmack et al., 2015). This may be due to an intermittent presentation format, which may have been more appropriate for detecting associations between delusional ideation and perceptual stability than the continuous presentation format used in our study (Weilnhammer et al., 2020). In contrast, the paradigm of *graded ambiguity* used here may have been more sensitive towards detecting perceptual abnormalities.

Additionally, previous research has suggested deficits in binocular depth perception in schizophrenia (Hui et al., 2017; Schechter et al., 2006; Wang et al., 2018). In the present study, perceptual thresholds were estimated using a psychophysical staircasing method, which yielded in no significant or deficient values in the patient sample. There was further no global deterioration of performance in patients. We thus likely did not find the current pattern due to low-level differences in acuity or sensitivity between controls and patients (Weilnhammer et al., 2020).

All experiments and hypotheses were derived from the predictive processing account of schizophrenia. This framework has the strength of unifying a multitude of heterogeneous symptoms under the umbrella of implicit Bayesian inference. However, several critics of the theory remark that it lacks specification and is hence immune to falsification (Kogo & Trengove, 2015; Litwin & Miłkowski, 2020). While the notion of a cortical processing hierarchy is empirically successful, important details and its biological underpinnings remain understudied (Haarsma, Knolle, et al., 2020; Haarsma, Kok, et al., 2020; Litwin & Miłkowski, 2020). With our experiments, we have contributed cross-modal evidence to constraining perceptual inference in psychosis across modalities and stimulus formats. We further stayed committed to practises of open science (pre-registration, open data and open-source code, open-access publications) for all studies to avoid selective reporting of results.

4.5. Implications for future research

The two presented studies open new avenues towards empirical studies of predictive processing in psychosis.

Future studies could be concerned with expanding on the modality-general approach used in *Study I* by investigating putative inferential mechanisms across visual, auditory, somatosensory, and olfactory modalities. The somatosensory modality did not find consideration in the present projects. Body-related hallucinations and delusions, however, are an important feature of psychosis and can be a central source of distress to patients. An improved understanding of somatosensory inference in schizophrenia may further our understanding of negative symptoms (e.g., anhedonia, catatonia) and disturbances of agency (Synofzik & Voss, 2010; Teufel et al., 2010). So far, several lines of evidence converge in suggesting that inference in psychosis is characterized by imprecise low-level beliefs. Stein and colleagues have further argued for an important role of NMDA receptors for both history effects as well as psychotic symptoms. Future research may rely on interventional studies to ascertain a causative relationship between NMDA, psychotic symptoms, and different forms of low-level prior information. In combination with computational modelling, they may provide causal and mechanistic insights. Genome-wide association studies could further used to establish the genetic basis of this inferential pattern in psychosis.

There have been several concentrated efforts aimed at identifying the neural correlates of conscious perception, also using bistable stimuli (Brascamp et al., 2015; Frässle et al., 2014; Knapen et al., 2011; Lumer et al., 1998; Megumi et al., 2015; Sterzer & Kleinschmidt, 2007). A study by our workgroup has identified a crucial role of the inferior frontal cortex (IFC) for bistable perception (Weilnhammer et al., 2021). Specifically, the IFC receives signals about perceptual conflict from V5/hMT+, and feedback signals from IFC resolve perceptual conflict (Weilnhammer et al., 2021). After disrupting neural activity in IFC using transcranial magnetic stimulation, we observed longer phase durations, i.e., a slower updating of conscious experience under bistable viewing conditions. In combination with results from *Study II*, where patients showed decreased phase duration with increased symptom severity, this finding points towards a potential therapeutic use of stimulating the IFC in patients. Whether increasing phase duration, which we considered an approximation for low-level priors, generalizes towards stabilizing inference across the cortical hierarchy, needs investigation in future studies.

5. Conclusion

The present work examined predictive processing and implicit perceptual inference in psychosis and psychosis proneness. It entails two studies concerned with testing specific predictions made by the predictive processing framework. Across experiments, study populations, and stimuli, evidence converges towards reduced low-level prior precision, relative to the sensory evidence, in psychosis. This was suggested by reduced choice history biases in perceptual decision-making (*Study I*) and an increased sensitivity to sensory evidence in bistable perception (*Study II*). These findings are in line with the predictions of a hierarchical predictive processing perspective on psychosis, where our results favour the interpretation of weak low-level priors in psychosis, rather than stronger high-level priors (cmp. Sterzer et al., 2018). Taken together, they suggest that reduced precision-weighting of low-level prior beliefs is a hallmark feature of information processing in psychosis. Future research is needed to understand the importance of compensatory interactions between different levels of the cortical hierarchy, the role of disease stage, as well as the neural underpinnings of reduced low-level prior beliefs in psychosis.

Reference list

Adams, R. A., Perrinet, L. U., & Friston, K. (2012). Smooth Pursuit and Visual Occlusion: Active Inference and Oculomotor Control in Schizophrenia. *PLOS ONE*, *7*(10), e47502. https://doi.org/10.1371/JOURNAL.PONE.0047502

Adams, R. A., Stephan, K. E., Brown, H. R., Frith, C. D., & Friston, K. J. (2013). The computational anatomy of psychosis. *Frontiers in Psychiatry*, *4*, 47.

Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J. K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behavior Research Methods*, *52*(1), 388–407.

Arciniegas, D. B. (2015). Psychosis. *Continuum : Lifelong Learning in Neurology*, *21*(3 Behavioral Neurology and Neuropsychiatry), 715. https://doi.org/10.1212/01.CON.0000466662.89908.E7

Arzounian, D., de Kerangal, M., & de Cheveigné, A. (2017). Sequential dependencies in pitch judgments. *The Journal of the Acoustical Society of America*, *142*(5), 3047–3057.

Ballard, D. H. (2015). *Brain computation as hierarchical abstraction*. MIT Press.

Bell, V., Halligan, P. W., & Ellis, H. D. (2006). The Cardiff Anomalous Perceptions Scale (CAPS): a new validated measure of anomalous perceptual experience. *Schizophrenia Bulletin*, *32*(2), 366–377.

Berking, M., & Rief, W. (2011). *Klinische psychologie und psychotherapie für bachelor* (M. Berking & W. Rief, Eds.; 1st ed.). Springer Medizin. https://doi.org/doi: 10.1007/978-3-642-16974-8

Bosch, E., Fritsche, M., Ehinger, B. v., & de Lange, F. P. (2020). Opposite effects of choice history and evidence history resolve a paradox of sequential choice bias. *Journal of Vision*, *20*(12), 9–9. https://doi.org/10.1167/JOV.20.12.9

Brascamp, J., Blake, R., & Knapen, T. (2015). Negligible fronto-parietal BOLD activity accompanying unreportable switches in bistable perception. *Nature Neuroscience 2015 18:11*, *18*(11), 1672–1678. https://doi.org/10.1038/nn.4130

Brascamp, J., Sterzer, P., Blake, R., & Knapen, T. (2018). Multistable Perception and the Role of the Frontoparietal Cortex in Perceptual Inference. *Annual Review of Psychology*, *69*, 77–103. https://doi.org/10.1146/ANNUREV-PSYCH-010417-085944

Braun, A., Urai, A. E., & Donner, T. H. (2018). Adaptive history biases result from confidence-weighted accumulation of past choices. *Journal of Neuroscience*, *38*(10), 2418–2429.

Byrne, M., Agerbo, E., Bennedsen, B., Eaton, W., & Mortensen, P. (2007). Obstetric conditions and risk of first admission with schizophrenia: a Danish national register based study. *Schizophrenia Research*, *97*(1–3), 51–59.

Cicchini, G. M., Benedetto, A., & Burr, D. C. (2021). Perceptual history propagates down to early levels of sensory analysis. *Current Biology*, *31*(6), 1245-1250.e2. https://doi.org/10.1016/j.cub.2020.12.004

Cicchini, G. M., Mikellidou, K., & Burr, D. (2017). Serial dependencies act directly on perception. *Journal of Vision*, *17*(14), 6.

Cicchini, G. M., Mikellidou, K., & Burr, D. C. (2018). The functional role of serial dependence. *Proceedings of the Royal Society B*, *285*(1890), 20181722.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181–204.

Corlett, P. R., Horga, G., Fletcher, P. C., Alderson-Day, B., Schmack, K., & Powers III, A. R. (2019). Hallucinations and strong priors. *Trends in Cognitive Sciences*, *23*(2), 114–127.

Crapse, T. B., & Sommer, M. A. (2008). Corollary discharge circuits in the primate brain. *Current Opinion in Neurobiology*, *18*(6), 552–557.

Dao-Castellana, M.-H., Paillère-Martinot, M.-L., Hantraye, P., Attar-Lévy, D., Rémy, P., Crouzel, C., Artiges, E., Féline, A., Syrota, A., & Martinot, J.-L. (1997). Presynaptic dopaminergic function in the striatum of schizophrenic patients. *Schizophrenia Research*, *23*(2), 167–174.

Davies, D. J., Teufel, C., & Fletcher, P. C. (2018). Anomalous perceptions and beliefs are associated with shifts toward different types of prior knowledge in perceptual inference. *Schizophrenia Bulletin*, *44*(6), 1245–1253.

Davies, G., Welham, J., Chant, D., Torrey, E., & McGrath, J. (2003). A systematic review and meta-analysis of Northern Hemisphere season of birth studies in schizophrenia. *Schizophrenia Bulletin*, *29*(3), 587–593.

Davis, J., Eyre, H., Jacka, F. N., Dodd, S., Dean, O., McEwen, S., Debnath, M., McGrath, J., Maes, M., Amminger, P., McGorry, P. D., Pantelis, C., & Berk, M. (2016). A review

of vulnerability and risks for schizophrenia: Beyond the two hit hypothesis. *Neuroscience & Biobehavioral Reviews*, *65*, 185–194. https://doi.org/10.1016/J.NEUBIOREV.2016.03.017

Denève, S., & Jardri, R. (2016). Circular inference: Mistaken belief, misplaced trust. In *Current Opinion in Behavioral Sciences* (Vol. 11, pp. 40–48). Elsevier Ltd. https://doi.org/10.1016/j.cobeha.2016.04.001

Dima, D., Roiser, J. P., Dietrich, D. E., Bonnemann, C., Lanfermann, H., Emrich, H. M., & Dillo, W. (2009). Understanding why patients with schizophrenia do not perceive the hollow-mask illusion using dynamic causal modelling. *NeuroImage*, *46*(4), 1180–1186. https://doi.org/10.1016/J.NEUROIMAGE.2009.03.033

Eckert, A.-L., Gounitski, Y., Guggenmos, M., & Sterzer, P. (2022). Cross-Modality Evidence for Reduced Choice History Biases in Psychosis-Prone Individuals. *Schizophrenia Bulletin*, *sbac168*. https://doi.org/10.1093/SCHBUL/SBAC168

Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*, *17*(5), 738–743. https://doi.org/10.1038/nn.3689

Fletcher, P. C., & Frith, C. D. (2009). Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. *Nature Reviews Neuroscience*, *10*(1), 48–58.

Fornaciai, M., & Park, J. (2018). Serial dependence in numerosity perception. *Journal of Vision*, *18*(9), 15.

Fornaciai, M., & Park, J. (2020). Neural dynamics of serial dependence in numerosity perception. *Journal of Cognitive Neuroscience*, *32*(1), 141–154.

Frässle, S., Sommer, J., Jansen, A., Naber, M., & Einhäuser, W. (2014). Binocular Rivalry: Frontal Activity Relates to Introspection and Action But Not to Perception. *Journal of Neuroscience*, *34*(5), 1738–1747. https://doi.org/10.1523/JNEUROSCI.4403-13.2014

Friston, K. (2005a). Hallucinations and perceptual inference. *Behavioral and Brain Sciences*, *28*(6), 764–766. https://doi.org/10.1017/S0140525X05290131

Friston, K. (2005b). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/RSTB.2005.1622

Fründ, I., Wichmann, F. A., & Macke, J. H. (2014). Quantifying the effect of intertrial dependence on perceptual decisions. *Journal of Vision*, *14*(7), 9.

Gaebel, W., Zielasek, J., & Cleveland, H. R. (2013). Psychotic disorders in ICD-11. *Psychiatrie*, *10*(1), 11–17. https://doi.org/10.1055/S-0038-1670831

Gage, S. H., Zammit, S., & Hickman, M. (2013). Stronger evidence is needed before accepting that cannabis plays an important role in the aetiology of schizophrenia in the population. *F1000 Medicine Reports*, *5*.

Ghirardo, C., Manassi, M., Canas-Bajo, T., Prinzmetal, W., & Whitney, D. (2020). Simulated tumor recognition in mammograms is biased by serial dependence. *Journal of Vision*, *20*(11), 1202.

Gilroy, L. A., & Blake, R. (2004). Physics embedded in visual perception of three-dimensional shape from motion. *Nature Neuroscience 2004 7:9*, *7*(9), 921–922. https://doi.org/10.1038/nn1297

Guillin, O., Abi-Dargham, A., & Laruelle, M. (2007). Neurobiology of Dopamine in Schizophrenia. *International Review of Neurobiology*, *78*, 1–39. https://doi.org/10.1016/S0074-7742(06)78001-1

Haarsma, J., Knolle, F., Griffin, J. D., Taverne, H., Mada, M., Goodyer, I. M., Fletcher, P. C., & Murray, G. K. (2020). Influence of prior beliefs on perception in early psychosis: Effects of illness stage and hierarchical level of belief. *Journal of Abnormal Psychology*, *129*(6), 581. https://doi.org/10.1037/ABN0000494

Haarsma, J., Kok, P., & Browning, M. (2020). The promise of layer-specific neuroimaging for testing predictive coding theories of psychosis. *Schizophrenia Research*.

Hachen, I., Reinartz, S., Brasselet, R., Stroligo, A., & Diamond, M. E. (2021). Dynamics of history-dependent perceptual judgment. *Nature Communications 2021 12:1*, *12*(1), 1–15. https://doi.org/10.1038/s41467-021-26104-2

Heinz, A., Murray, G. K., Schlagenhauf, F., Sterzer, P., Grace, A. A., & Waltz, J. A. (2019). Towards a Unifying Cognitive, Neurophysiological, and Computational Neuroscience Account of Schizophrenia. *Schizophrenia Bulletin*, *45*(5), 1092–1100. https://doi.org/10.1093/SCHBUL/SBY154

Heinz, A., & Schlagenhauf, F. (2010). Dopaminergic Dysfunction in Schizophrenia: Salience Attribution Revisited. *Schizophrenia Bulletin*, *36*(3), 472–485. https://doi.org/10.1093/SCHBUL/SBQ031

Hohwy, J. (2013). *The predictive mind*. Oxford University Press.

Hohwy, J., Roepstorff, A., & Friston, K. (2008). Predictive coding explains binocular rivalry: An epistemological review. *Cognition*, *108*(3), 687–701. https://doi.org/10.1016/J.COGNITION.2008.05.010

Hu, W., Macdonald, M. L., Elswick, D. E., & Sweet, R. A. (2015). The glutamate hypothesis of schizophrenia: evidence from human brain tissue studies. *Annals of the New York Academy of Sciences*, *1338*(1), 38–57. https://doi.org/10.1111/NYAS.12547

Hui, L., sen Xia, H., Shu Tang, A., Feng Zhou, Y., Zhong Yin, G., Long Hu, X., Dong Du, X., & Tang, Y. (2017). Stereopsis deficits in patients with schizophrenia in a Han Chinese population. *Scientific Reports 2017 7:1*, *7*(1), 1–7. https://doi.org/10.1038/srep45988

Jardri, R., & Denève, S. (2013). Circular inferences in schizophrenia. *Brain*, *136*(11), 3227–3241. https://doi.org/10.1093/BRAIN/AWT257

Kallmann, F. (1938). The genetics of schizophrenia. *J.J. Augustin*.

Kalm, K., & Norris, D. (2018). Visual recency bias is explained by a mixture model of internal representations. *Journal of Vision*, *18*(7), 1.

Kapur, S. (2003). Psychosis as a state of aberrant salience: a framework linking biology, phenomenology, and pharmacology in schizophrenia. *American Journal of Psychiatry*, *160*(1), 13–23.

Katthagen, T., Mathys, C., Deserno, L., Walter, H., Kathmann, N., Heinz, A., & Schlagenhauf, F. (2018). Modeling subjective relevance in schizophrenia and its relation to aberrant salience. *PLoS Computational Biology*, *14*(8), e1006319.

Kay, S. R., Opler, L. A., & Lindenmayer, J. P. (1989). The Positive and Negative Syndrome Scale (PANSS): Rationale and Standardisation. *The British Journal of Psychiatry*, *155*(S7), 59–65. https://doi.org/10.1192/S0007125000291514

Khashan, A. S., Abel, K. M., McNamee, R., Pedersen, M. G., Webb, R. T., Baker, P. N., Kenny, L. C., & Mortensen, P. B. (2008). Higher risk of offspring schizophrenia following antenatal maternal exposure to severe adverse life events. *Archives of General Psychiatry*, *65*(2), 146–152.

Kim, S., Burr, D., Cicchini, G. M., & Alais, D. (2020). Serial dependence in perception requires conscious awareness. *Current Biology*, *30*(6), R257–R258.

King, D. J., Hodgekins, J., Chouinard, P. A., Chouinard, V.-A., & Sperandio, I. (2017). A review of abnormalities in the perception of visual illusions in schizophrenia. *Psychonomic Bulletin & Review*, *24*(3), 734–751.

Kirihara, K., Tada, M., Koshiyama, D., Fujioka, M., Usui, K., Araki, T., & Kasai, K. (2020). A Predictive Coding Perspective on Mismatch Negativity Impairment in Schizophrenia. *Frontiers in Psychiatry*, *11*, 660. https://doi.org/10.3389/FPSYT.2020.00660/BIBTEX

Knapen, T., Brascamp, J., Pearson, J., van Ee, R., & Blake, R. (2011). The Role of Frontal and Parietal Brain Areas in Bistable Perception. *Journal of Neuroscience*, *31*(28), 10293–10301. https://doi.org/10.1523/JNEUROSCI.1727-11.2011

Kogo, N., & Trengove, C. (2015). Is predictive coding theory articulated enough to be testable? *Frontiers in Computational Neuroscience*, *9*. https://doi.org/10.3389/FNCOM.2015.00111/FULL

Kok, R., Taubert, J., der Burg, E., Rhodes, G., & Alais, D. (2017). Face familiarity promotes stable identity recognition: exploring face perception using serial dependence. *Royal Society Open Science*, *4*(3), 160685.

Laruelle, M. (2013). The second revision of the dopamine theory of schizophrenia: Implications for treatment and drug development. *Biological Psychiatry*, *74*(2), 80–81. https://doi.org/10.1016/J.BIOPSYCH.2013.05.016

Laruelle, M., Abi-Dargham, A., van Dyck, C. H., Gil, R., D'Souza, C. D., Erdos, J., McCance, E., Rosenblatt, W., Fingado, C., & Zoghbi, S. S. (1996). Single photon emission computerized tomography imaging of amphetamine-induced dopamine release in drug-free schizophrenic subjects. *Proceedings of the National Academy of Sciences*, *93*(17), 9235–9240.

Laruelle, M., Kegeles, L. S., & Abi-Dargham, A. (2003). Glutamate, Dopamine, and Schizophrenia. *Annals of the New York Academy of Sciences*, *1003*(1), 138–158. https://doi.org/10.1196/ANNALS.1300.063

Leopold, D. A., Wilke, M., Maier, A., & Logothetis, N. K. (2002). Stable perception of visually ambiguous patterns. *Nature Neuroscience 2002 5:6*, *5*(6), 605–609. https://doi.org/10.1038/nn0602-851

Lindström, L. H., Gefvert, O., Hagberg, G., Lundberg, T., Bergström, M., Hartvig, P., & Långström, B. (1999). Increased dopamine synthesis rate in medial prefrontal cortex and striatum in schizophrenia indicated by L-(β-11C) DOPA and PET. *Biological Psychiatry*, *46*(5), 681–688.

Litwin, P., & Miłkowski, M. (2020). Unification by Fiat: Arrested Development of Predictive Processing. *Cognitive Science*, *44*(7), e12867. https://doi.org/10.1111/COGS.12867

Lumer, E. D., Friston, K. J., & Rees, G. (1998). Neural correlates of perceptual rivalry in the human brain. *Science*, *280*(5371), 1930–1934. https://www.science.org/doi/10.1126/science.280.5371.1930

Maia, T. v., & Frank, M. J. (2017). An Integrative Perspective on the Role of Dopamine in Schizophrenia. *Biological Psychiatry*, *81*(1), 52–66. https://doi.org/10.1016/J.BIOPSYCH.2016.05.021

Manassi, M., Liberman, A., Chaney, W., & Whitney, D. (2017). The perceived stability of scenes: serial dependence in ensemble representations. *Scientific Reports*, *7*(1), 1–9.

Maruya, K., Yang, E., & Blake, R. (2007). Voluntary action influences visual competition. *Psychological Science*, *18*(12), 1090–1098. https://doi.org/10.1111/j.1467-9280.2007.02030.x

McCutcheon, R., Marques, T., & Howes, O. (2020). Schizophrenia—an overview. *JAMA Psychiatry*, *77*(2), 201–210. https://jamanetwork.com/journals/jamapsychiatry/article-abstract/2753514

McGrath, J. J. (2007). The surprisingly rich contours of schizophrenia epidemiology. *Archives of General Psychiatry*, *64*(1), 14–16.

McLoughlin, B. C., Pushpa-Rajah, J. A., Gillies, D., Rathbone, J., Variend, H., Kalakouti, E., & Kyprianou, K. (2014). Cannabis and schizophrenia. *Cochrane Database of Systematic Reviews*, *10*.

Megumi, F., Bahrami, B., Kanai, R., & Rees, G. (2015). Brain activity dynamics in human parietal regions during spontaneous switches in bistable perception. *NeuroImage*, *107*, 190–197. https://doi.org/10.1016/J.NEUROIMAGE.2014.12.018

Meltzer, H. Y., & Stahl, S. M. (1976). The dopamine hypothesis of schizophrenia: a review. *Schizophrenia Bulletin*, *2*(1), 19–76. https://doi.org/10.1093/SCHBUL/2.1.19

Müller, N. (2018). Inflammation in schizophrenia: pathogenetic aspects and therapeutic considerations. *Schizophrenia Bulletin*, *44*(5), 973–982.

Ng, M. Y. M., Levinson, D. F., Faraone, S. V., Suarez, B. K., DeLisi, L. E., Arinami, T., Riley, B., Paunio, T., Pulver, A. E., Irmansyah, A., Holmans, P. A., Escamilla, A., Wildenauer, D. B., Williams, N. M., Laurent, C., Mowry, B. J., Brzustowicz, L. M., Maziade, M., Sklar, P., Garver, D. L., Abecasis, G. R., Lerer, B., Fallin, M. D., Gurling, H. M. D., Gejman, P. V., Lindholm, E., Moises, H. W., Byerley, W., Wijsman, E. M., Forabosco, M., Tsuang, M. T., Hwu, H. G., Okazaki, Y., Kendler, K. S., Wormley, B., Fanous, A., Walsh, D., O'Neill, F. A., Peltonen, L., Nestadt, G., Lasseter, V. K., Liang, K. Y., Papadimitriou, G. M., Dikeos, D. G., Schwab, S. G., Owen, M. J., O'Donovan, M. C., Norton, N., Hare, E, Raventos, H., Nicolini, H., Albus, M., Maier, W., Nimgaonkar, V. L., Terenius, L., Mallet, J., Jay, M., Godard, S., Nertney, D., Alexander, M.,

Crowe, R. R., Silverman, J. M., Bassett, S. M., Roy, M. A., Mérette, C., Pato, C. N., Pato, M. T., Louw Roos, J., Kohn, Y., Amann-Zalcenstein, D., Kalsi, G., McQuillin, A., Curtis, D., Brynjolfson, J., Sigmundsson, T., Petursson, H., Sanders, A. R., Duan, J., Jazin, E., Myles-Worsley, M., Karayiorgou, M., & Lewis, C. M. (2009). Meta-analysis of 32 genome-wide linkage studies of schizophrenia. *Molecular Psychiatry*, *14*(8), 774–785. https://doi.org/10.1038/mp.2008.135

Notredame, C. E., Pins, D., Deneve, S., & Jardri, R. (2014). What visual illusions teach us about schizophrenia. *Frontiers in Integrative Neuroscience*, *8*(AUG), 63. https://doi.org/10.3389/FNINT.2014.00063/BIBTEX

Orbach, J., Ehrlich, D., & Heath, H. A. (1963). Reversibility of the Necker Cube. I. An Examination of the Concept of “Satiation of Orientation”. *Perceptual and Motor Skills*, *17*, 439–458. https://doi.org/10.2466/pms.1963.17.2.439

Palan, S., & Schitter, C. (2018). Prolific. ac—A subject pool for online experiments. *Journal of Behavioral and Experimental Finance*, *17*, 22–27.

Pankow, A., Katthagen, T., Diner, S., Deserno, L., Boehme, R., Kathmann, N., Gleich, T., Gaebler, M., Walter, H., Heinz, A., & Schlagenhauf, F. (2016). Aberrant Salience Is Related to Dysfunctional Self-Referential Processing in Psychosis. *Schizophrenia Bulletin*, *42*(1), 67–76. https://doi.org/10.1093/SCHBUL/SBV098

Patterson, P. H. (2002). Maternal infection: window on neuroimmune interactions in fetal brain development and mental illness. *Current Opinion in Neurobiology*, *12*(1), 115–118. https://doi.org/10.1016/S0959-4388(02)00299-4

Pearson, J., & Brascamp, J. (2008). Sensory memory for ambiguous vision. *Trends in Cognitive Sciences*, *12*(9), 334–341. https://doi.org/10.1016/J.TICS.2008.05.006

Peters, E. R., Joseph, S. A., & Garety, P. A. (1999). Measurement of delusional ideation in the normal population: introducing the PDI (Peters et al. Delusions Inventory). *Schizophrenia Bulletin*, *25*(3), 553–576.

Powers, A. R., Mathys, C., & Corlett, P. R. (2017). Pavlovian conditioning–induced hallucinations result from overweighting of perceptual priors. *Science*, *357*(6351), 596–600.

Rao, R., & Ballard, D. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience*, *2*(1), 79–87.

Reith, J., Benkelfat, C., Sherwin, A., Yasuhara, Y., Kuwabara, H., Andermann, F., Bachneff, S., Cumming, P., Diksic, M., & Dyve, S. E. (1994). Elevated dopa decarboxylase activity in living brain of patients with psychosis. *Proceedings of the National Academy of Sciences*, *91*(24), 11651–11654.

Schechter, I., Butler, P. D., Jalbrzikowski, M., Pasternak, R., Saperstein, A. M., & Javitt, D. C. (2006). A New Dimension of Sensory Dysfunction: Stereopsis Deficits in Schizophrenia. *Biological Psychiatry*, *60*(11), 1282–1284. https://doi.org/10.1016/J.BIOPSYCH.2006.03.064

Schmack, K., de Castro, A. G. C., Rothkirch, M., Sekutowicz, M., Rössler, H., Haynes, J. D., Heinz, A., Petrovic, P., & Sterzer, P. (2013). Delusions and the role of beliefs in perceptual inference. *Journal of Neuroscience*, *33*(34), 13701–13712. https://doi.org/10.1523/JNEUROSCI.1778-13.2013

Schmack, K., Schnack, A., Priller, J., & Sterzer, P. (2015). Perceptual instability in schizophrenia: Probing predictive coding accounts of delusions with ambiguous stimuli. *Schizophrenia Research: Cognition*, *2*(2), 72–77. https://doi.org/10.1016/J.SCOG.2015.03.005

Schmack, K., Weilnhammer, V., Heinzle, J., Stephan, K. E., & Sterzer, P. (2016). Learning what to see in a changing world. *Frontiers in Human Neuroscience*, *10*, 263. https://doi.org/10.3389/FNHUM.2016.00263/BIBTEX

Seth, A. (2021). *Being you: A new science of consciousness*. Penguin.

Seth, A. K., Suzuki, K., & Critchley, H. D. (2012). An interoceptive predictive coding model of conscious presence. *Frontiers in Psychology*, *3*(JAN), 395. https://doi.org/10.3389/FPSYG.2011.00395/BIBTEX

Seymour, K., Stein, T., Lira, L., Sanders, O., Guggenmos, M., Theophil, I., & Sterzer, P. (2013). Altered Contextual Modulation of Primary Visual Cortex Responses in Schizophrenia. *Neuropsychopharmacology 2013 38:13*, *38*(13), 2607–2612. https://doi.org/10.1038/npp.2013.168

Shergill, S. S., Samson, G., Bays, P. M., Frith, C. D., & Wolpert, D. M. (2005). Evidence for sensory prediction deficits in schizophrenia. *American Journal of Psychiatry*, *162*(12), 2384–2386.

Spratling, M. (2017). A review of predictive coding algorithms. *Brain and Cognition*, *112*, 92–97.

Spratling, M. W. (2017). A Hierarchical Predictive Coding Model of Object Recognition in Natural Images. *Cognitive Computation*, *9*(2), 151–167. https://doi.org/10.1007/S12559-016-9445-1

Stein, H., Barbosa, J., Rosa-Justicia, M., Prades, L., Morató, A., Galan-Gadea, A., Ariño, H., Martinez-Hernandez, E., Castro-Fornieles, J., Dalmau, J. & Compte, A. (2020). Reduced serial dependence suggests deficits in synaptic potentiation in anti-NMDAR encephalitis and schizophrenia. *Nature Communications*, *11*(1), 1–11.

Stephan, K., Baldeweg, T., & Friston, K. (2006). Synaptic plasticity and dysconnection in schizophrenia. *Biological Psychiatry*, *59*(10), 929–939.

Sterzer, P., Adams, R. A., Fletcher, P., Frith, C., Lawrie, S. M., Muckli, L., Petrovic, P., Uhlhaas, P., Voss, M., & Corlett, P. R. (2018). The predictive coding account of psychosis. *Biological Psychiatry*, *84*(9), 634–643.

Sterzer, P., Frith, C., & Petrovic, P. (2008). Believing is seeing: expectations alter visual awareness. *Current Biology*, *18*(16), R697–R698. https://doi.org/10.1016/J.CUB.2008.06.021

Sterzer, P., & Kleinschmidt, A. (2007). A neural for inference in ambiguity. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(1), 323–328. https://doi.org/10.1073/PNAS.0609006104/SUPPL_FILE/09006FIG6.PDF

Strauss, J. (1969). Hallucinations and delusions as points on continua function. *Archives of General Psychiatry*, *21*, 1581–1586. https://ci.nii.ac.jp/naid/10008370874/

Suárez-Pinilla, M., Seth, A. K., & Roseboom, W. (2018). Serial dependence in the perception of visual variance. *Journal of Vision*, *18*(7), 4.

Sundareswara, R., & Schrater, P. R. (2007). A Perceptual inference model for bistability. *Journal of Vision*, *7*(9), 803–803. https://doi.org/10.1167/7.9.803

Susser, E., Clair, D. S., & He, L. (2008). Latent Effects of Prenatal Malnutrition on Adult Health. *Annals of the New York Academy of Sciences*, *1136*(1), 185–192. https://doi.org/10.1196/ANNALS.1425.024

Synofzik, M., & Voss, M. (2010). Disturbances of the sense of agency in schizophrenia. *Neuropsychology of the Sense of Agency: From Consciousness to Action*, 145–155. https://doi.org/10.1007/978-88-470-1587-6_8/COVER

Tandon, R., Keshavan, M. S., & Nasrallah, H. A. (2008). Schizophrenia, “Just the Facts” What we know in 2008. 2. Epidemiology and etiology. *Schizophrenia Research*, *102*(1–3), 1–18. https://doi.org/10.1016/J.SCHRES.2008.04.011

Taubert, J., & Alais, D. (2016). Serial dependence in face attractiveness judgements tolerates rotations around the yaw axis but not the roll axis. *Visual Cognition*, *24*(2), 103–114.

Teufel, C., Kingdon, A., Ingram, J. N., Wolpert, D. M., & Fletcher, P. C. (2010). Deficits in sensory prediction are related to delusional ideation in healthy individuals. *Neuropsychologia*, *48*(14), 4169–4172.

Teufel, C., Subramaniam, N., Dobler, V., Perez, J., Finnemann, J., Mehta, P. R., Goodyer, I. M., & Fletcher, P. C. (2015). Shift toward prior knowledge confers a perceptual advantage in early psychosis and psychosis-prone healthy individuals. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(43), 13401–13406. https://doi.org/10.1073/PNAS.1503916112/-/DCSUPPLEMENTAL

Toda, M., & Abi-Dargham, A. (2007). Dopamine hypothesis of schizophrenia: Making sense of it all. *Current Psychiatry Reports 2007 9:4*, *9*(4), 329–336. https://doi.org/10.1007/S11920-007-0041-7

Trubetskoy, V., Pardiñas, A. F., Qi, T., Panagiotaropoulou, G., Awasthi, S., Bigdeli, T. B., Bryois, J., Chen, C., Dennison, C. A., Hall, L. S., Lam, M., Watanabe, K., Frei, O., Ge, T., Harwood, J. C., Koopmans, F., Magnusson, S., Richards, A. L., Sidorenko, J., Wu, Y., Zeng, J., Grove, J., Kim, M., Li, Z., Voloudakis, G., Zhang, W., Adams, M., Agartz, I., Atkinson, E. G., Agerbo, E., Al Eissa, M., Albus, M., Alexander, M., Alizadeh, B. Z., Alptekin, K., Als, T. D., Amin, F., Arolt, V., Arrojo, M., Athanasiu, L., Azevedo, M. H., Bacanu, S. A., Bass, N. J., Begemann, M., Belliveau, R. A., Bene, J., Benyamin, B., Bergen, S. E., Blasi, G., Bobes, J., Bonassi, S., Braun, A., Bressan, R. A., Bromet, E. J., Bruggeman, R., Buckley, P. F., Buckner, R. L., Bybjerg-Grauholm, J., Cahn, W., Cairns, M. J., Calkins, M. E., Carr, V. J., Castle, D., Catts, S. V., Chambert, K. D., Chan, R. C. K., Chaumette, B., Cheng, W., Cheung, E. F. C., Chong, S. A., Cohen, D., Consoli, A., Cordeiro, Q., Costas, J., Curtis, C., Davidson, M., Davis, K. L., de Haan, L., Degenhardt, F., DeLisi, L. E., Demontis, D., Dickerson, F., Dikeos, D., Dinan, T., Djurovic, S., Duan, S., Ducci, G., Dudbridge, F., Eriksson, J. G., Fañanás, L., Faraone, S. V., Fiorentino, A., Forstner, A., Frank, J., Freimer, N. B., Fromer, M., Frustaci, A., Gadelha, A., Genovese, G., Gershon, E. S., Giannitelli, M., Giegling, I., Giusti-Rodríguez, P., Godard, S., Goldstein, J. I., González Peñas, J., González-Pinto, A., Gopal, S., Gratten, J., Green, M. F., Greenwood, T. A., Guillin, O., Gülöksüz, S., Gur, R. E., Gur, R. C., Gutiérrez, B., Hahn, E., Hakonarson, H., Haroutunian, V., Hartmann, A. M., Harvey, C., Hayward, C., Henskens, F. A., Herms,

S., Hoffmann, P., Howrigan, D. P., Ikeda, M., Iyegbe, C., Joa, I., Julià, A., Kähler, A. K., Kam-Thong, T., Kamatani, Y., Karachanak-Yankova, S., Kebir, O., Keller, M. C., Kelly, B. C., Khrunin, A., Kim, S., Klovins, J., Kondratiev, N., Konte, B., Kraft, J., Kubo, M., Kučinskas, V., Kučinskiene, Z. A., Kusumawardhani, A., Kuzelova-Ptackova, H., Landi, S., Lazzeroni, L. C., Lee, P. H., Legge, S. A., Lehrer, D. S., Lencer, R., Lerer, B., Li, M., Lieberman, J., Light, G. A., Limborska, S., Liu, C., Lönnqvist, J., Loughland, C. M., Lubinski, J., Luykx, J. J., Lynham, A., Macek Jr, M., Mackinnon, A., Magnusson, P. K. E., Maher, B. S., Maier, W., Malaspina, D., Mallet, J., Marder, S. R., Marsal, S., Martin, A. R., Martorell, L., Mattheisen, M., McCarley, R. W., McDonald, C., McGrath, J. J., Medeiros, H., Meier, S., Melegh, B., Melle, I., Mesholam-Gately, R. I., Metspalu, A., Michie, P. T., Milani, L., Milanova, V., Mitjans, M., Molden, E., Molina, E., Molto, E. D., Mondelli, V., Moreno, C., Morley, C. P., Muntané, G., Murphy, K. C., Myin-Germeys, I., Nenadić, I., Nestadt, G., Nikitina-Zake, L., Noto, C., Nuechterlein, K. H., O'Brien, N. L., O'Neill, A., Oh, S., Olincy, A., Ota, V. K., Pantelis, C., Papadimitriou, G. N., Parellada, M., Paunio, T., Pellegrino, R., Periyasamy, S., Perkins, D. O., Pfuhlmann, B., Pietiläinen, O., Pimm, J., Porteous, D., Powell, J., Quattrone, D., Quested, D., Radant, A. D., Rampino, A., Rapaport, M. H., Rautanen, A., Reichenberg, A., Roe, C., Roffman, J. L., Roth, J., Rothermundt, M., Rutten, B. P. F., Saker-Delye, S., Salomaa, V., Sanjuan, J., Santoro, M. L., Savitz, A., Schall, U., Scott, R. J., Seidman, L. J., Sharp, S. I., Shi, J., Siever, L. J., Sigurdsson, E., Sim, K., Skarabis, N., Slominsky, P., So, H., Sobell, J. L., Söderman, E., Stain, H. J., Steen, N. E., Steixner-Kumar, A. A., Stögmann, E., Stone, W. S., Straub, R. E., Streit, F., Strengman, E., Scott Stroup, T., Subramaniam, M., Sugar, C. A., Suvisaari, J., Svrakic, D. M., Swerdlow, N. R., Szatkiewicz, J. P., Tam Ta, T., Takahashi, A., Terao, C., Thibaut, F., Toncheva, D., Tooney, P. A., Torretta, S., Tosato, S., Battista Tura, G., Turetsky, B. I., Üçok, A., Vaaler, A., van Amelsvoort, T., van Winkel, R., Veijola, J., Waddington, J., Walter, H., Waterreus, A., Webb, B. T., Weiser, M., Williams, N. M., Witt, S. H., Wormley, B. K., Qin Wu, J., Xu, Z., Yolken, R., Zai, C. C., Zhou, W., Zhu, F., Zimprich, F., Atbaşoğlu, E. C., Ayub, M., Benner, C., Bertolino, A., Black, D. W., Bray, N. J., Breen, G., Buccola, N. G., Byerley, W. F., Chen, W. J., Cloninger, C. R., Crespo-Facorro, B., Donohoe, G., Freedman, R., Galletly, C., Gandal, M. J., Gennarelli, M., Hougaard, D. M., Hwu, H., Jablensky, A. V., McCarroll, S. A., Moran, J. L., Mors, O., Mortensen, P. B., Müller-Myhsok, B., Neil, A. L., Nordentoft, M., Pato, M. T., Petryshen, T. L., Pirinen, M., Pulver, A. E., Schulze,

T. G., Silverman, J. M., Smoller, J. W., Stahl, E. A., Tsuang, D. W., Vilella, E., Wang, S., Xu, S., Indonesia Schizophrenia Consortium, PsychENCODE, Psychosis Endophenotypes International Consortium, The SynGO Consortium, Adolfsson, R., Arango, C., Baune, B. T., Belangero, S. I., Børglum, A. D., Braff, D., Bramon, E., Buxbaum, J. D., Campion, D., Cervilla, J. A., Cichon, S., Collier, D. A., Corvin, A., Curtis, D., Di Forti, M., Domenici, E., Ehrenreich, H., Escott-Price, V., Esko, T., Fanous, A. H., Gareeva, A., Gawlik, M., Gejman, P. V., Gill, M., Glatt, S. J., Golimbet, V., Hong, K. S., Hultman, C. M., Hyman, S. E., Iwata, N., Jönsson, E. J., Kahn, R. S., Kennedy, J. L., Khusnutdinova, E., Kirov, G., Knowles, J. A., Krebs, M., Laurent-Levinson, C., Lee, J., Lencz, T., Levinson, D. F., Li, Q. S., Liu, J., Malhotra, A. K., Malhotra, D., McIntosh, A., McQuillin, A., Menezes, P. R., Morgan, V. A., Morris, D. W., Mowry, B. J., Murray, R. M., Nimgaonkar, V., Nöthen, M. M., Ophoff, R. A., Paciga, S. A., Palotie, A., Pato, C. N., Qin, S., Rietschel, M., Riley, B. P., Rivera, M., Rujescu, D., Saka, M. C., Sanders, A. R., Schwab, S. G., Serretti, A., Sham, P. C., Shi, Y., St Clair, D., Stefánsson, H., Stefansson, K., Tsuang, M. T., van Os, J., Vawter, M. P., Weinberger, D. R., Werge, T., Wildenauer, D. B., Yu, X., Yue, W., Holmans, P. A., Pocklington, Roussos, P., Vassos, E., Verhage, M., Visscher, P. M., Yang, J., Posthuma, D., Andreassen, O. A., Kendler, K. S., Owen, M. J., Wray, N. R., Daly, M. J., Huang, H., Neale, B. M., Sullivan, P. F., Ripke, S., Walters, J. T. R., O'Donovan, M. C. & Schizophrenia Working Group of the Psychiatric Genomics Consortium (2022). Mapping genomic loci implicates genes and synaptic biology in schizophrenia. *Nature 2022 604:7906*, *604*(7906), 502–508. https://doi.org/10.1038/s41586-022-04434-5

Urai, A. E., Braun, A., & Donner, T. H. (2017). Pupil-linked arousal is driven by decision uncertainty and alters serial choice bias. *Nature Communications*, *8*(1), 1–11.

Valton, V., Karvelis, P., Richards, K. L., Seitz, A. R., Lawrie, S. M., & Seriès, P. (2019). Acquisition of visual priors and induced hallucinations in chronic schizophrenia. *Brain*, *142*(8), 2523–2537. https://doi.org/10.1093/BRAIN/AWZ171

van Bergen, R. S., & Jehee, J. F. M. (2019). Probabilistic Representation in Human Visual Cortex Reflects Uncertainty in Serial Decisions. *The Journal of Neuroscience*, *39*(41). https://doi.org/10.1523/JNEUROSCI.3212-18.2019

van der Burg, E., Rhode, G., & Alais, D. (2019). Positive sequential dependency for face attractiveness perception. *Journal of Vision*, *19*(12), 1–16. https://doi.org/10.1167/19.12.6

van Rossum, J. M. (1966). The significance of dopamine-receptor blockade for the mechanism of action of neuroleptic drugs. *Archives Internationales de Pharmacodynamie et de Therapie*, *160*(2), 492–494.

VandenBos, G. (Ed.). (2007). APA Dictionary of Psychology. In *American Psychological Association*.

Wandinger, K.-P., Saschenbrecker, S., Stoecker, W., & Dalmau, J. (2011). Anti-NMDA-receptor encephalitis: a severe, multistage, treatable disorder presenting with psychosis. *Journal of Neuroimmunology*, *231*(1–2), 86–91.

Wang, Z., Yu, Z., Pan, Z., Zhao, K., Zhao, Q., Zhou, D., Shen, H. W., & Wu, X. (2018). Impaired binocular depth perception in first-episode drug-naive patients with schizophrenia. *Frontiers in Psychology*, *9*, 850. https://doi.org/10.3389/FPSYG.2018.00850/BIBTEX

Weilnhammer, V., Fritsch, M., Chikermane, M., Eckert, A. L., Kanthak, K., Stuke, H., Kaminski, J., & Sterzer, P. (2021). An active role of inferior frontal cortex in conscious experience. *Current Biology*, *31*(13), 2868-2880.e8. https://doi.org/10.1016/J.CUB.2021.04.043

Weilnhammer, V., Röd, L., Eckert, A.-L., Stuke, H., Heinz, A., & Sterzer, P. (2020). Psychotic Experiences in Schizophrenia and Sensitivity to Sensory Evidence. *Schizophrenia Bulletin*, *46*(4), 927–936.

Weilnhammer, V., Stuke, H., Hesselmann, G., Sterzer, P., & Schmack, K. (2017). A predictive coding account of bistable perception-a model-based fMRI study. *PLoS Computational Biology*, *13*(5), e1005536.

Woods, K. J. P., Siegel, M. H., Traer, J., & McDermott, J. H. (2017). Headphone screening to facilitate web-based auditory experiments. *Attention, Perception, & Psychophysics*, *79*(7), 2064–2072.

World Health Organization. (2019). *ICD-11: International classification of diseases (11th revision)*.

Xia, Y., Leib, A. Y., & Whitney, D. (2016). Serial dependence in the perception of attractiveness. *Journal of Vision*, *16*(15), 28.

Yang, A. C., & Tsai, S. J. (2017). New Targets for Schizophrenia Treatment beyond the Dopamine Hypothesis. *International Journal of Molecular Sciences*, *18*(8), 1689. https://doi.org/10.3390/IJMS18081689

Ziegler, M., & Lincoln, T. (2012). Schizophrenie. In *Klinische Psychologie und Psychotherapie für Bachelor* (pp. 153–162). https://link.springer.com/chapter/10.1007/978-3-642-16974-8_8

Statutory Declaration

“I, Anna-Lena Eckert, by personally signing this document in lieu of an oath, hereby affirm that I prepared the submitted dissertation on the topic “*Sensory processing in psychosis: Evidence for aberrant low-level information processing from multiple modalities and experiments*” (German title: “Sensorische Verarbeitung unter Psychose: Evidenz für aberrante Verarbeitung niedrig-hierarchischer Informationen aus multiplen Modalitäten und Experimenten.”) independently and without the support of third parties, and that I used no other sources and aids than those stated.
All parts which are based on the publications or presentations of other authors, either in letter or in spirit, are specified as such in accordance with the citing guidelines. The sections on methodology (regarding practical work, laboratory regulations, statistical processing) and results (regarding figures, charts, and tables) are exclusively my responsibility.

Furthermore, I declare that I have correctly marked all of the data, the analyses, and the conclusions generated from data obtained in collaboration with other persons, and that I have correctly marked my own contribution and the contributions of other persons (cf. declaration of contribution). I have correctly marked all texts or parts of texts that were generated in collaboration with other persons.

My contributions to any publications to this dissertation correspond to those stated in the below joint declaration made together with the supervisor. All publications created within the scope of the dissertation comply with the guidelines of the ICMJE (International Committee of Medical Journal Editors; http://www.icmje.org) on authorship. In addition, I declare that I shall comply with the regulations of Charité – Universitätsmedizin Berlin on ensuring good scientific practice.

I declare that I have not yet submitted this dissertation in identical or similar form to another Faculty.

The significance of this statutory declaration and the consequences of a false statutory declaration under criminal law (Sections 156, 161 of the German Criminal Code) are known to me.”

Date Signature

Declaration of own contribution to the publications

Anna-Lena Eckert contributed the following to the below listed publications:

Publication 1:

Eckert, A. L., Gounitski, Y., Guggenmos, M., & Sterzer, P. (2022). Cross-modality evidence for reduced choice history biases in psychosis prone individuals. *Schizophrenia Bulletin,* sbac168, DOI: https://doi.org/10.1093/schbul/sbac168

Contribution:

Anna-Lena Eckert (ALE) developed the rationale and idea for this study under supervision of Prof. Dr. med. Philipp Sterzer (PS) and Prof. Dr. Matthias Guggenmos (MG). She further developed all software for the experimental procedures and analyses, publicly available under https://github.com/eckertal/choicehistpsych. Data collection for all experiments in this publication was organized and performed by ALE, with the assistance of Yael Gounitski (YG), who recruited and collected data from half the participants included in *Experiment 2*. All software for analysis (psychometric functions, logistic regression models, repetition probability) and visualization (Figures 1-3, table 1 as well as all supplementary figures and tables in the publication) was developed by ALE, under supervision of MG. All figures and tables in the final publication were created by ALE. ALE curated the content of the study for an online conference on experimental cognitive science under supervision of PS. ALE wrote the first and all ensuing versions of the manuscript, which was reviewed and edited by all authors, and handled the submission and publication process with *Schizophrenia Bulletin.*

CRediT author statement: Conceptualization: ALE & PS, Methodology: ALE, MG & PS, Software: ALE, Validation: ALE & MG, Formal analysis: ALE, Investigation: ALE, Data Curation: ALE & YG, Writing – Original Draft: ALE, Writing – Reviewing and Editing: all authors, Visualization: ALE, Supervision: MG & PS, Funding acquisition: ALE & PS

Publication 2:

Weilnhammer, V., Röd, L., **Eckert, A. L.**, Stuke, H., Heinz, A., & Sterzer, P. (2020). Psychotic experiences in schizophrenia and sensitivity to sensory evidence. *Schizophrenia Bulletin*, *46*(4), 927-936.

Contribution:

The study rationale and development of experimental software was led by VW. ALE organized and performed the recruitment and data collection on the majority of the patient sample included in this study, under supervision of VW. LR collected the data from the remaining participants, under supervision and in collaboration with VW. VW wrote all analyses and performed the statistical tests. VW created all figures in the final manuscript (Figures 1-4, Table 1, and all supplementary figures and tables in the published manuscript). VW wrote the initial draft of the manuscript and handled the publication process with *Schizophrenia Bulletin*. ALE reviewed and edited the manuscript alongside all authors. ALE curated the content for a conference poster presentation.

CRediT author statement: Conceptualization: VW & PS, Methodology: VW & PS, Software: VW, Formal analysis: VW, Investigation: VW, LR, ALE, Data Curation: LR, ALE, VW, Writing – Original Draft: VW, Writing – Reviewing and Editing: all authors, Visualization: VW, Supervision: PS, Funding acquisition: VW, PS

_____

Signature, date, and stamp of first supervising university professor / lecturer

_____

Signature of doctoral candidate

Excerpt from Journal Summary List

"**Eckert, A. L.**, Gounitski, Y., Guggenmos, M., & Sterzer, P. (2022). Cross-modality evidence for reduced choice history biases in psychosis prone individuals. *Schizophrenia bulletin*, sbac168, DOI: https://doi.org/10.1093/schbul/sbac168"

Schizophrenia Bulletin is among the top **7%** journals listed for the field of *Psychiatry*.

Journal Data Filtered By: **Selected JCR Year: 2020*** Selected Editions: SCIE, Selected Categories: **"PSYCHIATRY"** Selected Category Scheme: WoS **Gesamtanzahl: 156 Journale**				
Rank	**Full Journal Title**	**Total Cites**	**Journal Impact Factor**	**Eigenfactor Score**
1	World Psychiatry	9,619	49.548	0.020030
2	Lancet Psychiatry	14,839	27.083	0.036240
3	JAMA Psychiatry	19,105	21.596	0.052990
4	AMERICAN JOURNAL OF PSYCHIATRY	48,206	18.112	0.031970
5	PSYCHOTHERAPY AND PSYCHOSOMATICS	6,123	17.659	0.006750
6	MOLECULAR PSYCHIATRY	28,622	15.992	0.046220
7	BIOLOGICAL PSYCHIATRY	50,155	13.382	0.045540
8	JOURNAL OF NEUROLOGY NEUROSURGERY AND PSYCHIATRY	37,094	10.154	0.026380
9	BRITISH JOURNAL OF PSYCHIATRY	30,003	9.319	0.019160
10	SCHIZOPHRENIA BULLETIN	21,642	9.306	0.023290
…				

* the journal's 2022 impact factor was not known when this thesis was written.

Weilnhammer, V., Röd, L., **Eckert, A. L.**, Stuke, H., Heinz, A., & Sterzer, P. (2020). Psychotic experiences in schizophrenia and sensitivity to sensory evidence. *Schizophrenia bulletin*, *46*(4), 927-936.

Schizophrenia Bulletin is among the top **7%** journals listed for the field of *Psychiatry*.

Journal Data Filtered By: **Selected JCR Year: 2020** Selected Editions: SCIE, Selected Categories: **"PSYCHIATRY"** Selected Category Scheme: WoS **Gesamtanzahl: 156 Journale**				
Rank	**Full Journal Title**	**Total Cites**	**Journal Impact Factor**	**Eigenfactor Score**
1	World Psychiatry	9,619	49.548	0.020030
2	Lancet Psychiatry	14,839	27.083	0.036240
3	JAMA Psychiatry	19,105	21.596	0.052990
4	AMERICAN JOURNAL OF PSYCHIATRY	48,206	18.112	0.031970
5	PSYCHOTHER-APY AND PSY-CHOSOMATICS	6,123	17.659	0.006750
6	MOLECULAR PSYCHIATRY	28,622	15.992	0.046220
7	BIOLOGICAL PSYCHIATRY	50,155	13.382	0.045540
8	JOURNAL OF NEUROLOGY NEUROSUR-GERY AND PSY-CHIATRY	37,094	10.154	0.026380
9	BRITISH JOUR-NAL OF PSYCHI-ATRY	30,003	9.319	0.019160
10	SCHIZOPHRENIA BULLETIN	21,642	9.306	0.023290
…				

Printing copies of the publications

Publication 1

Eckert, A. L., Gounitski, Y., Guggenmos, M., & Sterzer, P. (2022). Cross-modality evidence for reduced choice history biases in psychosis prone individuals. *Schizophrenia Bulletin,* sbac168, https://doi.org/10.1093/schbul/sbac168.

Schizophrenia Bulletin
https://doi.org/10.1093/schbul/sbac168

Cross-Modality Evidence for Reduced Choice History Biases in Psychosis-Prone Individuals

Anna-Lena Eckert[*,1,2,3,●], Yael Gounitski[3], Matthias Guggenmos[3,4,5], and Philipp Sterzer[2,3,5,6]

[1]Charité – Universitätsmedizin Berlin, Einstein Center for Neurosciences Berlin, Charitéplatz 1, 10117 Berlin, Germany; [2]Bernstein Center for Computational Neuroscience Berlin, Unter den Linden 6, 10099 Berlin, Germany; [3]Department of Psychiatry and Neurosciences, Campus Mitte, Charité – Universitätsmedizin Berlin, Charitéplatz 1, 10117 Berlin, Germany; [4]Health and Medical University, Institute for Mind, Brain and Behavior, Olympischer Weg 1, 14471 Potsdam, Germany; [5]University of Basel, Department of Psychiatry (UPK), Wilhelm-Klein-Strasse 27, 4002 Basel, Switzerland

[6]These authors contributed equally.

[*]To whom correspondence should be addressed; Department of Psychiatry and Neuroscience, Campus Mitte Charité – Universitätsmedizin Berlin, Charitéplatz 1, 10117 Berlin, e-mail: anna-lena.eckert@charite.de

***Objectives*: Predictive processing posits that perception emerges from inferential processes within a hierarchical cortical system. Alterations of these processes may result in psychotic experiences, such as hallucinations and delusions. Central to the predictive processing account of psychosis is the notion of aberrant weights attributed to prior information and sensory input. Based on the notion that previous perceptual choices represent a relevant source of prior information, we here asked whether the propensity towards psychotic experiences may be related to altered choice history biases in perceptual decision-making. *Methods*: We investigated the relationship between choice history biases in perceptual decision-making and psychosis proneness in the general population. Choice history biases and their adaptation to experimentally induced changes in stimulus serial dependencies were investigated in decision-making tasks with auditory *(experiment 1)* and visual *(experiment 2)* stimuli. We further explored a potential compensatory mechanism for reduced choice history biases by reliance on predictive cross-modal cues. *Results*: In line with our preregistered hypothesis, psychosis proneness was associated with decreased choice history biases in both experiments. This association is generalized across conditions with and without stimulus serial dependencies. We did not find consistent evidence for a compensatory reliance on cue information in psychosis-prone individuals across experiments. *Conclusions*: Our results show reduced choice history biases in psychosis proneness. A compensatory mechanism between implicit choice history effects and explicit cue information is not supported unequivocally by our data.**

Key words: predictive processing/psychosis/choice history bias/perceptual decision/making/computational psychiatry

Introduction

Predictive processing theory conceptualizes prediction as a core strategy of the brain.[1,2] Since the brain does not have direct access to its surroundings, it is thought to entertain a hierarchical model of the world. This model is constrained by sensory information and constantly updated by mismatches between model predictions and sensory data (prediction errors).[3–5] In Bayesian terms, predictions and sensory information are modeled as prior belief (prior) and likelihood, respectively. They are represented by probability distributions and combined to compute an updated belief, the posterior. Critically, the weighting of prior and likelihood in computing the posterior is determined by their respective precisions: Low prior precision and high likelihood precision will result in large belief updates by precision-weighted prediction errors, and vice versa.[5,6]

It has been proposed that hallucinations and delusions, core features of psychosis, correspond to aberrant inference resulting from altered precision weighting.[4,6–10] Specifically, a reduced precision of priors, relative to the likelihood, may lead to increased precision-weighted prediction errors and thus enhanced weighting of sensory information relative to model predictions. The notion of imprecise priors is supported by the observation that individuals with psychosis are less susceptible to some visual illusions, which—in Bayesian terms—reflect reliance on precise perceptual priors.[11,12] Conversely, there is evidence for a higher

sensitivity to sensory information in individuals with psychosis.[13] In an attempt to compensate for perceptual uncertainty resulting from reduced prior precision at low hierarchical levels, the psychosis-prone brain may form overly precise beliefs at higher hierarchical levels.[7,10,14,15] Indeed, perceptual disturbances such as hallucinations[16,17] and the tenacious persistence of delusions in psychosis[4,10,18] have been related to increased prior precision.

A likely source for the formation of perceptual priors are previous perceptual judgments. In perceptual decision-making tasks, observers are required to make perceptual judgments under uncertainty, usually by choosing between two or more alternatives. A well-documented phenomenon in such tasks is that the current perceptual choice can be biased towards previous choices. Such *choice history biases* have been reported across a wide range of tasks and stimuli including visual motion,[19–21] orientation,[22–26] numerosity,[27,28] spatial location,[29] and face identity[30–32] but also in auditory two-tone discrimination,[33] tactile stimuli discrimination,[34] and time perception.[35] The influence of previous on current perceptual choices occurs implicitly[36,37] and has been conceptualized as an adaptive strategy to cope with uncertainty, whereby previous perceptual choices are used to form ad-hoc priors for the processing of subsequent sensory events.[23,38–40,41,42] Indeed, choice history biases scale with uncertainty[19,21,43,44] and adapt to environmental statistics.[21,45] Choice history biases, therefore, offer an opportunity to operationalize the role of implicit forms of prior beliefs in perceptual inference and thereby investigate inference mechanisms in relation to psychosis.

Based on this reasoning, we here examined the relationship between choice history biases and psychosis proneness in healthy individuals. To test whether individual differences would generalize across sensory modalities, we performed two experiments with analogous perceptual tasks in the auditory and visual modalities. Participants had to make perceptual choices under uncertainty but did not receive feedback on their choices. To manipulate the relevance of choice history, we implemented block-wise statistical regularities so that stimuli were presented either in random- or auto-correlated order. In addition, more explicit prior beliefs were induced by cues that were predictive of the upcoming stimulus. Given the more implicit nature of choice history effects, we here refer to choice history biases as reflecting lower-level priors, whereas we refer to the more explicit prior beliefs induced by predictive cues as higher-level priors. We note that this operationalization may deviate from classical models.[46] Still, it allows for an empirical investigation of different types of prior information, which we assume to be implemented at different hierarchical levels in the brain,[8,47,48] in relation to psychosis proneness. For the present work, we thus use the terminology as outlined above.

Our main hypothesis was that higher psychosis proneness would be associated with a reduced influence of choice history. We further explored whether choice history biases adapt to block statistics and the modulation of this adaptation by psychosis proneness. Finally, we investigated the relationship between psychosis proneness and the reliance on predictive cues, based on the notion that reduced weighting of prior information at lower hierarchical levels in psychosis proneness may be compensated by an increased reliance on higher-level prior beliefs.[10,15]

Methods

We conducted two behavioral experiments to investigate choice history biases in perceptual decision-making and its relationship to psychosis proneness (total $N = 154$, a priori sample size estimation with 1-$\beta = 0.8$). Both experiments were similar in structure, but differed in stimulus modality, apparatus, and setting. For more details on experimental methods, (see Supplementary Material S1). Across experiments, participants with average performance levels of <60% and >90% were excluded. As stated in our preregistrations, this maximizes statistical sensitivity for choice history effects. Both experiments were piloted.

Experiment 1

Experiment 1 was an online, gamified auditory perceptual decision-making task.[49] The experiment was preregistered (asPredicted.org, #50562), approved by the ethics committee of Charité – Universitätsmedizin Berlin (#EA1/134/20), and in line with the Declaration of Helsinki. All participants gave informed consent and received a monetary reward of £7.30/ hour. Participants were naïve to the purpose of the experiment and reported no hearing impairments. One-hundred-and-fifty participants were recruited via Prolific,[50] of which 113 were included (24.7 years ± 7.34 standard deviation (SD), 75 male). The experiment was created using Gorilla.[51] In the task, trains of click sounds were presented (see Supplementary Material S1). Participants had to indicate the ear to which more click sounds were presented (*target ear* in the following). There were 6 levels of discriminability, determined by the difference in clicks between the left and right channels. To induce high-level beliefs about the auditory stimulus, a visual cue was presented, which predicted the target ear accurately in 75%. Stimulus-response mappings were randomized trial-wise to preclude motor confounds. The experiment consisted of 8 blocks à 48 trials, resulting in 384 trials (~45 min). There were two types of blocks. In N-type (or neutral) blocks, the target ear was chosen randomly on each trial. In R-type (or repetitive) blocks, the target ear of trial $t - 1$ was repeated in trial t in 80% of subsequent trials, increasing the relevance of information from previous trials. Block sequences were either NRRNRNNR or RNNRNRRN,

counterbalanced across participants. Several measures to ensure data quality were implemented, such as attention- and headphone checks.[52] Upon completing all blocks, participants were debriefed and received global performance feedback.

Experiment 2

Experiment 2 was a laboratory-based visual decision-making task using random dot kinematograms (RDKs, **S1**). The experiment was preregistered (asPredicted.org, #71784) and approved by the ethics committee of Charité – Universitätsmedizin Berlin (#EA1/198/19). Experimental procedures were in line with the Declaration of Helsinki. All participants gave written informed consent. Fifty healthy participants were recruited via public and institutional participant pools, of which 43 were included (16 male, average 31 years, ± 10.6 SD). All participants had normal or corrected-to-normal vision and were naïve to the purpose of the experiment. Upon completion, participants received a monetary reward of 20€. The experiment was created using PsychoPy (v.2020.1.3).[53] Participants were asked to indicate the global motion direction of RDKs (left or right on the horizontal axis). There were six levels of discriminability, determined by the proportion of coherently moving dots. To induce high-level beliefs about the stimulus, an auditory cue preceded stimulus presentation. The cue accurately predicted the RDK's global motion direction in 75% of trials. Stimulus-response mappings were randomized trial-wise. The experiment consisted of 8 blocks (96 trials per block, 768 total). There were two types of blocks. In neutral (N-type) blocks, the stimulus' global motion direction was selected randomly. In repetitive (R-type) blocks, the motion direction in trial *t-1* was repeated in 80% of subsequent trials, increasing the relevance of choice history. There were two possible block sequences, NRRNRNNR or RNNRNRRN, which were counterbalanced across participants. In a subset of 14 participants, the block sequences differed slightly (counterbalanced NRNRNRNR or RNRNRNRN), which we accounted for in our statistical analysis. Upon completion, participants were debriefed and received global feedback about their performance.

Questionnaires

After the experimental tasks of both *Experiments 1* and *2*, participants completed 2 validated questionnaires measuring psychosis proneness, the Peters et al. Delusions Inventory, PDI,[54] and the Cardiff Anomalous Perceptions Scale, CAPS.[55] A global psychosis-proneness score (PPS) per subject was calculated by summing the global z-transformed CAPS- and PDI sum scores. Considering usually high correlations between CAPS and PDI scores,[8] our main analyses utilized this global PPS. To elucidate the contributions of delusion- and hallucination proneness separately, we performed exploratory analyses on PDI- and CAPS scores (Supplementary Material S4).

Statistical Analyses

Behavioral data were analyzed with a mixed logistic regression model. The model was fit using R[56] (v.4.1.1), the lmer4 package[57] (v.1.1-27.1), using maximum likelihood, and the optimx package[58] (v. 2021-10.12), with method nlminb for quadratic optimization. Explained variance or R^2 was computed using the MuMIn package[59] (v.1.43.17). All variables were z-transformed. Variance Inflation factors (VIF) were computed using the car library (v.3.0-12). The logistic model was defined as (R-style notation):

$$r_t = s_t * d_t + s_{t-1} * d_{t-1} + r_{t-1} * PPS * blocktype + c_t * PPS * blocktype + (1|subject) + (1|block : subject) \quad (1)$$

The dependent variable was the choice (or response) in trial t (r_t, 0 = right, 1 = left). Considered predictors were the current (s_t) and previous (s_{t-1}) stimulus (0 = right, 1 = left), discriminability of current and previous trial (d_t and d_{t-1}; Δclicks (1–6) in *experiment 1* and coherence levels (0.005–0.5) in *Experiment 2*), block type (*block type*, where 0 = repetitive, 1 = neutral blocks), current cue (c_t, 0 = right, 1 = left) and *PPS*. Interactions were defined along our hypotheses: An interaction of the previous choice and *PPS* and an interaction of cue and *PPS*, while considering the influence of the block statistics (ie, *block type*). Note that we focused our analyses of choice history on the immediately preceding choice (ie, r_{t-1}), which has been found to exert the strongest bias.[21,25,60] To illustrate choice history effects and their adaptation to block statistics, we fitted psychometric functions of the form:

$$p(r = 1) = \frac{1}{1 + exp\left(\frac{\pi(x-\delta)}{\sqrt{3}\sigma}\right)} \quad (2)$$

We assumed a logistic noise distribution with a variance $\sigma^2 = \frac{\sigma^2\pi^2}{3}$ where σ captures decision noise. δ is a systematic bias towards right (r = 0, δ >0) or left (r = 1, δ < 1) choices, and x represents the stimulus variable. We split the data with respect to the previous choice and fit two psychometric functions representing trials preceded by "left" or "right" choices, respectively.

To further illustrate the relationship between choice history and psychosis proneness, we analyzed the correlation between PPS and the tendency to repeat the previous choice (repetition probability). The mean repetition probability per individual was given by summing over all instances of choice repetitions and dividing by the total

Table 1. Distribution of Age and Psychosis Proneness Scores (Mean ± Standard Deviation) Across Experiments

	Age	Performance	PDI	CAPS
Experiment 1	24.79 ± 7.34	80.1% ± 7.1	6.6 ± 3.1 (range: 0–17)	6.5 ± 5.2 (range 0–28)
Experiment 2	31.0 ± 10.6	71.9% ± 5.0	7.3 ± 6.9 (range 0–35)	5.0 ± 5.2 (range 0–20)

number of trials. Subject-specific repetition probabilities were correlated with PPS.[14,18]

Results

In *Experiment 1*, participants performed perceptual decisions on auditory stimuli in an online, gamified 2AFC task.

On average, task performance was at 80.1% correct responses (± 7.1 *SD*), ranging from 61.2% to 89.8%. 2.1% of trials timed out (response time >2500 ms) and were excluded from further analyses.

Mean PDI sum score was 6.6 (± 3.1 SD), with sum scores ranging from 0 to 17. Mean CAPS score was 6.5 (± 5.2 SD), with sum scores ranging from 0 to 28. CAPS and PDI scores were strongly correlated ($r = 0.71$, $P < .001$, table 1; Supplementary Material S2).

In *Experiment 2*, participants made decisions on RDK stimuli with 71.9% average accuracy (± 5.0 SD). Performance levels ranged from 65.5% to 79.3% of correct choices. Less than 1% of trials timed out (response time >2500ms) and were excluded from further analyses.

Mean CAPS score was 5.0 (± 5.2 SD; range 0–20), and mean PDI score was 7.3 (± 6.9 SD, range 0–35). The scores were strongly correlated ($r = 0.82$, $P < .001$, **S2**).

We fit separate trial-by-trial logistic mixed regression models for both datasets. The logistic choice model allowed us to estimate the influence of eg, stimulus, cue, and previous trial events and their interactions with PPS on current choice. Residuals were normally distributed in both *Experiment 1* (scaled residuals, *min* = −6.67, *max* = 6.12, $1Q = -0.49$, $3Q = 0.47$; number of observations = 42 601) and *Experiment 2* model fits (scaled residuals, *min* = −11.38, *max* = 15.75, $1Q = -0.63$, $3Q = 0.61$, number of observations = 31 087). Marginal corrected R^2 values were $R^2 = 0.49$ for *experiment 1* and $R^2 = 0.55$ for *Experiment 2*. Maximum VIF in *Experiment 1* was VIF = 1.33 (previous stimulus), in *Experiment 2,* it was VIF = 1.67 (previous stimulus), indicating no significant problems with collinearity.

Choice History Biases in Perceptual Decision-Making

We found a significant main effect of previous choice in *Experiment 1* and *Experiment 2* (see also figure 1; *Experiment 1:* $\beta = 0.15 \pm 0.02$, $P < .001$*; Experiment 2:* $\beta = 0.13 \pm 0.02$, $P < .001$). The general effect of previous choice is visible as a horizontal offset between psychometric functions fitted on previous left vs previous-right choices (figure 2).

Choice history bias was stronger in repetitive (coded 0) versus neutral (coded 1) blocks in both experiments, as indicated by significant interactions between previous choice and block type (*Experiment 1:* $\beta = -0.04 \pm 0.01$, $P = .001$; *Experiment 2*: $\beta = -0.05 \pm 0.01$, $P = .005$, figure 2). Thus, participants' choice history biases adapted to block structure.

Choice History Biases Decrease With Psychosis Proneness

In line with our main hypothesis, the logistic choice model revealed a significant interaction between PPS and previous choice in both experiments (*Experiment 1*: $\beta = -0.06 \pm 0.01$, $P < .001$; *Experiment 2*: $\beta = -0.09 \pm 0.01$, $P < .001$). The negative weight indicates decreasing choice history biases with increasing PPS. The relationship between participant-specific choice repetition probabilities and PPS is further illustrated in figure 3. It held across neutral and repetitive blocks in both experiments (Supplementary Material S3). We further found robust interactions between individual CAPS- and PDI scores and choice history (Supplementary Material S4).

The 3-way interaction between choice history, PPS, and block type was indistinguishable from 0 in *experiment 1* ($\beta = 0.01 \pm 0.01$; $P = .63$) and trend-wise significant in *experiment 2* ($\beta = 0.02 \pm 0.01$, $P = .09$). The trend in *experiment 2* suggests that the negative choice history * PPS interaction tended to be more pronounced in repetitive blocks (figure 3, Supplementary Material S7).

Psychosis Proneness and High-Level Prior Beliefs

Finally, we tested our exploratory hypothesis that decreased choice history biases in psychosis-prone individuals are compensated by an increased reliance on cue information. We confirmed that the cue exerted a significant main effect on perceptual choices (see also Supplementary Material S3, S6; *Experiment 1*: $\beta = 0.22 \pm 0.01$, $P < .001$; *Experiment 2*: $\beta = 0.54 \pm 0.01$, $P < .001$). The interaction effect between cue and PPS was inconsistent between experiments. In *Experiment 1,* the interaction was negative ($\beta = -0.05 \pm 0.01$, $P < .001$). Thus, contrary to our hypothesis, we here found reduced cue reliance in individuals with higher PPS. In contrast, *Experiment 2* yielded a positive interaction between cue

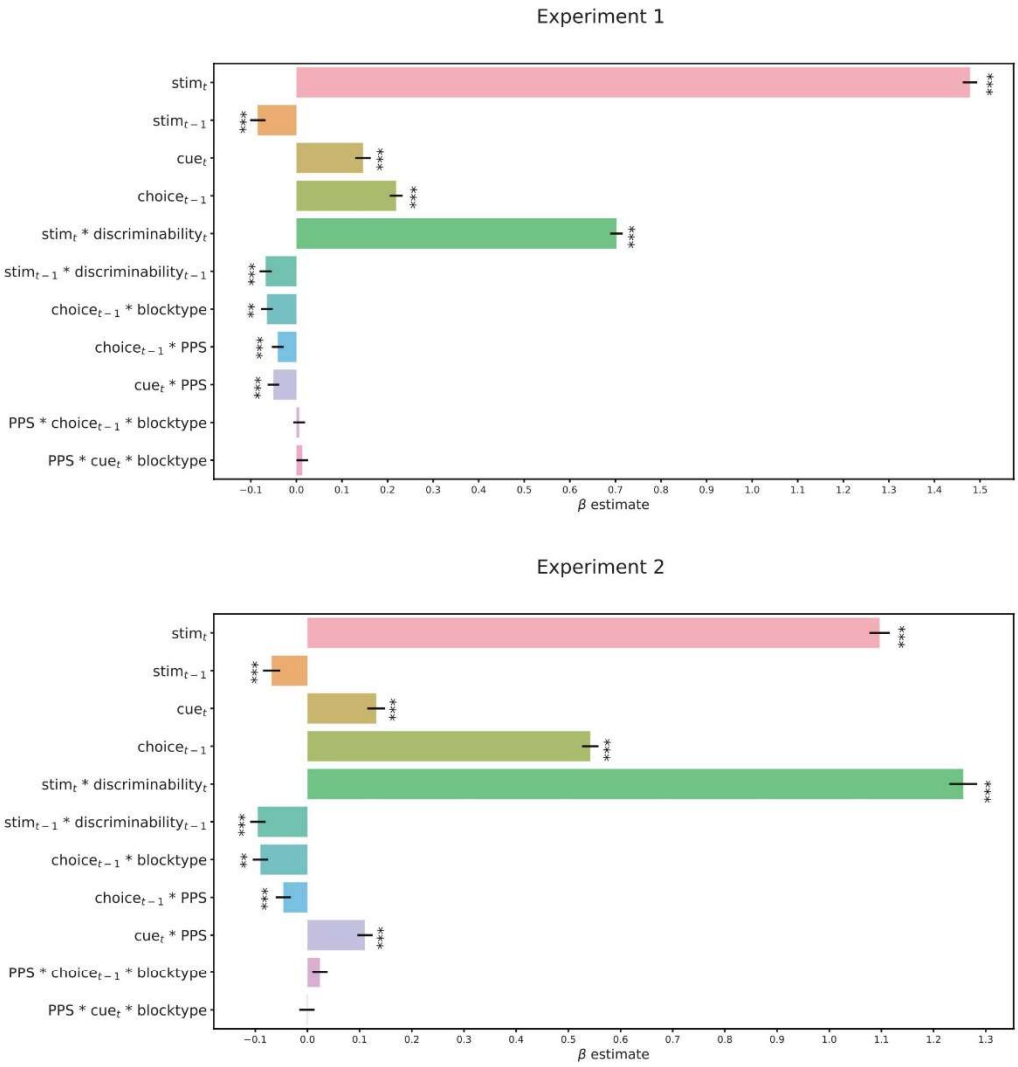


Fig. 1. Coefficients of the logistic choice model. **(A)** *Experiment 1*. **(B)** *Experiment 2*. Colored bars: Coefficient estimates, black lines: Standard errors. $stim_t/stim_{t-1}$: (previous) stimulus, *PPS*: psychosis proneness score. Only parameters of interest are shown (S3.1&2 for detailed estimates).

and PPS ($\beta = 0.11 \pm 0.01$, $P < .001$). When examining the interactions between cue and PDI and CAPS scores separately, we found that cue reliance was modulated by PDI scores in both experiments, albeit in opposite directions. The interaction of cue and CAPS scores did not generalize across experiments (see Supplementary Material S4). Results are hence inconsistent across experiments and measures. The interaction between cue and PPS was not significantly modulated by block type.

Discussion

In the present work, we examined how the effects of different types of prior information varied with psychosis proneness in visual and auditory decision-making. Choice history significantly influenced perceptual decision-making and adapted to statistical regularities in stimulus sequences in the visual modality. Supporting our main hypothesis, choice history biases decreased with increasing psychosis proneness across modalities.

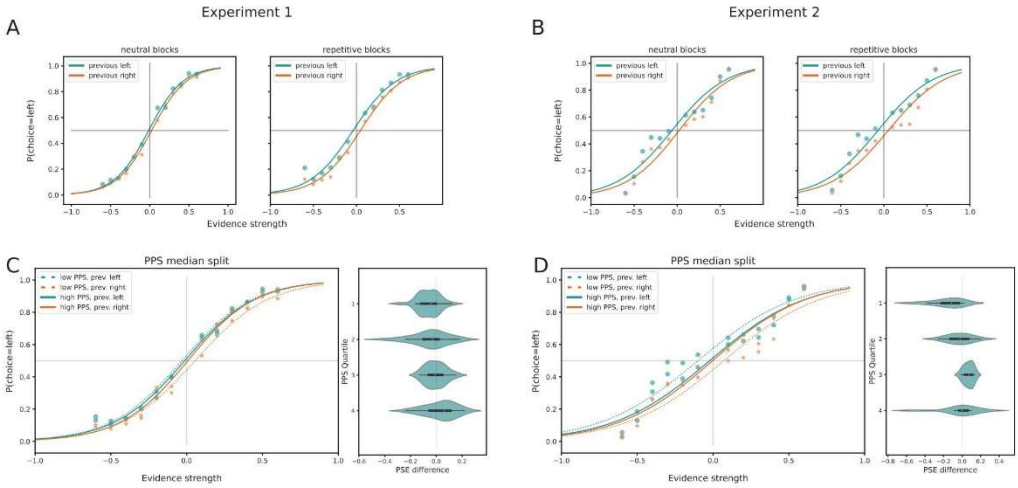


Fig. 2. Psychometric functions (PMF). PMFs show the probability of a "left" choice, separately for trials preceded by "left" (turquoise) and "right" (orange) choices. Markers represent averaged data per discriminability level. Data are either separated by block types (**A, B**) or psychosis proneness scores (PPS, **C, D**). Violin plots (C, D) show shifts in point of subjective equality between left and right PMF per PPS quartile.

The negative relationship between psychosis proneness and choice history was stronger in repetitive blocks and thus a setting in which the reliance on choice history was adaptive (significantly so only in the visual modality). Finally, we explored the impact of explicit cue information on perceptual decision-making but found no conclusive evidence for an effect of psychosis proneness.

Overall, we found robust evidence for our main hypothesis of reduced choice history biases in psychosis proneness, which generalized across perceptual modalities, experimental settings, and block statistics. This finding may be in line with the predictive processing account of psychosis, according to which reduced reliance on low-level prior information leads to insufficiently constrained internal models.[4,7,10,11] Considering delusion- and hallucination proneness separately, we found that choice history was modulated by both. This may suggest that delusions and hallucinations share a common underlying mechanism, rooted in aberrant perceptual inference.

When probing the adaptivity of choice history biases through a repetitive stimulus sequence, we found significant adaptation to block statistics in both experiments, but only *Experiment 2* showed a trend towards reduced adaptation of choice history biases in psychosis-prone individuals. Thus, taken together we found no consistent evidence for altered adaptivity of choice history biases to block statistics in psychosis proneness.

Regarding our hypothesis of a compensatory, increased effect of an explicit, cross-modal cue,[7,10,18] we found conflicting evidence in *Experiments 1* and *2*. In *Experiment 1*, cue reliance decreased in more psychosis-prone individuals, while in *Experiment 2*, it increased with psychosis proneness. This inconsistency may be due to the difference between the cues across experiments: In *Experiment 1, visual* cues were implemented to induce high-level beliefs about auditory stimuli, while in *Experiment 2*, *auditory* cues were implemented to induce beliefs about visual stimuli. It is possible that the auditory cue in *Experiment 2* was more salient. Also, reduced attentional levels in the online setting cannot be ruled out. This may have been especially true in more psychosis-prone participants, leading to a decrease in cue reliance in *Experiment 1*. Overall, these inconsistencies preclude strong conclusions regarding compensatory mechanisms between prior information on different hierarchical levels, as suggested in the context of predictive processing.[10]

It should be noted that our trial-wise manipulation of cue information through cross-modal, explicit cues differed from previous studies that had pointed towards strong priors in psychosis. Powers et al.[17] found that learned expectations had an increased influence on perception in hallucinating individuals. Possibly, if our tasks had involved learning cue-stimulus associations, more psychosis-prone individuals might have shown stronger cue reliance. Schmack and colleagues[14] manipulated higher-level beliefs by inducing abstract beliefs about the effect of viewing glasses in a placebo-like manner and found an increased influence of these beliefs on perception in psychosis-prone individuals. Others have manipulated high-level beliefs by varying semantic context[52] or learned letter-sound associations.[53] In contrast to these manipulations, trial-wise cues as used here operate on

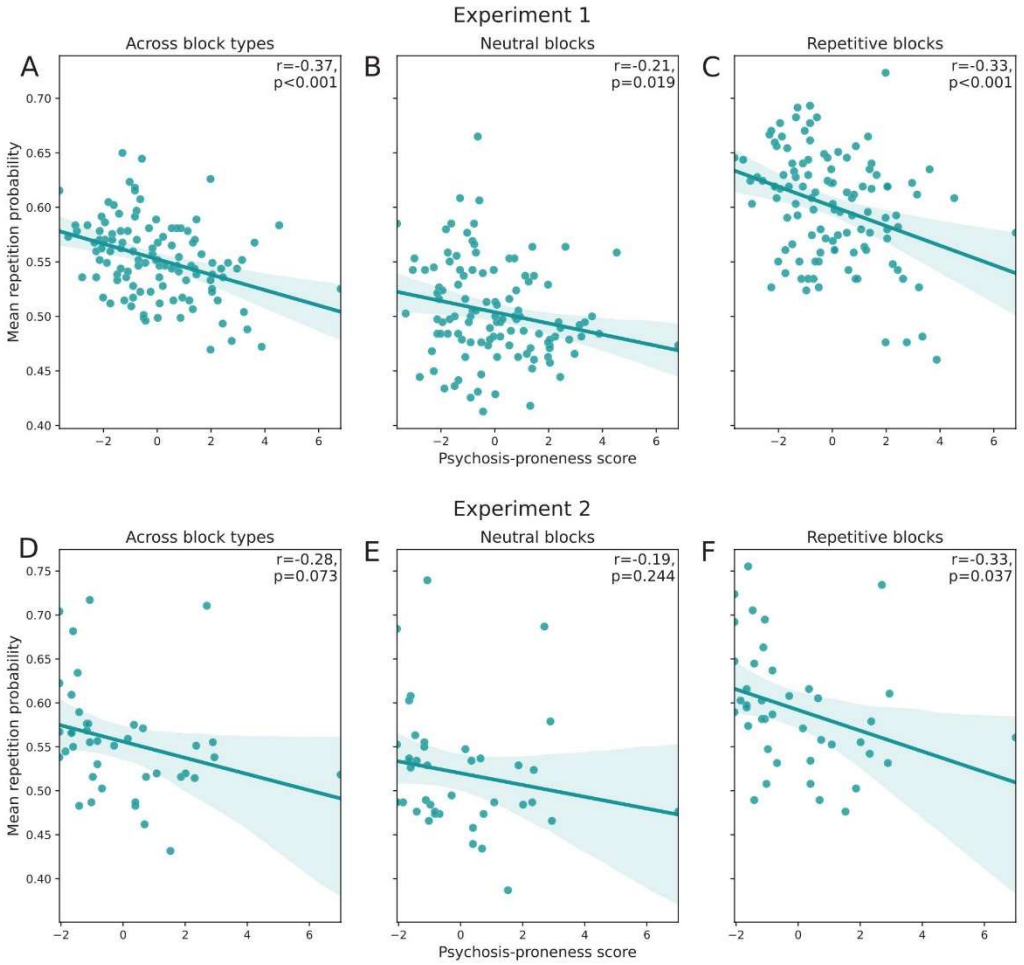


Fig. 3. Repetition probability decreases with PPS. **A–C** *experiment 1*. (**A**) across block types, (**B**) neutral blocks, (**C**) repetitive blocks. **D–F** *experiment 2*, across block types (**D**), for neutral (**E**), and repetitive blocks (**F**).

shorter timescales. Still, the cross-modal cues can be regarded as high-level information as they provide explicit cognitive information (ie, probability of the next percept) and require integration at a higher modality-independent processing level. However, the hypothesized over-reliance on high-level information in psychosis-proneness may require the buildup of priors at longer timescales. The relevance of different types of high-level priors for psychosis, therefore, needs further investigation.

The main finding of decreasing choice history biases in psychosis proneness extends recent work by Stein and colleagues in patients with schizophrenia and anti-NMDAr-encephalitis. Both patient groups showed decreased effects of trial history in a spatial working memory task compared to controls.[29] In the case of acute anti-NMDAr-encephalitis, choice history effects normalized with recovery, suggesting the importance of NMDAr for psychosis and history effects. In combination with our findings in a non-clinical context, this suggests that reduced weighting of choice history in perceptual information processing may represent a trait marker predisposing for psychotic experiences.[29]

Although we consider the generalization of our main hypothesis across modalities and experimental settings as a strength, this heterogeneity may have been a limiting factor. In particular, *Experiment 1* was performed as an online study, which may lead to concerns regarding data quality.[61,62] Therefore, we implemented several data

quality checks. Additionally, the *Experiment 1* task was easier than the visual task of *Experiment 2*. These differences may have contributed to the inconsistency between experiments with regard to the effects of predictive cues as discussed above. Future research should control for task performance, eg, via adaptive stair casing procedures, when investigating these effects in the auditory modality.

Overall, our results support the notion of decreased choice history biases as a trait marker of psychosis. This seems to hold for both diagnosed patients[29] and across the psychosis spectrum generally. Further investigations of choice history biases in other diagnostic groups reporting psychotic experiences, such as bipolar disorder, Parkinson's-or Alzheimer's disease, will clarify whether the reduced weighting of choice history is a general mechanism underlying psychotic experiences beyond diagnostic categories.

Additionally, computational modeling may provide fruitful avenues towards an improved understanding of perceptual inference in psychosis.[7,10,63] Specifically, Bayesian models of perception may help to explicitly model priors, hidden states, and precision estimates and their relationship to psychosis proneness.[64] While the application of such Bayesian modeling approaches is an interesting avenue for future research, it is beyond the scope of the present study, which was optimized for quantifying choice history effects and their modulation by psychosis proneness. Similarly, modeling of evidence accumulation, eg, using drift-diffusion models, may elucidate the mechanisms underlying aberrant perceptual decision-making in more psychosis-prone individuals.[65] However, the use of drift-diffusion modeling was beyond the scope of the current study, especially as we did not collect the necessary reaction time data.

An open question relates to the neural underpinnings of reduced choice history biases in clinical and subclinical psychosis. The exact origin and implementational level of choice history biases are under debate, with several studies suggesting an important role in post-perceptual processes.[34,42,46,66] Previous neuro-imaging work in healthy individuals has also shown a neural substrate for choice history biases in the early visual cortex, which is, however, compatible with the involvement of post-perceptual processes.[67] It is currently unclear how these earlier findings implicating visual cortex translate to other perceptual modalities and how they might relate to altered perceptual inference in psychosis. To discern subtle aberrancies regarding different types of prior beliefs, as well as a sharpened precision of sensory feedforward signals, future studies may use layer-specific neuroimaging to constrain predictive processing models of psychosis.[4,68,69] Moreover, it should be noted that, given the abovementioned uncertainties regarding neural implementation, our labeling of choice history biases as a type of low-level prior should be interpreted in relative terms (compared to cross-modal cue information) and is restricted to the context of this study. Based on previous work, one might speculate that the proposed implicit priors reflected in choice history biases in our study involve sensory cortices and parts of parietal cortex (assuming the biases are of perceptual origin), while higher-level priors as those induced by predictive cues likely rely on associative, context-sensitive brain regions such as hippocampus and prefrontal cortex.[34,48,67,70]

In conclusion, the present work provides cross-modal evidence for decreased choice history biases in individuals prone to psychotic experiences. The hypothesized compensatory mechanisms of an increased reliance on cues was not supported across modalities. Taken together, our results emphasize the notion of a reduced influence of prior information in perceptual inference as a hallmark of psychotic experience.

Supplementary Material

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

Funding

The authors report no conflicts of interest. We thank Daniel Schulze for statistical consulting and Anke Braun and Veith Weilnhammer for helpful discussions. This research was funded by the German Research Foundation (grants GU 1845/1-1 and STE 1430/8-1) and the Einstein Center for Neurosciences Berlin (ALE). PS was supported by a Clinical Fellowship grant from Stiftung Charité.

Data Availability

Code and data are available here.

References

1. Clark A. Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav Brain Sci.* 2013; 36(3):181–204.
2. Friston K, Kiebel S. Predictive coding under the free-energy principle. *Philos Trans Royal Soc B: Biol Sci.* 2009; 364(1521):1211–1221.
3. Friston KJ, Stephan KE, Montague R, Dolan RJ. Computational psychiatry: the brain as a phantastic organ. *Lancet Psychiatry* 2014;1(2):148–158.
4. Haarsma J, Kok P, Browning M. The promise of layer-specific neuroimaging for testing predictive coding theories of psychosis. *Schizophr Res.* 2020.
5. Hohwy J. *The Predictive Mind*. Oxford University Press; 2013.
6. Ballard DH. *Brain Computation as Hierarchical Abstraction*. MIT Press; 2015.
7. Adams RA, Stephan KE, Brown HR, Frith CD, Friston KJ. The computational anatomy of psychosis. *Front Psychiatry.* 2013;4:47.

8. Davies DJ, Teufel C, Fletcher PC. Anomalous perceptions and beliefs are associated with shifts toward different types of prior knowledge in perceptual inference. *Schizophr Bull.* 2018;44(6):1245–1253.
9. Fletcher PC, Frith CD. Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. *Nat Rev Neurosci.* 2009;10(1):48–58.
10. Sterzer P, Adams RA, Fletcher P, *et al*. The predictive coding account of psychosis. *Biol Psychiatry.* 2018;84(9): 634–643.
11. King DJ, Hodgekins J, Chouinard PA, Chouinard VA, Sperandio I. A review of abnormalities in the perception of visual illusions in schizophrenia. *Psychon Bull Rev.* 2017;24(3):734–751.
12. Notredame CE, Pins D, Deneve S, Jardri R. What visual illusions teach us about schizophrenia. *Front Integr Neurosci.* 2014;8(AUG):63.
13. Weilnhammer V, Röd L, Eckert AL, Stuke H, Heinz A, Sterzer P. Psychotic experiences in schizophrenia and sensitivity to sensory evidence. *Schizophr Bull.* 2020.
14. Schmack K, de Castro AGC, Rothkirch M, *et al*. Delusions and the role of beliefs in perceptual inference. *J Neurosci.* 2013;33(34):13701–13712.
15. Heinz A, Murray GK, Schlagenhauf F, Sterzer P, Grace AA, Waltz JA. Towards a unifying cognitive, neurophysiological, and computational neuroscience account of schizophrenia. *Schizophr Bull.* 2019;45(5):1092–1100. doi: 10.1093/SCHBUL/SBY154.
16. Teufel C, Subramaniam N, Dobler V, *et al*. Shift toward prior knowledge confers a perceptual advantage in early psychosis and psychosis-prone healthy individuals. *Proc Natl Acad Sci USA.* 2015;112(43):13401–13406.
17. Powers AR, Mathys C, Corlett PR. Pavlovian conditioning–induced hallucinations result from overweighting of perceptual priors. *Science* . 2017;357(6351):596–600.
18. Corlett PR, Horga G, Fletcher PC, Alderson-Day B, Schmack K, Powers IA. Hallucinations and strong priors. *Trends Cogn Sci.* 2019;23(2):114–127.
19. Akaishi R, Umeda K, Nagase A, Sakai K. Autonomous mechanism of internal choice estimate underlies decision inertia. *Neuron.* 2014;81(1):195–206.
20. Bae GY, Luck SJ. Serial dependence in vision: merely encoding the previous-trial target is not enough. *Psychon Bull Rev.* 2020;27(2):293–300.
21. Braun A, Urai AE, Donner TH. Adaptive history biases result from confidence-weighted accumulation of past choices. *J Neurosci.* 2018;38(10):2418–2429.
22. Abrahamyan A, Silva LL, Dakin SC, Carandini M, Gardner JL. Adaptable history biases in human perceptual decisions. *Proc Natl Acad Sci USA.* 2016;113(25):E3548–E3557.
23. Cicchini GM, Mikellidou K, Burr D. Serial dependencies act directly on perception. *J Vis.* 2017;17(14):6.
24. Collins T. Serial dependence alters perceived object appearance. *J Vis.* 2020;20(13):9.
25. Fischer J, Whitney D. Serial dependence in visual perception. *Nat Neurosci.* 2014;17(5):738–743.
26. Fritsche M, Mostert P, de Lange FP. Opposite effects of recent history on perception and decision. *Curr Biol.* 2017; 27(4):590–595.
27. Fornaciai M, Park J. Attractive serial dependence in the absence of an explicit task. *Psychol Sci.* 2018;29(3):437–446.
28. Fornaciai M, Park J. Serial dependence in numerosity perception. *J Vis.* 2018;18(9):15.
29. Stein H, Barbosa J, Rosa-Justicia M, *et al*. Reduced serial dependence suggests deficits in synaptic potentiation in anti-NMDAR encephalitis and schizophrenia. *Nat Commun.* 2020;11(1):1–11. Accessed November 23, 2020. https://www.nature.com/articles/s41467-020-18033-3.
30. Taubert J, Alais D. Serial dependence in face attractiveness judgements tolerates rotations around the yaw axis but not the roll axis. *Vis Cogn.* 2016;24(2):103–114.
31. Kok R, Taubert J, der Burg E, Rhodes G, Alais D. Face familiarity promotes stable identity recognition: exploring face perception using serial dependence. *R Soc Open Sci.* 2017;4(3):160685.
32. Xia Y, Leib AY, Whitney D. Serial dependence in the perception of attractiveness. *J Vis.* 2016;16(15):28.
33. Lieder I, Adam V, Frenkel O, Jaffe-Dax S, Sahani M, Ahissar M. Perceptual bias reveals slow-updating in autism and fast-forgetting in dyslexia. *Nat Neurosci.* 2019;22(2):256–264.
34. Akrami A, Kopec CD, Diamond ME, Brody CD. Posterior parietal cortex represents sensory history and mediates its effects on behaviour. *Nature.* 2018;554(7692):368–372.
35. Togoli I, Fedele M, Fornaciai M, Bueti D. Serial dependence in time and numerosity perception is dimension-specific. *J Vis.* 2021;21(5):1–15. doi: 10.1167/jov.21.5.6.
36. Collins T. Serial dependence alters perceived object appearance. *J Vis.* 2020;20(13):9–9. doi: 10.1167/JOV.20.13.9.
37. Bilacchi CM, Sirius EVP, Cravo AM, de Azevedo Neto RM. Temporal dynamics of implicit memory underlying serial dependence. *Mem Cognit.* 2022;50(2):449–458.
38. Angela JY, Cohen JD. Sequential effects: superstition or rational behavior? *Adv Neural Inf Process Syst.* 2008;21:1873.
39. Rahnev D, Denison RN. Suboptimality in perceptual decision making. *Behav Brain Sci.* 2018;41:1–107. doi: 10.1017/S0140525X18000936.
40. Cicchini GM, Burr DC. Serial effects are optimal. *Behav Brain Sci.* 2018;41:e–229.
41. Cicchini GM, Mikellidou K, Burr DC. The functional role of serial dependence. *Proc Biol Sci.* 2018;285(1890): 20181722.
42. Pascucci D, Mancuso G, Santandrea E, Libera C, Plomp G, Chelazzi L. Laws of concatenated perception: vision goes for novelty, decisions for perseverance. *PLoS Biol.* 2019;17(3): e3000144. doi: 10.1371/JOURNAL.PBIO.3000144.
43. van Bergen RS, Jehee JFM. Probabilistic representation in human visual cortex reflects uncertainty in serial decisions. *J Neurosci.* 2019;39(41). doi: 10.1523/JNEUROSCI.3212-18.2019.
44. Samaha J, Switzky M, Postle BR. Confidence boosts serial dependence in orientation estimation. *J Vis.* 2019;19(4):25.
45. Son S, Lee J, Kwon OS, Kim YJ. Effect of spatiotemporally changing environment on serial dependence in ensemble representations. Published online 2021. doi: 10.1101/2021.11.30.470662.
46. Ceylan G, Herzog MH, Pascucci D. Serial dependence does not originate from low-level visual processing. *Cognition.* 2021;212:104709. doi: 10.1016/j.cognition.2021.104709.
47. Teufel C, Fletcher PC. Forms of prediction in the nervous system. *Nat Rev Neurosci.* 2020;21(5):297. doi: 10.1038/S41583-020-0296-0.
48. Wacongne C, Labyt E, van Wassenhove V, Bekinschtein T, Naccache L, Dehaene S. Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proc Natl Acad Sci USA.* 2011;108(51):20754–20759. doi: 10.1073/PNAS.1117807108.

49. Brunton BW, Botvinick MM, Brody CD. Rats and humans can optimally accumulate evidence for decision-making. *Science.* 2013;340(6128):95–98.
50. Palan S, Schitter C. Prolific. ac—A subject pool for online experiments. *J Behav Exp Finance* 2018;17:22–27.
51. Anwyl-Irvine AL, Massonnié J, Flitton A, Kirkham N, Evershed JK. Gorilla in our midst: an online behavioral experiment builder. *Behav Res Methods.* 2020;52(1):388–407.
52. Woods KJP, Siegel MH, Traer J, McDermott JH. Headphone screening to facilitate web-based auditory experiments. *Atten Percept Psychophys* 2017;79(7):2064–2072.
53. Peirce J, Gray JR, Simpson S, *et al*. PsychoPy2: experiments in behavior made easy. *Behav Res Methods.* 2019;51(1):195–203. doi: 10.3758/S13428-018-01193-Y.
54. Peters ER, Joseph SA, Garety PA. Measurement of delusional ideation in the normal population: introducing the PDI (Peters *et al*. Delusions Inventory). *Schizophr Bull.* 1999; 25(3):553–576.
55. Bell V, Halligan PW, Ellis HD. The Cardiff Anomalous Perceptions Scale (CAPS): a new validated measure of anomalous perceptual experience. *Schizophr Bull.* 2006;32(2): 366–377.
56. R Core Team. R: A Language and Environment for Statistical Computing. Published online 2021. https://www.R-project.org/.
57. Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Stat Softw* 2015;67(1):1–48. doi: 10.18637/jss.v067.i01.
58. Nash JC, Varadhan R. Unifying optimization algorithms to aid software system users: optimx for R. *J Stat Softw* 2011;43(9):1–14. doi: 10.18637/JSS.V043.I09.
59. Barton K, Barton M. Package "mumin." *Version.* 2015;1(18): 439. Accessed February 4, 2022. https://cran.hafro.is/web/packages/MuMIn/MuMIn.pdf.
60. Gekas N, McDermott KC, Mamassian P. Disambiguating serial effects of multiple timescales. *J Vis.* 2019;19(6):24.
61. Kohavi R, Longbotham R. Online experiments: lessons learned. *Computer (Long Beach Calif).* 2007;40(9):103–105.
62. Kohavi R, Longbotham R, Walker T. Online experiments: practical lessons. *Computer (Long Beach Calif).* 2010;43(09):82–85.
63. Benrimoh D, Parr T, Vincent P, Adams R, Friston K. Active inference and auditory hallucinations. *Computational Psychiatry*. 2018;2:183. Accessed April 29, 2022. https://www.ncbi.nlm.nih.gov/pmc/articles/pmc6317754/.
64. Smith R, Friston KJ, Whyte CJ. A step-by-step tutorial on active inference and its application to empirical data. *J Math Psychol.* 2022;107:102632. doi: 10.1016/J.JMP.2021.102632.
65. Fard PR, Park H, Warkentin A, Kiebel SJ, Bitzer S. A bayesian reformulation of the extended drift-diffusion model in perceptual decision making. *Front Comput Neurosci.* 2017; 11:29.
66. Papadimitriou C, White RL, Snyder LH. Ghosts in the machine II: neural correlates of memory interference from the previous trial. *Cereb Cortex.* 2017;27(4):2513–2527.
67. John-Saaltink ES, Kok P, Lau HC, de Lange FP. Serial dependence in perceptual decisions is reflected in activity patterns in primary visual cortex. *J Neurosci.* 2016;36(23):6186–6192.
68. Lawrence SJD, Norris DG, de Lange FP. Dissociable laminar profiles of concurrent bottom-up and top-down modulation in the human visual cortex. *Elife* 2019;8:e44422.
69. Lawrence SJD, Formisano E, Muckli L, de Lange FP. Laminar fMRI: applications for cognitive neuroscience. *Neuroimage* 2019;197:785–791.
70. Weilnhammer VA, Stuke H, Sterzer P, Schmack K. The neural correlates of hierarchical predictions for perceptual decisions. *J Neurosci.* 2018;38(21):5008–5021. doi: 10.1523/JNEUROSCI.2901-17.2018.

Publication 2

Weilnhammer, V., Röd, L., **Eckert, A. L.**, Stuke, H., Heinz, A., & Sterzer, P. (2020). Psychotic experiences in schizophrenia and sensitivity to sensory evidence.
Schizophrenia bulletin, *46*(4), 927-936.

Schizophrenia Bulletin vol. 46 no. 4 pp. 927–936, 2020
doi:10.1093/schbul/sbaa003
Advance Access publication 24 February 2020

Psychotic Experiences in Schizophrenia and Sensitivity to Sensory Evidence

Veith Weilnhammer*[,1], Lukas Röd[2], Anna-Lena Eckert[1,3,4], Heiner Stuke[1], Andreas Heinz[1,3,4], and Philipp Sterzer[1–4]

[1]Department of Psychiatry, Charité Universitätsmedizin Berlin, 10117 Berlin, Germany; [2]Berlin School of Mind and Brain, Humboldt-Universität zu Berlin, 10099 Berlin, Germany; [3]Bernstein Center for Computational Neuroscience, Charité Universitätsmedizin Berlin, 10117 Berlin, Germany; [4]Einstein Center for Neurosciences Berlin, Charite Universitatsmedizin Berlin, 10117 Berlin, Germany

*To whom correspondence should be addressed; Department of Psychiatry, Charité Campus Mitte, Charitéplatz 1, 10117 Berlin, tel: 0049-(0)30-450-517-317, fax: 0049-(0)30-450-517-944, e-mail: veith-andreas.weilnhammer@charite.de

Perceptual inference depends on an optimal integration of current sensory evidence with prior beliefs about the environment. Alterations of this process have been related to the emergence of positive symptoms in schizophrenia. However, it has remained unclear whether delusions and hallucinations arise from an increased or decreased weighting of prior beliefs relative to sensory evidence. To investigate the relation of this prior-to-likelihood ratio to positive symptoms in schizophrenia, we devised a novel experimental paradigm which gradually manipulates perceptually ambiguous visual stimuli by disambiguating stimulus information. As a proxy for likelihood precision, we assessed the sensitivity of individual participants to sensory evidence. As a surrogate for the precision of prior beliefs in perceptual stability, we measured phase duration in ambiguity. Relative to healthy controls, patients with schizophrenia showed a stronger increment in congruent perceptual states for increasing levels of disambiguating stimulus evidence. Sensitivity to sensory evidence correlated positively with the individual patients' severity of perceptual anomalies and hallucinations. Moreover, the severity of such experiences correlated negatively with phase duration. Our results indicate that perceptual anomalies and hallucinations are associated with a shift of perceptual inference toward sensory evidence and away from prior beliefs. This reduced prior-to-likelihood ratio in sensory processing may contribute to the phenomenon of aberrant salience, which has been suggested to give rise to the false inferences underlying psychotic experiences.

Key words: psychosis/Bayesian perceptual inference/predictive coding/bistable perception

Introduction

When perceiving our surroundings, we are confined to inherently noisy and ambiguous sensory representations of the environment. However, conscious experience usually provides us with an unequivocal impression of our world. According to Bayesian theories,[1–3] our brain bridges this gap by actively employing beliefs to interpret sensory information and forms a hypothesis (or *posterior* probability distribution, figure 1A) about the cause of current sensory data.[4] Along this line of thought, conscious experience represents a *controlled hallucination*, that is concurrently being shaped by internally generated beliefs (*prior* distributions) and constrained by external sensory information (the *likelihood* distribution).[5]

Alterations in the relative weighting (or *precision*[6]) of prior and likelihood may lead to false (or dysfunctional) inferences[7–9]: If prior precision is overestimated relative to the likelihood (increased prior-to-likelihood ratio, figure 1B), inference will be driven too strongly by prior beliefs and violations of prior beliefs by sensory data (ie, *prediction errors*) will be overly attenuated. In contrast, a decreased prior-to-likelihood ratio (figure 2C) will lead to a stronger weighting of the sensory data, thus instigating aberrant prediction errors.

Previous work has discussed both increases and decreases of the prior-to-likelihood ratio in relation to cognitive and perceptual anomalies in psychosis-prone individuals and patients with schizophrenia (Scz, for review, see[10] and[11]). Interestingly, delusions have often been related to a decreased prior-to-likelihood ratio,[8,12–16] whereas studies on hallucinations have pointed to an increased prior-to-likelihood ratio.[17–22] As it seems unlikely that delusions and hallucinations, 2 frequently co-occurring symptom domains, should be due to opposing alterations in inference, it was recently proposed that these apparently contradictory findings may be reconciled within the framework of hierarchical predictive coding[1,2,23]: The prior-to-likelihood ratio may indeed be generally reduced at low levels, eg, in early sensory areas, leading to aberrant salience of sensory stimuli and the emergence of delusions.[24,25]

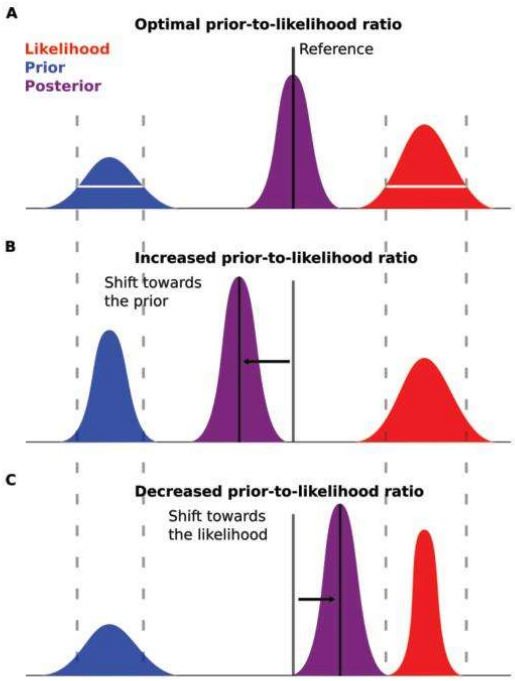


Fig. 1. The prior-to-likelihood ratio in Bayesian perceptual inference. Perceptual inference depends on the ratio of prior and likelihood precision. (**A**) Here, we depict a reference scenario with optimal precision estimates (Gaussian distributions, variance in white, mean of the posterior in black). (**B**) Changes in these estimates of precision may lead to alterations in perception. In case of an overestimation of prior precision and/or underestimation of likelihood precision, the posterior is shifted toward the prior. (**C**) By analogy, an overestimation of likelihood precision and/or underestimation of prior precision is associated with a shift of the posterior toward the likelihood.

In contrast, higher-level priors may become overly precise in an attempt to compensate for aberrant salience and contribute to the emergence of hallucinations.[10,11,26]

In the present study, we tested the hypothesis that psychotic experiences in Scz are related to a decreased prior-to-likelihood ratio at low hierarchical levels. We asked whether the precision of the likelihood mapping between the causes of sensations and the sensory consequences was elevated in Scz relative to healthy controls. This precision is often referred to as sensory precision, where an elevated precision is sometimes attributed to a failure of sensory attenuation. Moreover, we tested whether such a stronger weighting of sensory evidence is associated with the experience of delusions, hallucinations, or both.

We developed a novel experimental paradigm based on bistable perception, ie, the spontaneous alternation between 2 perceptual states that occurs when sensory information is ambiguous.[27] Predictive coding posits that the dynamics of bistability reflect the 2 components of the prior-to-likelihood ratio[28,29]: The current perceptual state represents the best hypothesis (ie, the prior) about the cause of sensory information (ie, the likelihood). Due to ambiguity, neither of the 2 mutually exclusive perceptual hypotheses can fully account for the sensory data. Hence, a prediction error accumulates and eventually leads to a perceptual transition.

Here, we induced the phenomenon of *graded ambiguity* by parametrically manipulating the available sensory evidence for the 2 alternative perceptual hypotheses of an ambiguous Lissajous figure (see figure 2A and Supplementary Video 1). When a perceptual hypothesis is congruent to disambiguating stimulus evidence, prediction errors should be reduced and perceptual transitions to the incongruent perceptual states less likely. Incongruence, in turn, should lead to enhanced prediction errors and increased probability of a transition to the congruent perceptual state. In sum, the probability of perceptual states congruent with disambiguating stimulus evidence should vary with the individual participants' sensitivity to sensory evidence. Thus, it serves as a proxy for the prior-to-likelihood ratio.

We studied the sensitivity to disambiguating stimulus evidence in patients with paranoid Scz and a matched control group. Under the assumption of a decreased prior-to-likelihood ratio in psychosis, we expected an increased sensitivity to disambiguating stimulus evidence in patients with Scz. We furthermore hypothesized a positive correlation of sensitivity to disambiguating stimulus evidence with the severity of delusions and hallucinations.

Methods

Participants

We excluded 1 control due to impaired stereovision, 3 controls due to elevated scores for Cardiff Anomalous Perception Scale (CAPS) and Peters Delusion Inventory (PDI) (threshold/scores ≥ 3 SDs above the group's mean), 1 control due to reduced frequency of congruent perceptual states (frequency ≤ 3 SDs below the mean computed across groups in any of the conditions D1–D7), and 1 patient who did not complete the experiment. The final sample was matched for gender, age, and handedness (see table 1) and consisted of 23 patients (International Classification of Diseases 10: F20.0, 18 male, age = 37.13 ± 2.42) recruited from in- and out-patient services at Charité Universitätsmedizin Berlin and 23 control participants (17 male, age = 33.57 ± 1.74 y). All participants had (corrected-to-)normal vision, were naive to the purpose of the study, and gave informed, written consent prior to the experiment authorized by the Charité Ethics Committee.

Questionnaires and Clinical Rating

Participants completed the 40-item PDI[30] to quantify delusional ideation[13,14,17,31–33] and the 32-item CAPS[34] to

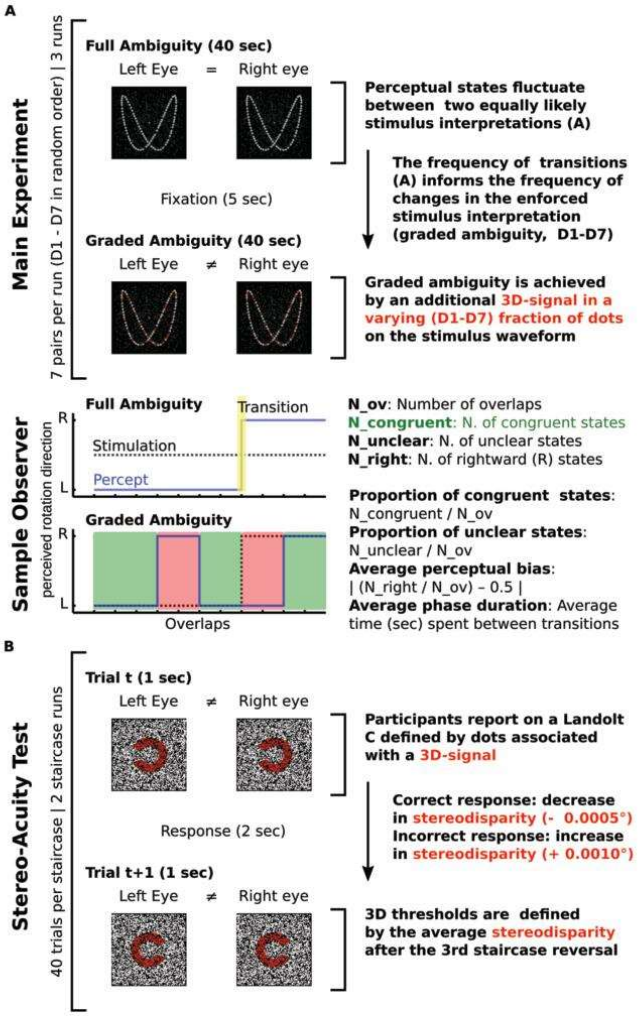


Fig. 2. Behavioral experiment. **(A)** In the main experiment, we measured the individual participants' sensitivity to disambiguating stimulus evidence as a proxy for the prior-to-likelihood ratio. To visualize relevant variables, the lower panel displays typical perceptual responses in an ambiguous block and the corresponding partially disambiguated block. (B) To probe potential differences in stereovision, we determined individual stereo-disparity thresholds in an independent stereoacuity test.

Table 1. Sample Characteristics

Group	*N*	Female	Smoking	Stat	Age	ED	CAPS	PDI	PANSS: P	*N*	G	DOI	CPZe
				Mean	33.6	77	6.7	22	NA	NA	NA	NA	NA
Controls	23	6	10	SD	8.4	40	9.2	28	NA	NA	NA	NA	NA
				Mean	37.1	75	65.0	139	18.4	19.4	33	15	190
Patients	23	5	15	SD	11.6	44	50.1	80	6.3	8.2	10	12	172

Note: Patients with Scz scored higher than controls on the PDI (patients: 138.83 ± 16.64 SEM, controls: 21.87 ± 5.75, Welch 2-sample *t*-test: $T(27) = 6.64$, $P = 3.81 \times 10^{-7}$) and CAPS (patients: 64.96 ± 10.45, controls: CAPS of 6.65 ± 1.91, $T(23) = 5.49$, $P = 1.32 \times 10^{-5}$). One patient received a typical antipsychotic, 18 patients were prescribed an atypical antipsychotic, and 4 were without medication.

measure perceptual anomalies. Reported scores reflect sums over questionnaire subscales. We assessed clinical symptom severity using the Positive and Negative Syndrome Scale (PANSS).[35]

Behavioral Experiments

Apparatus. We presented all stimuli using a mirror stereoscope placed in front of a 98PDF-CRT-Monitor (60 Hz, 1042 × 768 pixels, 59.50 cm viewing distance, 30.28 pixels per degree visual angle; °) using Psychtoolbox 3[36] and Matlab R2007b (MathWorks).

Main Experiment. The main experiment (figure 2A) assessed the modulation of perceptual states by levels of disambiguating stimulus evidence. In 3 runs (10.52 min each), participants viewed 7 pairs of ambiguous and partially disambiguated versions of a rotating discontinuous Lissajous figure (see Supplementary Video 1) presented in blocks of 40.08 s each, separated by 5 s of fixation. We randomly placed 300 dots (0.05°) on the stimulus waveform (2.05° × 2.05°) defined by the perpendicular intersection of 2 sinusoids [$x(t) = sin(A * t)$ and $y(t) = cos(B * t + \delta)$ with A = 3, B = 6, and δ increasing from 0 to 2π at 6.80 s per revolution and 6 revolutions per block]. We relocated the dots at a probability of 0.02 per frame. Stimuli were surrounded by rectangular fusion frames and presented on the background of random-dot noise (700 dots of 0.05°, 1.98°/s speed, changes in motion direction at 1 Hz). We displayed a fixation cross in the center of the visible screen (0.10°).

During ambiguous blocks, we presented identical Lissajous figures to the 2 eyes. Participants indicated changes in the perceived direction of rotation by pressing the left (rotation of the front surface to the left, right index finger), right (rotation to the right, right ring finger), or down (unclear direction of rotation, right middle finger) arrow key on a standard USB keyboard.

The indicated direction of rotation in an ambiguous block determined the time-points of changes in sensory evidence in the upcoming disambiguated block. To add additional sensory evidence (graded disambiguation) to the Lissajous figure, we shifted a proportion of the stimulus dots by a δ of 0.02π in the corresponding direction between monocular channels. Crucially, we varied the amount of disambiguating stimulus evidence across 7 conditions (D1: 1.25%, D2: 3.75%, D3: 8.75%, D4: 16.25%, D5: 26.25%, D6: 50.00%, and D7: 100.00% of dots disambiguated). Each condition appeared once per run and in random order. Participants reported changes in the perceived direction of rotation as well as unclear perceptual states.

Stereoacuity. We assessed stereo-disparity thresholds in an independent stereoacuity test (similar to[37], figure 2B). To this end, we presented a number of 5000 dots (each at 0.15°) within a square of 11 × 11°. We attached a stereo-disparity signal to dots lying on a Landolt C, ie, a circle (1.37° radius, 2.06° width) with a 90° gap located at the left, top, right, or bottom. Following 5 s of fixation and 1 s of stimulus presentation, participants reported the location of the gap in the Landolt C by pressing the up-, down-, left-, or right-arrow key (response interval = 2 s). Fixation crosses (0.10°) were presented in the center of visible screen.

Participants performed 2 runs of 40 trials each. At each trial, we determined the amount of presented stereo disparity based on the response from the previous trial by a 2-up-1-down staircase procedure (correct response: decrease in the available stereo disparity by 1 step; incorrect response: increase by 2 steps, initial step size: 0.001°, reduction to 0.0005° after first reversal). The initial stereo disparity was 0.0045° in run 1 and 0.0005° in run 2.

Analyses

Main Experiment. For the main experiment, we based our analyses on perceptual transitions reported by the participants. Because perceptual transitions occur at overlapping configurations of the Lissajous figure,[29,38–41] we corrected the timing of each perceptual transition to the time of the overlap preceding the corresponding button press. This decomposed the perceptual time course into a sequence of discrete perceptual states (leftward, rightward, and unclear rotation of the front surface, 3.40 s inter-overlap interval).

As variable-of-interest (see figure 2A), we computed the proportion of congruent perceptual states (ie, perceptual states perceived in congruence with the disambiguating stimulus evidence) for all parametric levels of disambiguation (D1–D7). This variable served as a proxy for the prior-to-likelihood balance during graded ambiguity. In addition, we determined individual perceptual stability in terms of average phase duration (ie, time spent between 2 perceptual transitions). As potential confounds, we computed the probability of unclear perceptual states for all conditions (ambiguity and D1–D7) separately and absolute perceptual bias[42] (ie, the absolute difference between the probability of both perceptual states and chance level) in ambiguous blocks. Within participants, we averaged all dependent variables across runs.

We performed group-level statistics using mixed ANOVA (within-subject factor: levels of disambiguating stimulus evidence D1–D7; between-subject factor: diagnostic group). Given heteroscedasticity between groups for congruent perceptual states (Levene test: P = .043), we used a linear mixed-effects (nlme R-package) model. The diagnostic group and disambiguating stimulus evidence defined fixed effects. Individual participants defined random effects. Weights were adjusted to account for unequal variance between groups.

We further fitted a set of functions [linear: $y = a + b * x$; exponential: $y = c * exp(g * x)$; sigmoid: $y = 0.5 + (0.5 - l)/(1 + exp(-(x - m)/n))$] to the proportion of congruent perceptual states across conditions D1–D7. After identifying the exponential fit by means of the highest adjusted R^2, we compared individual growth rates as surrogates for the sensitivity to sensory evidence between groups. Because the number of free parameters (ie, complexity) in these models was fixed, the measure of accuracy can be treated as model evidence (ie, we performed a simple form of model comparison). Due to non-normality (Kolmogorov-Smirnov test: $P < .0001$), we used bootstrapping (R-dabestr[43]) to estimate confidence intervals (CI) for between-group differences in growth rates (see Supplementary Materials 1 for analyses of the linear fit) and perceptual bias.

In Supplementary Materials 2, we provide post hoc simulation analyses to illustrate the relation of our psychophysical approach to the predictive coding model of bistable perception.[29]

Stereo Disparity. We determined stereo-disparity thresholds by computing the average of presented stereo disparity at trials following the third reversal of each run and averaged across runs. Due to non-normality (Kolmogorov-Smirnov test: $P < .0001$), we probed a potential between-group difference by bootstrapping CIs.

Correlative Analyses. Finally, we asked whether individual questionnaire scores (PDI and CAPS; Bonferroni-corrected) correlated with the sensitivity to sensory evidence and average phase duration. In addition, we tested correlations with the PANSS subitems P1 (delusions) and P3 (hallucinations). Control analyses probed potential correlations to perceptual bias, unclear perceptual states, stereoacuity, as well as negative and general PANSS subscales (see Supplementary Materials 1 for median split analyses of CAPS/P3 and complete correlograms). Due to non-normality (Kolmogorov-Smirnov tests $P < .0001$ for all variables), we computed standard Spearman correlations. To correct for potential confounds that may influence performance in the Lissajous task and/or the severity of psychotic experiences, we assessed partial correlation coefficients. Such factors comprised stereoacuity (due to its potential influence on graded ambiguity, see above), the participants' age (due to its impact on bistable perception[44]), as well as the duration of illness and chlorpromazine equivalents as measures of disease severity. To ascertain specificity for the dimensions of psychotic experience, we also included scores on the alternative questionnaire (for correlations with PDI/CAPS), the respective alternative PANSS subitems (for correlations with P1/P3) and PANSS subscales (general and negative).

Results

Main Experiment

The nlme R-package model indicated a main effect of disambiguating stimulus evidence on the fraction of congruent perceptual states [$F(6) = 15.16$, $P = 6.44 \times 10^{-15}$], but no main effect of group [$F(1) = 0.02$, $P = .88$]. Importantly, we observed a significant interaction between diagnostic group and disambiguating stimulus evidence [$F(6) = 2.52$, $P = .02$, see figure 3A]. Mixed ANOVA yielded qualitatively identical results.

The change in the fraction of congruent perceptual states across D1–D7 was best fit by an exponential function (adjusted $R^2 = 0.39 \pm 0.10$, best fit in 70% of Scz patients and 65% of controls) as compared with linear (adjusted $R^2 = 0.38 \pm 0.10$) and sigmoid (adjusted $R^2 = 0.10 \pm 0.10$) functions. Sensitivity to additional sensory evidence as expressed by the growth rate of the exponential function was equal to 0.06 ± 0.01 in patients and 0.02 ± 0.02 in controls. Bootstrapping revealed a borderline significant difference between patients and controls (95% CI = 0.004 to −0.08, see figure 3B). Analysis of the linear fit yielded qualitatively identical results (see Supplementary Materials 1).

Mixed ANOVA did not yield a main effect of group or disambiguating stimulus evidence nor a between-factor interaction for the proportion of unclear perceptual states (patients: 0.01 ± 0.001; controls: 0.004 ± 0.001) or phase duration (patients: 21.25 ± 0.35 s; controls: 21.56 ± 0.36 s; see Supplementary Materials 1). Furthermore, we did not observe a significant between-group difference with regard to perceptual biases in ambiguity (patients: 0.09 ± 0.02, controls: 0.10 ± 0.02, 95% CI = −0.06 to 0.04).

Stereoacuity

Stereo-disparity thresholds amounted to $0.003 \pm 0.001^{\circ}$ in patients and $0.003 \pm 0.001^{\circ}$ in controls with no significant between-group difference (95% CI = –0.002 to 0.001).

Correlative Analyses

Within patients, sensitivity to disambiguating stimulus evidence correlated positively with the CAPS ($R = 0.51$, $P = .02$; figure 4). This was corroborated by the respective partial correlation ($R = 0.55$, $P = .03$, see above). Similarly, there was a significant correlation of the sensitivity parameter to PANSS subitem P3 (standard correlation: $R = 0.52$, $P = .01$; partial correlation: $R = 0.52$, $P = .04$). We did not observe a significant association between sensitivity to disambiguating stimulus evidence and PDI (standard correlation: $R = 0.36$, $P = .19$; partial correlation: $R = -0.35$, $P = .19$) or P1 (standard correlation: $R = 0.35$, $P = .11$; partial correlation: $R = 0.07$, $P = .78$). Analyses of the linear fit yielded qualitatively identical results.

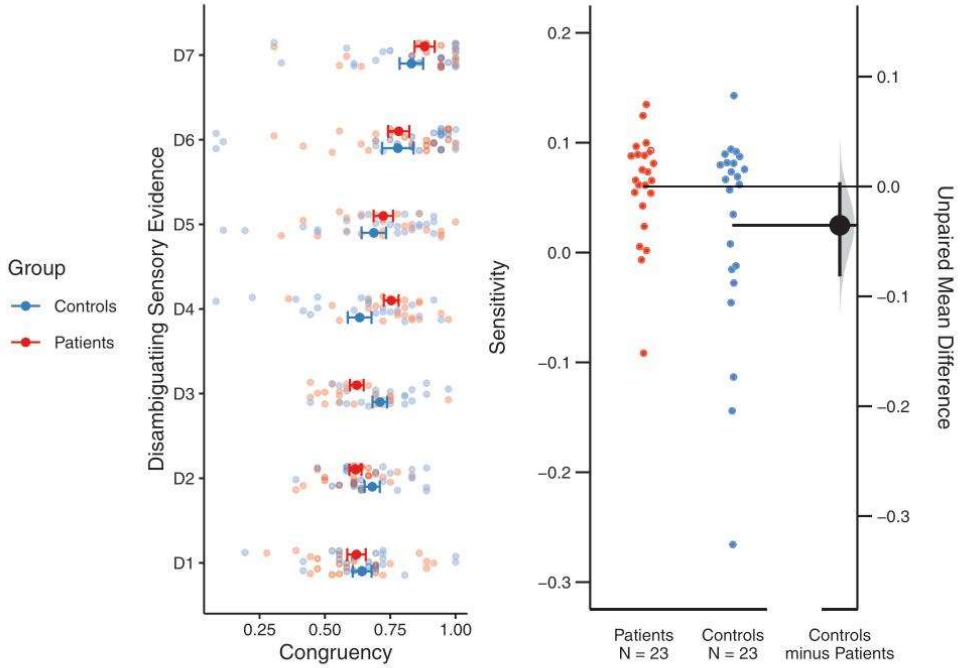


Fig. 3. Sensitivity to disambiguating stimulus evidence. We depict the fraction of congruency between perceptual states and sensory evidence across the levels of disambiguating stimulus evidence (D1–D7, left panel). Error bars represent the respective standard error of the mean. The nlme model yielded a main effect of disambiguating stimulus evidence [$F(6) = 15.16$, $P = 6.44 \times 10^{-15}$], and a significant interaction between the diagnostic group and the disambiguating stimulus evidence [$F(6) = 2.52$, $P = .02$]. The left panel shows the implicit interaction between levels of disambiguating stimulus evidence and diagnostic group: At low levels of disambiguation (D1–D3), controls exhibit a marginally higher proportion of congruent perceptual states. This is reversed for higher levels of disambiguating stimulus evidence (D4–D7), where patients show a greater proportion of congruency. We used the growth rate of individual exponential fits to the fraction of congruent perceptual states to express the individual sensitivities to disambiguating stimulus evidence during graded ambiguity (right panel; horizontal lines point to sample means; vertical line spans over the 95% CI). Bootstrapping revealed a borderline-significant between-group difference (estimated 95% CI = 0.004 to −0.08).

Furthermore, we observed a significant negative correlation of average perceptual phase duration with the CAPS (standard correlation: $R = -0.54$, $P = .01$; partial correlation: $R = -0.64$, $P = .01$) and a trendwise correlation to P3 (standard correlation: $R = -0.39$, $P = .07$; partial correlation: $R = -0.46$, $P = .07$). We did not find a significant association of phase duration to PDI or P1 in standard (PDI: $R = -0.21$, $P = .68$; P1: $R = -0.26$, $P = .23$) or partial correlations (PDI: $R = -0.35$, $P = .19$; P1: $R = -0.21$, $P = .44$).

Confirmatory analyses indicated a significant positive correlation of the sensitivity parameter to the positive and general PANSS subscale ("Positive": $R = 0.5$, $P = .02$; "General": $R = 0.52$, $P = .01$; "Negative": $R = 0.11$, $P = .61$). Interestingly, there were no significant correlations between sensory precision and negative symptoms or signs. CAPS and PDI were highly correlated in patients ($R = 0.76$, $P = 2.81 \times 10^{-5}$) and showed a trend for controls ($R = 0.35$, $P = .1$).

Neither of the 2 questionnaire scores (PDI/CAPS) and PANSS subitems (P1/P3) correlated with perceptual biases, fraction of unclear perceptual states, stereo-disparity thresholds, duration of illness, or chlorpromazine equivalents. Within controls, we did not find any significant correlation between questionnaire scores and the aforementioned variables (see Supplementary Materials 1 for additional correlation analyses and correlograms).

Discussion

In this study, we asked whether the experience of psychotic symptoms is associated with an increased impact of sensory evidence on perceptual inference relative to prior predictions (ie, a reduced prior-to-likelihood ratio at sensory processing levels).

Firstly, Scz patients showed an increased proportion of disambiguation-congruent perceptual states at high levels of stimulus information (D4–D7). At low levels (D1–D3),

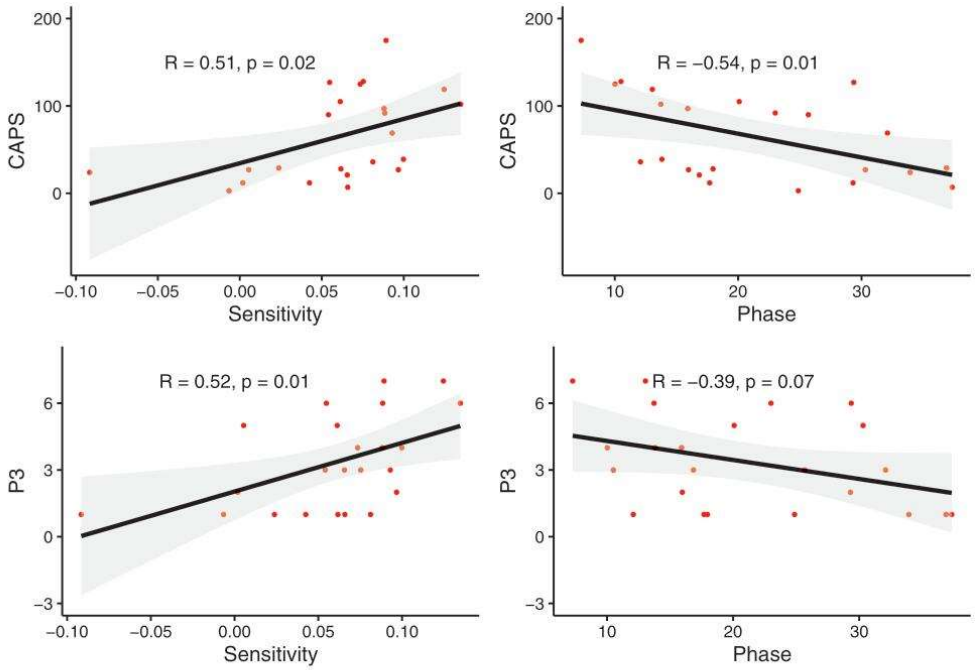


Fig. 4. Individual symptom severity. Here, we depict the individual patients' symptom severity with regard to perceptual anomalies (CAPS, top) and hallucination (P3, bottom) against the sensitivity to stimulus evidence (left) and phase duration (right) alongside regression lines (black) and 95% CI (light gray).

this proportion was similar between groups or even appeared to be reduced in patients (D3). This interaction thus speaks against a global increase in sensitivity to sensory evidence in Scz. Rather, it may suggest that patients show a greater benefit (or *gain*) at increasing levels of stimulus information. Indeed, due to this nonlinearity, these findings defy a simple explanation. Supplementary Materials 2 provides post hoc simulations of this interaction from a predictive coding model of bistable perception.[28,29]

Secondly, we found that the severity of perceptual anomalies and hallucinations correlated *positively* with the sensitivity to disambiguating stimulus evidence and *negatively* with average phase duration in Scz. Predictive coding models of bistable perception[28,29] relate enhanced sensory sensitivity to a shift of precision estimates *toward stimulus representations* (ie, the likelihood). In turn, such models assume that shorter phase durations signal a shift of precision estimates *away from implicit predictions* about perceptual stability (see[29] and Supplementary Materials 2). Through this lens, the two behavioral results, therefore, suggest that hallucinations are related to a decreased prior-to-likelihood ratio at sensory processing levels. At the same time, they contradict the hypothesis that a global shift toward prior precision (ie, an increased prior-to-likelihood ratio) underlies the experience of hallucinations.

These findings align with the "canonical" predictive coding account of Scz,[10] which assumes that psychotic symptoms arise due to a relative shift of inference away from priors and toward sensory evidence.[8] Along these lines, our results reverberate with the association of Scz to a reduced susceptibility to visual illusions,[16] impaired smooth pursuit,[45] and reduced sensory attenuation during force matching.[15,46] While our findings speak for a decrease as opposed to an increase in the prior-to-likelihood ratio, they cannot distinguish between a decrease in prior precision alone, an increase in likelihood precision alone or a combination of the two. Moreover, our results are compatible with alternative algorithms of dynamic belief updating such as circular inference[47,60] and alternative implementational frameworks of bistable perception such as mutual inhibition and adaption models.[48] In this context, differences in the excitation-inhibition balance[49] may lead to weaker inhibition between competing neuronal populations, which could explain why hallucinations correlated with individual characteristics of bistable perception.

Importantly, our results seem to contradict the association of hallucinations to overly precise priors.[19,21,22] However, this apparent discrepancy may be resolved by a differential modulation of the prior-to-likelihood ratio

across levels of the predictive coding hierarchy: Our paradigm targeted the interaction of prior and likelihood at sensory levels. A reduced prior-to-likelihood ratio may elicit the aberrant salience of sensory events.[24,25] This may drive higher levels into an overly strong weighting of priors and entail enhanced top-down influences on perception.[11] Finally, such a compensatory mechanism may trigger hallucinations,[21] thereby *explaining away*[5] aberrant salience at sensory levels.

Albeit strongly correlated with perceptual anomalies and hallucinations, our current findings did not reveal an association of delusional ideation to either sensitivity to sensory evidence or perceptual stability. This discrepancy to previous work[14] may result from differences between the experimental paradigms (Schmack et al.[14] stabilized perceptual states through intermittent presentation,[50] while we used a continuous stimulus). Speculatively, intermittent paradigms may boost perceptual priors and thus be more sensitive toward the relation of perceptual stability and delusions. In turn, manipulating sensory evidence through graded ambiguity may be more apt to detect associations to perceptual abnormalities. To resolve this discrepancy, future work should combine the novel paradigm of graded ambiguity with both intermittent presentation of bistable stimuli[13,14] and manipulations of higher-level beliefs.[33,51–53]

In contrast to our findings, previous research has revealed deficits in binocular depth perception in Scz.[54–57] Our stereoacuity assessment was analogous to the established *Random-Dot test*,[37,55] but estimated perceptual thresholds in a psychophysical staircase. This yielded values in the range commonly reported for stereoacuity.[55] In addition, our study did not show a global reduction in perceptual performance in Scz patients relative to controls. It thus seems less likely that low-level deficits (eg, reduced stereoacuity, contrast sensitivity,[55] or motion intergration[58]) can account for the current findings. Finally, perceptual biases (eg, when perceiving facial expressions[59]) are frequently reported in Scz. In the context of bistable perception, global differences in the probabilities of perceptual alternatives are a common phenomenon.[42] Importantly, this study did not reveal any significant effect of bias, which is thus unlikely to contribute to our results.

In sum, this study associates the experience of psychotic symptoms with an altered integration of prior beliefs and sensory evidence. Our results relate perceptual anomalies and hallucinations to a reduction of the prior-to-likelihood ratio in perception. This provides empirical evidence for the view that predictive processing deficits contribute to the emergence of psychotic symptoms and will enable novel approaches to the pathophysiological mechanisms of psychosis.

Supplementary Material

Supplementary data are available at *Schizophrenia Bulletin* online.

Acknowledgment

We thank Dr Rick Adams for a very valuable discussion on a previous version of the manuscript. The authors have declared that there are no conflicts of interest in relation to the subject of this study.

Funding

V.W. and H.S. were supported by the Berlin Institute of Health (BIH). A.H. and P.S. were supported by Deutsche Forschergemeinschaft (DFG; Funding Identification: HE 2597/19-1 and STE 1430/8-1). A.E. was supported by the Einstein Center for Neurosciences (ECN) Berlin.

References

1. Lee TS, Mumford D. Hierarchical Bayesian inference in the visual cortex. *J Opt Soc Am A Opt Image Sci Vis.* 2003;20(7):1434–1448.
2. Friston K. A theory of cortical responses. *Philos Trans R Soc Lond B Biol Sci.* 2005;360(1456):815–836.
3. Clark A. Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav Brain Sci.* 2013;36(3):181–204.
4. Hohwy J. Attention and conscious perception in the hypothesis testing brain. *Front Psychol.* 2012;3:96.
5. Clark A. *Surfing Uncertainty: Prediction, Action and The Embodied Mind.* Oxford, UK: Oxford University Press; 2016:424.
6. Mathys C, Daunizeau J, Friston KJ, Stephan KE. A Bayesian foundation for individual learning under uncertainty. *Front Hum Neurosci.* 2011;5:39.
7. Fletcher PC, Frith CD. Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. *Nat Rev Neurosci.* 2009;10(1):48–58.
8. Adams RA, Stephan KE, Brown HR, Frith CD, Friston KJ. The computational anatomy of psychosis. *Front Psychiatry.* 2013;4:47.
9. Stephan KE, Mathys C. Computational approaches to psychiatry. *Curr Opin Neurobiol.* 2014;25:85–92.
10. Sterzer P, Adams RA, Fletcher P, et al. The predictive coding account of psychosis. *Biol Psychiatry.* 2018;84(9):634–643.
11. Corlett PR, Horga G, Fletcher PC, Alderson-Day B, Schmack K, Powers AR 3rd. Hallucinations and Strong Priors. *Trends Cogn Sci.* 2019;23(2):114–127.
12. Jardri R, Hugdahl K, Hughes M, et al. Are hallucinations due to an imbalance between excitatory and inhibitory influences on the brain? *Schizophr Bull.* 2016;42(5):1124–1134.
13. Schmack K, Gòmez-Carrillo de Castro A, Rothkirch M, et al. Delusions and the role of beliefs in perceptual inference. *J Neurosci.* 2013;33(34):13701–13712.
14. Schmack K, Schnack A, Priller J, Sterzer P. Perceptual instability in schizophrenia: probing predictive coding accounts of delusions with ambiguous stimuli. *Schizophr Res Cogn.* 2015;2(2):72–77.
15. Teufel C, Kingdon A, Ingram JN, Wolpert DM, Fletcher PC. Deficits in sensory prediction are related to delusional ideation in healthy individuals. *Neuropsychologia.* 2010;48(14):4169–4172.
16. Notredame CE, Pins D, Deneve S, Jardri R. What visual illusions teach us about schizophrenia. *Front Integr Neurosci.* 2014;8:63.

17. Teufel C, Subramaniam N, Dobler V, et al. Shift toward prior knowledge confers a perceptual advantage in early psychosis and psychosis-prone healthy individuals. *Proc Natl Acad Sci U S A.* 2015;112(43):13401–13406.
18. Davies DJ, Teufel C, Fletcher PC. Anomalous perceptions and beliefs are associated with shifts toward different types of prior knowledge in perceptual inference. *Schizophr Bull.* 2018;44(6):1245–1253.
19. Powers AR III, Kelley M, Corlett PR. Hallucinations as top-down effects on perception. *Biol Psychiatry Cogn Neurosci Neuroimaging.* 2016;1(5):393–400.
20. Alderson-Day B, Lima CF, Evans S, et al. Distinct processing of ambiguous speech in people with non-clinical auditory verbal hallucinations. *Brain.* 2017;140(9):2475–2489.
21. Powers AR, Mathys C, Corlett PR. Pavlovian conditioning-induced hallucinations result from overweighting of perceptual priors. *Science.* 2017;357(6351):596–600.
22. Cassidy CM, Balsam PD, Weinstein JJ, et al. A perceptual inference mechanism for hallucinations linked to striatal dopamine. *Curr Biol.* 2018;28(4):503–514.e4.
23. Rao RP, Ballard DH. Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nat Neurosci.* 1999;2(1):79–87.
24. Heinz, A. Dopaminergic dysfunction in alcoholism and schizophrenia–psychopathological and behavioral correlates. *Eur Psychiatry.* 2002;17:9–16.
25. Kapur S. Psychosis as a state of aberrant salience: a framework linking biology, phenomenology, and pharmacology in schizophrenia. *Am J Psychiatry.* 2003;160(1):13–23.
26. Heinz, A. et al. Towards a unifying cognitive, neurophysiological, and computational neuroscience account of schizophrenia. *Schizophr Bull.* 2018;45(5):1092–1100.
27. Brascamp J, Sterzer P, Blake R, Knapen T. Multistable perception and the role of the frontoparietal cortex in perceptual inference. *Annu Rev Psychol.* 2018;69:77–103.
28. Hohwy J, Roepstorff A, Friston K. Predictive coding explains binocular rivalry: an epistemological review. *Cognition.* 2008;108(3):687–701.
29. Weilnhammer V, Stuke H, Hesselmann G, Sterzer P, Schmack K. A predictive coding account of bistable perception – a model-based fMRI study. *PLoS Comput Biol.* 2017;13(5):e1005536.
30. Peters ER, Joseph SA, Garety PA. Measurement of delusional ideation in the normal population: introducing the PDI (Peters et al. Delusions Inventory). *Schizophr Bull.* 1999;25(3):553–576.
31. Stuke H, Stuke H, Weilnhammer VA, Schmack K. Correction: psychotic experiences and overhasty inferences are related to maladaptive learning. *PLoS Comput Biol.* 2017;13(2):e1005393.
32. Preti A, Rocchi MB, Sisti D, et al. The psychometric discriminative properties of the Peters *et al*. Delusions Inventory: a receiver operating characteristic curve analysis. *Compr Psychiatry.* 2007;48(1):62–69.
33. Schmack K, Rothkirch M, Priller J, Sterzer P. Enhanced predictive signalling in schizophrenia. *Hum Brain Mapp.* 2017;38(4):1767–1779.
34. Bell V, Halligan PW, Ellis HD. The Cardiff Anomalous Perceptions Scale (CAPS): a new validated measure of anomalous perceptual experience. *Schizophr Bull.* 2006;32(2):366–377.
35. Kay SR, Fiszbein A, Opler LA. The Positive and Negative Syndrome Scale (PANSS) for schizophrenia. *Schizophr Bull.* 1987;13(2):261–276.
36. Brainard DH. The Psychophysics Toolbox. *Spat Vis.* 1997;10(4):433–436.
37. Tittes J, Baldwin AS, Hess RF, et al. Assessment of stereovision with digital testing in adults and children with normal and impaired binocularity. *Vision Res.* 2019;164:69–82.
38. Pastukhov A, Vonau V, Braun J. Believable change: bistable reversals are governed by physical plausibility. *J Vis.* 2012;12(1):17, 1–16.
39. Weilnhammer VA, Ludwig K, Hesselmann G, Sterzer P. Frontoparietal cortex mediates perceptual transitions in bistable perception. *J Neurosci.* 2013;33(40):16009–16015.
40. Weilnhammer VA, Ludwig K, Sterzer P, Hesselmann G. Revisiting the Lissajous figure as a tool to study bistable perception. *Vision Res.* 2014;98:107–112.
41. Weilnhammer VA, Sterzer P, Hesselmann G. Perceptual stability of the Lissajous figure is modulated by the speed of illusory rotation. *PLoS One.* 2016;11(8):e0160772.
42. Zhang X, Xu Q, Jiang Y, Wang Y. The interaction of perceptual biases in bistable perception. *Sci Rep.* 2017;7:42018.
43. Ho J, Tumkaya T, Aryal S, Choi H, Claridge-Chang A. Moving beyond *P* values: everyday data analysis with estimation plots. *Nat Methods.* 2019;16(7):565–566.
44. Díaz-Santos M, Mauro S, Cao B, Yazdanbakhsh A, Neargarder S, Cronin-Golomb A. Bistable perception in normal aging: perceptual reversibility and its relation to cognition. *Neuropsychol Dev Cognition B Aging Neuropsychol Cogn.* 2017;24;115–134.
45. Thakkar KN, Diwadkar VA, Rolfs M. Oculomotor prediction: a window into the psychotic mind. *Trends Cogn Sci.* 2017;21(5):344–356.
46. Shergill SS, Samson G, Bays PM, Frith CD, Wolpert DM. Evidence for sensory prediction deficits in schizophrenia. *Am J Psychiatry.* 2005;162(12):2384–2386.
47. Jardri R, Duverne S, Litvinova AS, Denève S. Experimental evidence for circular inference in schizophrenia. *Nat Commun.* 2017;8:14218.
48. Wilson HR. Minimal physiological conditions for binocular rivalry and rivalry memory. *Vision Res.* 2007;47(21):2741–2750.
49. Lisman J. Excitation, inhibition, local oscillations, or large-scale loops: what causes the symptoms of schizophrenia? *Curr Opin Neurobiol.* 2012;22(3):537–544.
50. Pearson J, Brascamp J. Sensory memory for ambiguous vision. *Trends Cogn Sci.* 2008;12(9):334–341.
51. Schmack K, Weilnhammer V, Heinzle J, Stephan KE, Sterzer P. Learning what to see in a changing world. *Front Hum Neurosci.* 2016;10:263.
52. Kornmeier J, Wörner R, Riedel A, Tebartz van Elst L. A different view on the Necker cube-differences in multistable perception dynamics between Asperger and non-Asperger observers. *PLoS One.* 2017;12(12):e0189197.
53. Weilnhammer VA, Stuke H, Sterzer P, Schmack K. The neural correlates of hierarchical predictions for perceptual decisions. *J Neurosci.* 2018;38(21):5008–5021.
54. Schechter I, Butler PD, Jalbrzikowski M, Pasternak R, Saperstein AM, Javitt DC. A new dimension of sensory dysfunction: stereopsis deficits in schizophrenia. *Biol Psychiatry.* 2006;60(11):1282–1284.
55. Kantrowitz JT, Butler PD, Schecter I, Silipo G, Javitt DC. Seeing the world dimly: the impact of early visual deficits on visual experience in schizophrenia. *Schizophr Bull.* 2009;35(6):1085–1094.

56. Hui L. Xia HS, Tang AS, et al. Stereopsis deficits in patients with schizophrenia in a Han Chinese population. *Sci. Rep*. 2017;7:45988.
57. Wang Z. Yu Z, Pan Z, et al. Impaired binocular depth perception in first-episode drug-naive patients with schizophrenia. *Front Psychol.* 2018;9:850.
58. Carter O, Bennett D, Nash T, et al. Sensory integration deficits support a dimensional view of psychosis and are not limited to schizophrenia. *Transl Psychiatry.* 2017;7(5):e1118.
59. Huang J, Chan RC, Gollan JK, et al. Perceptual bias of patients with schizophrenia in morphed facial expression. *Psychiatry Res.* 2011;185(1–2):60–65.
60. Leptourgos P, Notredame C-E, Eck M, Jardri R, Denève S. Circular inference in bistable perception. *bioRxiv.* 2019;521195.

Curriculum Vitae

Mein Lebenslauf wird aus datenschutzrechtlichen Gründen in der elektronischen Version meiner Arbeit nicht veröffentlicht.

My C.V. is not included in the digital version of my thesis due to data protection concerns.

Publication list

2022

Eckert, A. L., Gounitski, Y., Guggenmos, M., & Sterzer, P. (2022). Cross-modality evi dence for reduced choice history biases in psychosis prone individuals. *Schizophrenia Bulletin (Oxford University Press)*

Eckert, A.L., Pabst, K., Endres, D.M. (2022) A Bayesian Model for Chronic Pain. *Frontiers in Pain Research, 152*(1), DOI https://doi.org/10.3389/fpain.2022.966034

Kirchner, L., **Eckert, A.L.**, Berg, M. (2022) From Broken Models to Treatment Selection: Active Inference as a Tool to Guide Clinical Research and Practice. *Clinical Psychology in Europe, 4*(2), 1-5.

Kirchner*, L.**, Eckert*, A.L.,** Berg, M., Endres, D., Straube, B. & Rief, W. (*pre-print*) Better Safe than sorry? – An active inference approach to biased inference on social Contexts in depression. DOI: 10.31234/osf.io/bp9re

** these authors contributed equally.*

2021

Eckert, A.L., Riepenhausen, A., Wieland, L. (2021). Psychische Gesundheit im Wissen schafts-betrieb. *Personal in Hochschule und Wissenschaft entwickeln, 5*, 32-36

Weilnhammer, V., Fritsch, M., Chikermane, M., **Eckert, A. L.**, Kanthak, K., Stuke, H., Kaminski, J. & Sterzer, P. (2021). An active role of inferior frontal cortex in conscious experience. *Current Biology*, *31*(13), 2868-2880.

2020

Weilnhammer, V., Röd, L., **Eckert, A. L.**, Stuke, H., Heinz, A., & Sterzer, P. (2020). Psychotic experiences in schizophrenia and sensitivity to sensory evidence. *Schizophrenia bulletin*, *46*(4), 927-936.

Conference abstracts

2021

Eckert, A.-L., Guggenmos, M., Sterzer, P. (2021) Psychosis proneness is associated With decreased reliance on low-level prior expectations in auditory decision-making. *TeaP, 2021 (virtual conference),* 63, p.65.

2019

Eckert, A.-L., Weilnhammer, V., Reichenbach, K., Sterzer, P. (2019) A Novel Tool to Study Prediction Error Processing in Bistable Perception. *PERCEPTION* 48, p.177-177

Weilnhammer, V., Röd, L., **Eckert, A.-L.**, Sterzer, P. (2019) The Impact of Sensory Evidence and Prior Predictions on Perceptual Decisions in Patients with Paranoid Schizophrenia. *PERCEPTION* 48, p.44-44

Acknowledgments

Completing a Ph.D. is hard – completing a Ph.D. during a global pandemic is harder. I am deeply indebted to many individuals and institutions who supported me in this endeavour. I am grateful to the Einstein Center for Neurosciences for supporting me financially. They have created an exciting, international community of young neuroscientists that I had the pleasure to be a part of these past years. Especially Oliver Mai and Benedikt Salmen provided invaluable support also for endeavours outside of academic research, such as our Scholar Minds initiative. I would like to thank the researchers from the Berlin Neuroscience community whom I had the privilege to meet and work with during my Ph.D. time, especially the members of the Visual Perception Group at the Klinik für Psychiatrie und Psychotherapie on Campus Mitte. I would especially like to thank Prof. Dr. Philipp Sterzer and Prof. Dr. Matthias Guggenmos for their guidance and supervision throughout my Ph.D. project. I am also grateful to Dr. Veith Weilnhammer, who has made the start into my Ph.D. time smooth and productive. I am also indebted to Prof. Dr. Felix Blankenburg and Prof. Dr. Carsten Finke, who co-supervised this project and provided helpful support as part of my supervisory committee.

I would further like to thank Dr. Elisa Filevich, who supervised a lab rotation at the beginning of my Ph.D. and adopted me into her office space at the BCCN in the final months. I would like to thank Lisa Velenosi and Margret Franke, who keep the BCCN PhD program running, providing invaluable support, and creating exciting events for us BCCN juniors. The BCCN was a continuous source of connection and inspiration throughout my years in Berlin. One example for this was my BCCN-funded coaching sessions with Julia Lemmle, which have proved invaluable to me. I would like to thank Prof. Dominik Endres in Marburg for giving me a very bright and motivating perspective for my future in science. Further, the Nowhere Lab has given me the inspiration and support to finish this project when I thought that the circumstances might not allow me to.

My fiancé Majed Kikhia was vital to my PhD in both emotional and practical ways. Whenever I lost patience or hope, you would step in – sometimes by polishing off a figure in Inkscape, sometimes by shutting down my laptop and bike-supporting me on one of the many long runs we did throughout Berlin and Brandenburg. I am so thankful for you. You were a crucial part of this journey.

Ich widme diese Arbeit meinen Eltern Heike und Philipp Eckert. Ihr habt mich immer in meinen Entscheidungen unterstütz und mir die Freiheit gegeben, meinen Interessen zu folgen – Wurzeln zum wachsen, und Flügel zum fliegen. Wenn die Dinge schwierig werden, weiß ich, dass ich mich immer an euch wenden kann. Danke.