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Characterizing early auditory deficits in schizophrenia using drift-diffusion modeling

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ABSTRACT

Introduction: While tone-matching disturbances have been extensively documented in schizophrenia, it remains unclear if impaired tone-matching performance is solely related to early sensory dysfunction or if the ability to appropriately translate early levels of processing into behavioral responses contributes to the deficit. Using an evidence accumulation model to analyze tone-matching performance, we aim to deconstruct perceptual decision-making into its core computational components, providing a more precise characterization of tone-matching deficits in schizophrenia.

Methods: Thirty (30) individuals diagnosed with schizophrenia and 30 matched healthy controls performed a task requiring discrimination between pairs of pure tones. Behavioral performance was evaluated using Bayesian mixed-effects models of accuracy and reaction times, and further decomposed via a Drift Diffusion Model (DDM) to quantify underlying decision-making parameters.

Results: Individuals with schizophrenia exhibit significantly lower accuracy and prolonged reaction times relative to controls, with a diminished impact of pitch difference levels on performance. DDM analysis revealed that individuals with schizophrenia accumulate sensory evidence at a slower rate (lower drift rate) and demonstrate increased non-decision time, reflecting delays in sensory encoding and/or motor execution. No significant differences were observed in starting point bias or boundary separation.

Conclusions: These findings suggest that tone-matching impairments in schizophrenia are primarily attributable to deficits in evidence accumulation and the translation of sensory information into behavioral responses. This study provides novel insights into the cognitive pathophysiology of schizophrenia and underscores the utility of computational modeling to elucidate the mechanisms underlying perceptual and decisional deficits in this population.

1. Introduction

Schizophrenia is a chronic medical condition for which prevalence approaches 1 % internationally (Jauhar et al., 2022). Cognitive deficits are a hallmark of the disorder, and are strong predictors of symptom severity and functional outcome (Fett et al., 2011; Fioravanti et al.,

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2012). Cognitive deficits have been linked to structural and functional impairments in large-scale brain circuits, mostly involving the prefrontal and parietal cortices, the basal ganglia and the hippocampus (Sui et al., 2015). Increasing investigations support that more basic and early sensory dysfunctions are also an integral and important part of the cognitive pathophysiology of schizophrenia. Although such deficits were already demonstrated in Kraepelin's studies (Dondé et al., 2019a), they did not penetrate general conceptualizations of schizophrenia until the last decades. Recent accounts of schizophrenia now consider a more distributed pattern of cognitive dysfunctions, including early sensory dysfunctions that involve cortico-subcortical sensory circuits (rev. in Dondé et al., 2023; Javitt and Sweet, 2015).

Sensory processing deficits in schizophrenia are most prominently observed in the primary auditory system, where the integrity of sensory function is frequently evaluated using simple behavioral assessments such as tone-matching task (Dondé et al., 2017, 2020). The tone-matching task is a two-alternative forced-choice paradigm in which participants are presented with short pairs of pure tones in series, within which tones have either identical or different pitches. After each pair, the participant responds “the two tones were identical” or “the two tones were different” by a key press. In that way, the task involves both fine-grained sensory coding of pure tones, and subsequent perceptual decision-making processes. Originally based on the “echoic memory” concept, this task measures how information gathered at the level of the primary auditory area is used to form a perceptual decision (Dondé et al., 2019b; Javitt and Sweet, 2015; Strous et al., 1995).

Tone-matching deficits in schizophrenia have been shown to relate to higher-order disturbances involving neural circuits in auditory association regions and extra-auditory areas. For instance, tone-matching impairments have been repeatedly correlated to impairments in complex pitch-pattern detection (Dondé et al., 2019e), to impairments in the perceiving social intent as conveyed through speech or prosody (Dondé et al., 2019e; Kantrowitz et al., 2013, 2014) and to incorrect sourcing of perceptual material or source-monitoring (Dondé et al., 2019d). In addition, tone-matching performance predicts the severity of clinical symptoms (Bruder, 2004) and functional outcome in schizophrenia, including impairments in educational achievement (Carrión et al., 2015; Friedman et al., 2012) and reading (Dondé et al., 2019c; Revheim et al., 2014). Moreover, tone-matching performance differentiates two clinically distinct schizophrenia subtypes: one with preserved abilities and another with severe tone-matching impairment. The latter subgroup is more prevalent among inpatient cohorts and is characterized by larger cognitive deficits, reduced functional capacity, and significantly diminished functional connectivity between subcortical and cortical auditory regions (Dondé et al., 2019b). These distinctions have potential implications for treatment strategies. Auditory-based cognitive training improves verbal learning and negative symptoms specifically in patients with tone-matching deficits (Medalia et al., 2019; Saperstein et al., 2025), while transcranial direct current stimulation (tDCS) appears more effective in reducing auditory verbal hallucinations among those with preserved early auditory processing (Kantrowitz et al., 2019).

Neurophysiological mechanisms underlying behavioral tone-matching deficits in schizophrenia can be efficiently probed using EEG and auditory event-related potentials (ERPs), which enable tracking of information flow through the early auditory system (rev. in Dondé et al., 2023). Mismatch negativity (MMN), an ERP component generated primarily in the superior temporal and inferior frontal cortices in response to deviant auditory stimuli, reflects echoic memory processing (Schönwiesner et al., 2007). MMN is reliably reduced in schizophrenia, with robust associations to tone-matching deficits and functional outcomes (Avissar et al., 2018; Javitt et al., 2000). The P300 component, indexing conscious deviant detection and context updating, is likewise diminished, particularly in relation to lower likelihood of clinical remission (Clementz et al., 2022; Hamilton et al., 2024). Early sensory responses such as P1/P50 and N1—linked to sensory gating and phonetic processing—are also disrupted, reflecting impaired cholinergic inhibition and reduced auditory discrimination (Martin and Freedman, 2007). Finally, the 40-Hz auditory steady-state response (ASSR), which reflects the brain's capacity to synchronize with rhythmic auditory input and relies on intact gamma-band oscillatory activity, is consistently impaired in schizophrenia. ASSR deficits have been strongly associated with auditory cortical dysfunction, cognitive impairments, and the persistence of auditory hallucinations (Koshiyama et al., 2021; Thuné et al., 2016).

While both pathophysiological and clinical importance of tone-matching disturbances at the level of the auditory cortex have been extensively documented in schizophrenia, it remains unclear if impaired tone-matching performance is solely related to early sensory dysfunction or if the ability to appropriately translate early levels of processing into behavioral responses contributes to the deficit. Drift-diffusion models (DDMs) offer a powerful computational framework for characterizing the dynamics of perceptual decision-making, and hold significant promise for disentangling sensory encoding from higher-order decisional processes underlying tone-matching impairments in schizophrenia. The DDM assumes that two-choice decisions are made according to a noisy, continuous stochastic process that accumulates sensory information over time from a starting point toward one of two choice criteria or boundaries, the *boundary separation* corresponding to the distance between two decisional thresholds – corresponding respectively to “same” and “different” responses in tone-matching task. The underlying assumption is that the brain derives and accumulates, per time unit, a constant piece of evidence from the representation of the stimulus disturbed by noise, until reaching a decision boundary for one of the two alternatives at hand. The “drift rate” of the accumulation process depends on the sensory signal quality (i.e., stimulus features and complexity) and on sensory noise, responsible for variable decision accuracy and decision time, as indexed by error rate and response time distribution, respectively. Evidence accumulation models explain the non-decisional part of response times, such as the sensory encoding of the stimulus or the motor response in a single parameter (Ratcliff and Rouder, 1998; Ratcliff and Smith, 2004). At the neural level, evidence accumulation has been consistently linked to activity within a fronto-parietal network, partially overlapping with neural correlates of choice bias during perceptual decision-making. In parallel, the modulation of decision thresholds engages fronto-basal ganglia circuits, which also contribute to the implementation of choice biases (rev. in Deco et al., 2013; Mulder et al., 2014).

While no study to date has applied drift-diffusion modeling (DDM) to the tone-matching paradigm specifically, DDM has been effectively employed to dissect cognitive mechanisms in a variety of two-choice tasks in schizophrenia. In a reward–punishment learning task, significantly reduced mean drift rates were observed in patients, particularly following punishment trials, indicating impaired feedback integration and maladaptive stimulus–response updating (Moustafa et al., 2015). In a visual letter oddball task with varying working memory load, lower drift rates were found to correlate with short-term memory deficits not only in patients but also in their unaffected relatives, supporting reduced drift rate as a potential cognitive endophenotype (Fish et al., 2018). Evidence accumulation, however, appeared relatively preserved in a motion discrimination task involving random-dot kinetograms, suggesting that such impairments may be task-dependent (Faivre et al., 2021). Inefficient evidence accumulation and elevated decision thresholds have been shown to underlie aberrant gaze perception in schizophrenia, marked by a self-referential interpretive bias. These alterations suggest a compensatory shift toward increased decisional caution, whereby patients prioritize accuracy over speed to mitigate perceptual uncertainty (Lasagna et al., 2024). Moreover, schizophrenia patients displayed significantly slower drift rates during a response inhibition task, with reductions correlating with symptom severity, thereby linking DDM parameters to clinical phenotypes (Patel et al., 2025). Collectively, these studies demonstrate the utility of DDM for disentangling latent cognitive processes in schizophrenia and for identifying potential mechanistic targets underlying key behavioral impairments.

Using an evidence accumulation model to analyze tone-matching performance, we aim to deconstruct perceptual decision-making into its core computational components, providing a more precise characterization of tone-matching deficits in schizophrenia. Individuals with schizophrenia and healthy controls performed a two-choice tone-matching task. Response accuracy and response time distributions were then modelled using the drift diffusion model. Model parameters were compared among individuals with schizophrenia and healthy controls. Given that the RTP task has proven suitable for probing the dynamics of auditory perceptual decision-making, its implementation in tone-matching paradigms provides a compelling rationale for applying drift-diffusion modeling (DDM) to dissect the latent cognitive processes underlying auditory discrimination impairments in schizophrenia. Our study extends previous work using a DDM to model behavioral data from healthy participants performing a random tone-pitch task –indicating whether sequences of tones increase or decrease in pitch (Mulder et al., 2013).

While sensory encoding deficits in tone-matching have been well-documented at the auditory cortical level, substantial evidence indicates that higher-order processing, whereby sensory information informs behavioral responses, predominantly occurs within frontal brain regions such as the anterior cingulate and prefrontal cortices (Domenech and Dreher, 2010; Fleming et al., 2012; Heekeren et al., 2008). Knowing that functional deficits in these areas contribute to impaired sensory processing in schizophrenia. (Dunn et al., 2016; Kirino et al., 2019; Koshiyama et al., 2020; Takahashi et al., 2013), we predicted that both abnormalities in drift rate and non-decision time would account for tone-matching deficits in schizophrenia. This study complements previous work by being the first to apply DDM to the tone-matching task in schizophrenia, providing new insight into how both early sensory encoding and later decision-making processes contribute to auditory discrimination deficits in the disorder.

2. Methods

2.1. Sample and design

A between-subjects design compared 30 participants with a diagnosis of schizophrenia or schizoaffective disorder according to DSM-5.0 and 30 healthy controls, matched for age, gender and handedness (Table 1). Diagnoses were confirmed by a trained psychiatrist using the Structured Clinical Interview for DSM-5 Disorders (SCID-5). Control participants were also evaluated by a trained psychiatrist using the Mini-International Neuropsychiatric Interview to verify the absence of any current DSM-defined psychiatric disorder and any lifetime history of schizophrenia-spectrum conditions. Exclusion criteria were auditory or neurological impairment, history of intellectual disability, substance use disorder (except for tobacco), brain neuromodulation procedures in the last 3 months. Professional musicians were excluded due to their well-documented superior ability to detect fine-grained auditory pitch changes (Bianchi et al., 2017; Micheyl et al., 2006). The study was approved by a local ethics committee (Comité de Protection des Personnes Sud-Est 6, Lyon, France; NCT02887794). The study was carried out in accordance with ethical principles for medical research involving humans (WMA, Declaration of Helsinki). The experiment consisted of a single visit. Participants were first informed of the protocol and signed the informed consent. Then, participants were assessed with the auditory task in a quiet, isolated room.

Table 1
Socio-demographic and clinical data across groups.

	Schizophrenia ($N = 30$)	**Control** ($N = 30$)
Age (years)	37.4 (11.6)	33.9 (12.6)
Sex ratio (M/F)	21/9	24/6
Lateralization (R/L)	28/1	25/4
Education (years)*	11.0 (3.4)	15.9 (3.7)
Illness duration (years)	14.0 (9.4)	–
CPZ equivalents (mg/d)	1118.6 (995.9)	–
PANSS total	81.9 (18.5)	–
Positive	19.0 (6.1)	–
Negative	23.4 (7.6)	–
General Psychopathology	37.8 (10.2)	–

PANSS: Positive and Negative Syndrome Scale, CPZ: chlorpromazine.

* Significant difference ($p < 0.05$) observed between groups.

2.2. Tone-matching task

Auditory stimulus presentation was controlled by a laptop computer with the sound volume fixed at 70 dB for each participant and kept throughout the test. Participants listen to the auditory stimuli binaurally through headphones connected to the laptop. They were presented with 100 pairs of short 100-ms pure tones (440 +/− 44 Hz) in series, with a 300-ms intertone interval. Within each pair, tones were either identical (25 % of trials) or differ by a specific level of frequency difference (Δ2.5 %, Δ5%, Δ10%, Δ20%, Δ50% Hz). The order of presentation of tone pairs was randomized across participants. Participants had to listen to the pairs of tones and then respond by pressing "the two tones were identical" or "the two tones were different" on a 2-button press (i.e., 50 % chance performance). Participants were instructed to respond as rapidly as possible without compromising accuracy. The test was preceded by audiometric screening to ensure absence of hearing impairment, and by a series of practice pairs to ensure correct understanding of the task. The test took 15–20 min to complete.

2.3. Analyses

2.3.1. Descriptive statistics

Socio-demographic characteristics between groups were compared using independent-sample Fisher's exact F-tests for categorical variables and two-sided Student's *t*-tests for continuous variables: Socio-demographic variables, illness duration, medication dosage (expressed in chlorpromazine equivalents).

2.3.2. Behavioral data

Response accuracy was analysed using a Bayesian mixed-effects logistic regression including group and sensory evidence as fixed effects, random intercepts for participants, and random slopes for each fixed effect (i.e., full random effect structure). Response times were analysed using a Bayesian generalized mixed-effects regression with gamma family and logarithmic link function, including group, sensory evidence, and response accuracy as fixed effects, random intercepts for participants, and random slopes for each fixed effect (i.e., full random effect structure). All priors over fixed effects were set as normal (mean = 0, SD = 1) distributions. Bayes factors offer the distinct advantages of quantifying the strength of evidence and enabling the assessment of evidence in favor of the null hypothesis, a capability not afforded by traditional frequentist statistical methods. All other priors followed the default values from the *brms* package (Bürkner, 2017).

2.3.3. Drift-diffusion model

We further analysed response accuracy and response time using a drift-diffusion model, following a tutorial by Henrik Singmann on the Wiener diffusion model in *brms* (*http://singmann.org/wiener-model-analysis-with-brms-part-i/*). We chose to exclude "same" trials from the DDM since when the two stimuli are identical, there is no perceptual evidence to be accumulated, and therefore drift rate should be zero. Arguably, the decisional process involved when judging the absence of a difference between two stimuli is of a different nature, and modeling it would be beyond the scope of the present work. Recent theoretical advances in visual detection suggest that decisions about the absence of a difference is inferred based on counterfactual reasoning rather than direct sensory evidence (Mazor et al., 2025). Applied to our paradigm, this framework suggests that participants decide that two stimuli are identical based on their prior beliefs about their capacity to detect a difference.

According to drift-diffusion models, decisions are the by-product of four parameters: the *bias* corresponding to the starting point where evidence starts to accumulate, the *drift rate* corresponding to the rate at which evidence accumulates, the *boundary separation* corresponding to the distance between the two decisional thresholds (in tone-matching task: “same” or “different”), and the *non-decision time* accounting for non-decisional processes such as sensory encoding and motor response. We assumed that sensory evidence only impacted the drift rate, as the other parameters could not vary based on stimulus characteristics that were fully randomized and therefore remained undetermined before the start of the trial. In other words, we allowed the drift rate to vary as a function of sensory evidence, while other parameters (boundary separation, non-decision time, and starting point) were kept constant across trials and estimated at the participant level. All priors over fixed effects and intercepts were set as normal distributions (mean = 0, SD = 1; except for the drift rate intercept: mean = 0, SD = 5). The prior over the standard deviation of the random intercepts was set as an exponential distribution with a scale of 1. All other priors followed the default values from the *brms* package. In the specified Wiener diffusion model, the drift rate used an identity link function, the boundary and the non-decision time used a log link function, and the starting point used a logit link function to map the parameters onto their respective valid ranges.

2.3.4. *Model fitting*

All Bayesian models were fitted using 6 Markov Chain Monte-Carlo chains with 5000 iterations each, including 2000 warmup iterations. We report the median fixed effect estimate and corresponding 95 % Credible Interval (95 % CI). We interpret effects for which 95 % CI did not overlap with zero based on their practical significance, which corresponds to the proportion of the posterior distribution outside the region of practical equivalence (ROPE; (Makowski et al., 2019)). Following the Sequential Effect eXistence and sIgnificance Testing (SEXIT) framework, the ROPE was defined as $|0.09|$ for the analysis of response accuracy and $|0.05|$ for the analysis of response times and drift-diffusion parameters, following the default parameters from the bayestestR package (Makowski et al., 2019). Convergence and stability of the Bayesian sampling were assessed using R-hat, which were below 1.01 (Vehtari et al., 2021), and Effective Sample Sizes (ESS), which were greater than 1000 (Bürkner, 2017).

3. Results

3.1. *Sample*

The two groups did not differ significantly in terms of age, sex (control: $N = 30$, 24 females, mean age = 33.9, SD = 12.6; schizophrenia ($N = 23$)/ schizoaffective disorder ($N = 7$): N = 30, 9 females, mean age = 37.4, SD = 11.6, $p = 0.27$, BF = 0.45), but differed in terms of education (control: mean years of education = 15.9, SD = 3.68; schizophrenia: 11.0, SD = 3.35, $p < 0.001$, BF > 8000). Participants with schizophrenia had a mean illness duration of illness of 14.0 years (SD = 9.2) (Table 1).

3.2. *Behavioral analysis*

We started by analyzing response accuracy as a function of the group and sensory evidence (i.e., difference in pitch between the two short tones of each pair) focusing on trials containing different tones. Trials with reaction times above 5-s or below 0-s were excluded, corresponding to 2.2 % of trials. A Bayesian mixed-effects logistic regression revealed a main effect of sensory evidence (Median = 1.54, 95 % CI [1.27, 1.83], probability of being significant ≥ 0.99), and of group (Median = 1.11, 95 % CI [0.51, 1.73], probability of being significant = 0.99), indicating that accuracy was lower in participants with schizophrenia than control participants and increased with sensory evidence in both groups (Fig. 1A).

Additionally, the model indicated that the influence of sensory evidence on accuracy was lower in participants with schizophrenia compared to controls (interaction effect: Median = 0.35, 95 % CI [0.09, 0.61], probability of being significant = 0.98). However, visual inspection of the graph suggests a potential ceiling effect in controls that may partly account for this difference. The same analysis focusing on trials containing identical tones confirmed the effect of the group, with lower accuracy in participants with schizophrenia compared to controls (Median = 0.40, 95 % CI [0.08, 0.73], probability of being significant = 0.97) (Fig. 1B). No other effects were significant.

Next, we analysed response times using a generalized Bayesian mixed-effects regression with sensory evidence, group, and response accuracy as fixed effects. The model revealed shorter response times for controls than for participants with schizophrenia (Median = −0.05, 95 % CI [−0.09, −5.87e-03], probability of being significant = 0.45), and for correct than incorrect responses (Median = −0.13, 95 % CI [−0.17, −0.10], probability of being significant >0.99) (Fig. 1C). An interaction between sensory evidence and response accuracy revealed that the difference in pitch had a speeding effect on correct but not incorrect responses (Median = −0.03, 95 % CI [−0.04, −0.01], probability of being significant = 0.11). The same analysis focusing on trials containing identical sounds confirmed the effect of accuracy, with shorter response times for correct than for incorrect responses (Median = −0.14, 95 % CI [−0.17, −0.10], probability of being significant >0.99) (Fig. 1D).

Those differences remained similar when the level of education, which differed between groups, was entered as a covariate (see supplementary information).

3.3. *Drift-diffusion model*

We analysed response time and accuracy using a Drift Diffusion Model (DDM), focusing on trials with different stimuli only. The model assumed that sensory evidence corresponding to the difference in pitch between the two stimuli is accumulated toward two possible decision bounds, corresponding to correct and incorrect responses. The model's explanatory power was moderate (R2 = 0.19, 95 % CI [0.17, 0.21]). Posterior predictive checks revealed that the model generated data that resembled observed data (Fig. 2, Top panels).

The analysis showed that individuals with schizophrenia had a lower drift rate (Median = −0.53, 95 % CI [−0.89, −0.17], probability of being significant = 0.99) and higher non-decision time (Median = 0.13, 95 % CI [0.06, 0.21], probability of being significant = 0.98). No difference between groups was found regarding the bias and the bound. As expected, sensory evidence increased the drift rate (Median = 0.25, 95 % CI [0.23, 0.27], probability of being significant >0.99), albeit similarly across the two groups (interaction sensory evidence x group: Median = 0.001, 95 % CI [−0.03, 0.05], probability of being significant = 0.02). Together, these results indicate that individuals with schizophrenia accumulate evidence toward a decision slower than healthy controls, irrespective of the quality of sensory evidence available. They also present a longer non-decision time, indicating a slowing of sensory processing and/or motor execution (Fig. 2, Lower panels).

To ensure that diagnostic heterogeneity did not drive our findings, we reanalyzed the data including only patients with a diagnosis of schizophrenia only ($N = 23$). This subgroup showed similar patterns of impaired tone-matching performance compared to the full sample including schizoaffective disorder (Supplementary Figure). These results confirm the robustness of our main findings across diagnostic subgroups.

4. Discussion

This study examined performance in a two-choice tone-matching

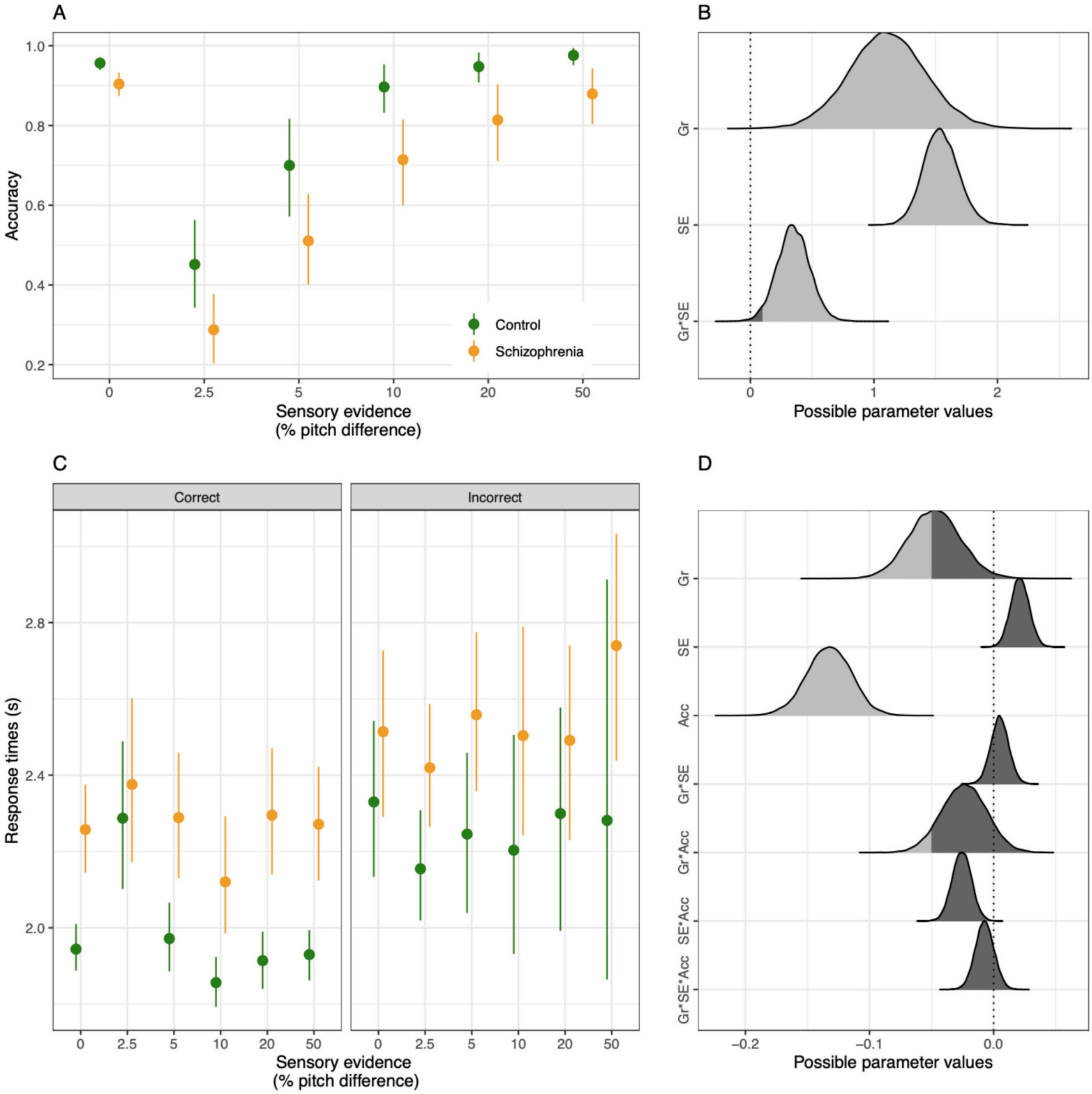

Fig. 1. Behavioral results.
A. Average tone-matching task response accuracy as a function of sensory evidence in control participants (green) and individuals with schizophrenia (yellow). **B.** Posterior distributions of fixed effects from the analysis of response accuracy. **C.** Average response time as a function of sensory evidence in control participants (green) and individuals with schizophrenia (yellow). **D.** Posterior distributions of fixed effects from the analysis of response times. Note that statistical analyses were performed separately on trials with null and non-null sensory evidence.
In panels A and C, dots represent the mean and error bars represent the bootstrapped 95 % confidence intervals. In panels B and D, posterior values are represented in light gray if they are outside the region of practical equivalence, or in dark gray if they are in it. fixed effects are abbreviated as follows: Gr: Group, SE: Sensory evidence, Acc: Accuracy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

task, focusing on accuracy and response time, in individuals with schizophrenia compared to healthy controls. The objective was to determine whether specific sensory and decisional processing measures involved in tone-matching were altered in individuals with schizophrenia compared to healthy controls. Our primary finding reveals that individuals with schizophrenia exhibit significant impairments in tone-matching performance, as evidenced by reduced accuracy (% correct responses) and prolonged response time. Consistent with previous reports (rev. in Dondé et al., 2017, 2023; Javitt and Sweet, 2015), these findings underscore the well-documented deficits in pitch difference detection associated with schizophrenia. We observed that the magnitude of this deficit decreased with the amount of sensory evidence (i.e., pitch difference between the two tones). This result aligns with prior studies demonstrating elevated pitch discrimination thresholds in individuals with schizophrenia (Dondé et al., 2019d; Kantrowitz et al., 2014; Rabinowicz et al., 2000). Here, we present the first evidence that schizophrenia is associated with prolonged response time in a tone-matching task, consistent with previous findings of impaired manual choice response times across a variety of sensory and cognitive tasks (Gale and Holzman, 2000; Vinogradov et al., 1998).

The drift-diffusion model enabled us to break down response time into distinct components and examine their differences between groups. Our analysis revealed a reduced mean drift rate in individuals with schizophrenia, regardless of task difficulty, indicating a general

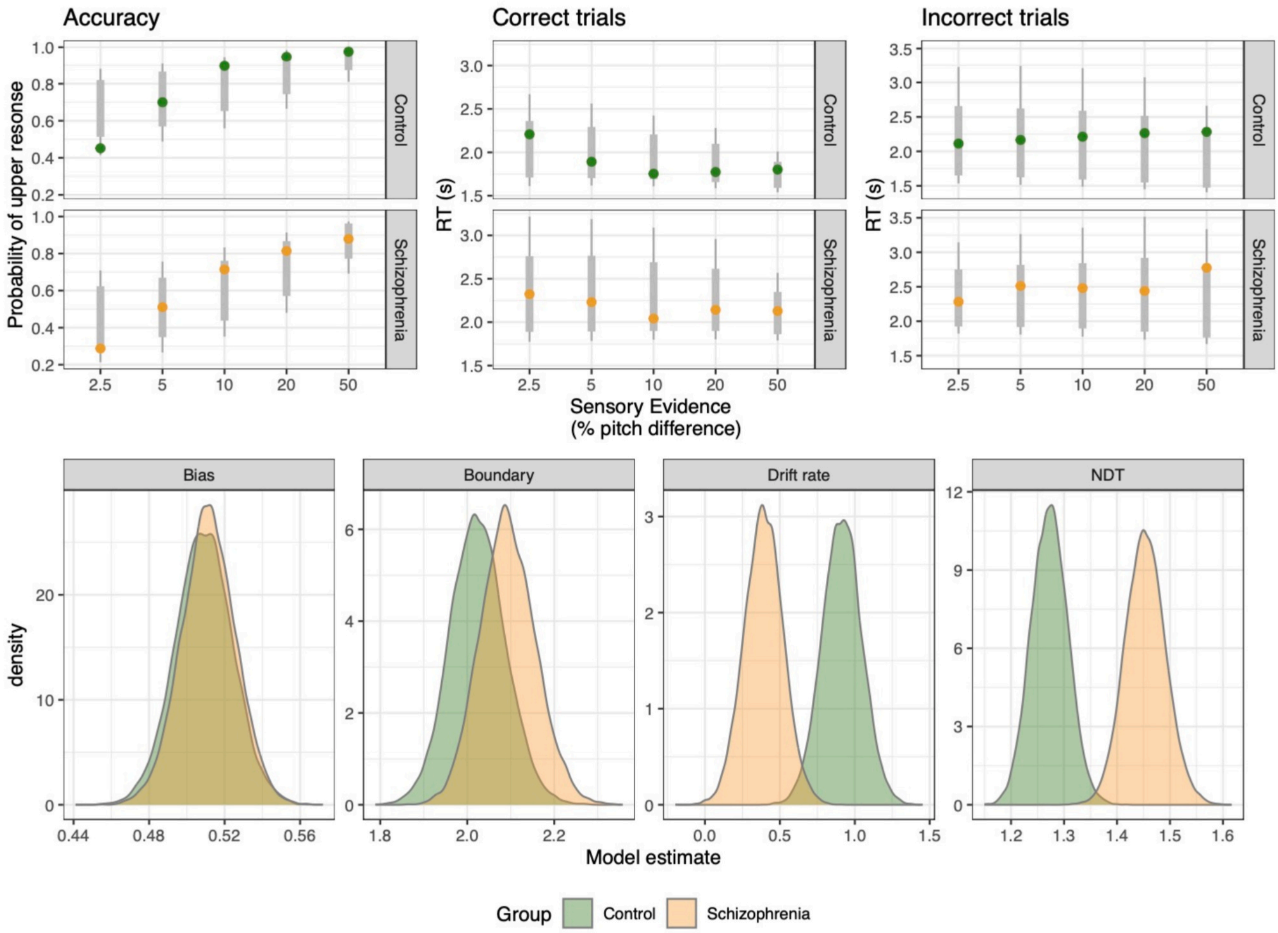

Fig. 2. Drift-diffusion model.

Top panels: Observed and predicted response accuracies and correct/incorrect response times as a function of sensory evidence. Average observed data from control participants and individuals with schizophrenia are represented by green and yellow dots. The 90 % and 95 % confidence intervals of the model predictions are represented by thin and thick gray bars. **Lower panels.** Posterior distributions of model estimates for the bias, boundary, drift rate, and non-decision time in the control (green) and schizophrenia group (yellow). NDT = non-decision time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impairment in evidence accumulation leading to a perceptual decision. A reduced drift rate to reach correct decisions has also been demonstrated in individuals with schizophrenia using the drift-diffusion model. Moustafa et al. (2015) reported a significant reduction in mean drift rate in a reward-punishment task, especially for trials followed by punishment, indicating lower ability to learn how to correctly match a visual stimulus with a reward (Moustafa et al., 2015). Deficits in short-term working memory have been shown to correlate with a reduced drift rate in individuals with schizophrenia while performing a simple visual decision-making task (Fish et al., 2018; see Faivre et al., 2021 for preserved evidence accumulation in a visual discrimination task). At the neural level, the drift rate parallels signals observed in single neurons across various brain regions during reaction time in primates (Smith and Ratcliff, 2004) and humans (Pereira et al., 2021). Studies using two-choice decision tasks have identified neural firing rates in oculomotor regions, such as the frontal eye field, lateral intraparietal cortex, and superior colliculus, as relevant correlates of behavioral decision-making, analogous to drift rate (rev. in Gold and Shadlen, 2001; Hanks and Summerfield, 2017; Schall, 2003). Neuroimaging investigations have implicated the lateral prefrontal cortex as a candidate structure involved in decision-making processes (Heekeren et al., 2004). Supporting this, transient inactivation of this region using transcranial magnetic stimulation has been shown to reduce the estimated drift rate in human perceptual decision-making tasks (Philiastides et al., 2011). Building on this framework, we hypothesize that the reduced drift rate observed in individuals with schizophrenia reflects lower neuronal firing rates during stimulus processing, particularly involving glutamatergic and *N*-methyl-D-aspartate receptor (NMDAR)-mediated processes in relevant brain regions (Dondé et al., 2023). Moreover, EEG studies have identified a positive potential, termed centro-parietal positivity, recorded over midline parietal electrodes that increases in a signal-independent and effector-independent manner as sensory evidence accumulates (Kelly and O'Connell, 2013). This potential shares similarities with the P300 in both topography and dynamics (Twomey et al., 2015). Given that reduced P300 amplitude in early detection of novel or salient stimuli is a well-established deficit in schizophrenia (Hamilton et al., 2024), we propose that diminished P300 amplitude and reduced drift rate reflect shared manifestations of an altered decision-making process.

Another key finding of our study is the increased non-decision time observed in individuals with schizophrenia. This prolongation, reflecting slowed sensory processing and/or motor execution, aligns with prior research (Fish et al., 2018; Lasagna et al., 2024; Moustafa et al., 2015; Patel et al., 2025). It has been proposed that individuals with schizophrenia exhibit impairments in decision-making processes due to deficits in retrieving potential options. This deficit may contribute to the prolonged non-decision time and could also account for the observed slower drift rate. The observed delay in sensory processing is further supported by findings from tone-matching and mismatch negativity

(MMN) studies in schizophrenia. The MMN is a short-latency cognitive event-related potential elicited by deviant auditory stimuli that reflects the preattentive stage of sensory information processing. Decreased MMN amplitude and longer MMN latency to deviants indicate that individuals with schizophrenia encode pitch information less precisely or robustly than controls (Avissar et al., 2018; Mori et al., 2021). We suggest that imprecise encoding disrupts comparisons between the second tone and a locally maintained representation of the first tone at the level of the thalamic-primary auditory cortex circuit (Lakatos et al., 2020), leading to aberrant information transfer from auditory cortex to higher, extra-auditory, cortical regions to determine the degree of match or mismatch between tones reflected by slower drift rate. While non-decision time integrates both sensory encoding and motor execution, these components cannot be entirely disentangled within this measure. However, the strict separation between decisional and motor processes has been questioned by further extensions of the drift diffusion model (Dendauw et al., 2024; Weindel et al., 2021). Moreover, the contribution of motor processes to prolonged non-decision time is likely in schizophrenia, given the well-established evidence of generalized motor slowness and impairments in those individuals (Midorikawa et al., 2008; Sehatpour et al., 2023).

The fact that response bias was close to 0.5 in both groups suggests that patients and controls had no tendency to choose the correct or incorrect response before any evidence is accumulated (e.g., expecting one class of stimuli to be correct more often). In parallel, the similarity in decision boundaries implies that both groups required a similar amount of accumulated evidence before committing to a response, indicating no differences in speed-accuracy trade-off strategy between groups. This suggests that the observed tone-matching impairments in schizophrenia may primarily reflect disruptions in evidence accumulation processes, such as reduced drift rate, which could indicate deficits in the integration or utilization of auditory sensory information. In other words, performance deficits in the schizophrenia group are not attributable to an overly cautious response strategy—such as prioritizing accuracy over speed by accumulating more evidence before committing to a decision—but rather to a slower rate of evidence accumulation itself. Clinically, this suggests that impaired auditory discrimination in schizophrenia may stem less from decisional hesitancy and more from fundamental disruptions in the quality or efficiency of sensory evidence extraction, which could contribute to downstream impairments in higher-order cognition and functional capacity.

Strengths and limitations

To our knowledge, this study is among the first to apply the drift-diffusion model to tone-matching in schizophrenia. By decomposing decision-making into its constituent components, the DDM offers deeper insights than traditional measures of accuracy and average reaction time. Although previous studies have shown reduced accuracy and slowed responses in schizophrenia, our DDM approach quantifies, for the first time, the relative contributions of delayed sensory encoding and motor response versus impaired evidence accumulation—distinctions that conventional tone-matching analyses cannot resolve. Here, we demonstrate that individuals with schizophrenia exhibit both a reliable reduction in drift rate, indicative of slower integration of auditory information, and an increase in non-decision time, suggestive of delayed sensory encoding or motor initiation during tone-matching. Although we did not collect direct neurophysiological data, these computational findings align with previously reported delays in early auditory evoked potentials in schizophrenia, supporting the notion that DDM parameters may serve as behavioral indicators of underlying neural dysfunction. While further work is needed to validate these measures against physiological and clinical outcomes, our results illustrate how tone-matching can be reinterpreted as a more mechanistically informative tool for probing early sensory and decisional processes in schizophrenia.

Despite the novel findings of this study, certain limitations must be acknowledged. First, it is possible that individuals with schizophrenia may perform worse and slower on tone-matching task due to heightened attentional lapses, a well-documented cognitive impairment in schizophrenia (Fioravanti et al., 2012). However, prior research has demonstrated that, after accounting for sensitivity deficits, individuals with schizophrenia do not exhibit greater susceptibility than controls to various attention-related manipulations (Dondé et al., 2019d; Rabinowicz et al., 2000). Furthermore, higher levels of sensory evidence were associated with shorter response times exclusively for correct responses in the present study, suggesting sustained attentional engagement in individuals with schizophrenia throughout the task. These findings suggest that the observed deficits are more likely attributable to imprecise auditory representations rather than increased distractibility. Second, all participants with schizophrenia were receiving antipsychotic medication, making it impossible to entirely rule out the influence of these treatments on non-decision sensor/motor time and the drift rate at which evidence accumulates. Future research should address this limitation by investigating the relationship between antipsychotic dosage and response time distributions in schizophrenia. Third, while it is important to link computational markers to real-world functioning, our study did not include direct neurocognitive or functional assessments. The relationship between DDM parameters and clinical features is important, yet not feasible to study in this context due to the hierarchical nature of the DDM model, which complicates individual-level correlations. Additionally, the absence of defined clinical scores in the control group further limits the ability to use clinical variables as predictors for DDM parameters. It remains to be tested whether lower drift rates and longer non-decision times indeed correspond to poorer performance on functional capacity tests or to slower completion of everyday activities. Future research should address these questions to validate DDM parameters as reliable behavioral proxies for cognitive and functional impairments in schizophrenia.

5. Conclusion

This study demonstrated that individuals with schizophrenia exhibit a processing speed deficit during a simple perceptual decision task. Cognitive modeling of the response time distribution using the drift-diffusion model revealed impairments in both the rate of evidence accumulation required to reach a decision (drift rate) and sensory encoding of auditory stimuli/motor execution of behavioral response. Further investigations incorporating neural and computational approaches may help elucidate the precise neurocognitive mechanisms underlying these deficits and their relationship to real-world functional impairments. Replication in larger samples will be essential to confirm and extend these preliminary findings.

CRediT authorship contribution statement

Clément Dondé: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Michael Pereira:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ladislas Nalborczyk:** Writing – review & editing, Validation, Supervision. **Paul Roux:** Writing – original draft, Validation. **Nathan Faivre:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jérôme Brunelin:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition.

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Declaration of competing interest

None of the authors have a financial interest in any organization or commercial product providing financial support for this research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.schres.2025.07.024.

References

Avissar, M., Xie, S., Vail, B., Lopez-Calderon, J., Wang, Y., Javitt, D.C., 2018. Meta-analysis of mismatch negativity to simple versus complex deviants in schizophrenia. Schizophr. Res. 191, 25–34. https://doi.org/10.1016/j.schres.2017.07.009.

Bianchi, F., Hjortkjær, J., Santurette, S., Zatorre, R.J., Siebner, H.R., Dau, T., 2017. Subcortical and cortical correlates of pitch discrimination: evidence for two levels of neuroplasticity in musicians. NeuroImage 163, 398–412. https://doi.org/10.1016/j.neuroimage.2017.07.057.

Bruder, G., 2004. Verbal memory in schizophrenia: additional evidence of subtypes having different cognitive deficits. Schizophr. Res. 68, 137–147. https://doi.org/10.1016/S0920-9964(03)00156-7.

Bürkner, P.-C., 2017. brms: an R package for Bayesian multilevel models using Stan. J. Stat. Softw. 80. https://doi.org/10.18637/jss.v080.i01.

Carrión, R.E., Cornblatt, B.A., McLaughlin, D., Chang, J., Auther, A.M., Olsen, R.H., Javitt, D.C., 2015. Contributions of early cortical processing and reading ability to functional status in individuals at clinical high risk for psychosis. Schizophr. Res. 164, 1–7. https://doi.org/10.1016/j.schres.2015.01.030.

Clementz, B.A., Parker, D.A., Trotti, R.L., McDowell, J.E., Keedy, S.K., Keshavan, M.S., Pearlson, G.D., Gershon, E.S., Ivleva, E.I., Huang, L.-Y., Hill, S.K., Sweeney, J.A., Thomas, O., Hudgens-Haney, M., Gibbons, R.D., Tamminga, C.A., 2022. Psychosis biotypes: replication and validation from the B-SNIP consortium. Schizophr. Bull. 48, 56–68. https://doi.org/10.1093/schbul/sbab090.

Deco, G., Rolls, E.T., Albantakis, L., Romo, R., 2013. Brain mechanisms for perceptual and reward-related decision-making. Prog. Neurobiol. 103, 194–213. https://doi.org/10.1016/j.pneurobio.2012.01.010.

Dendauw, E., Evans, N.J., Logan, G.D., Haffen, E., Bennabi, D., Gajdos, T., Servant, M., 2024. The gated cascade diffusion model: an integrated theory of decision making, motor preparation, and motor execution. Psychol. Rev. 131, 825–857. https://doi.org/10.1037/rev0000464.

Domenech, P., Dreher, J.-C., 2010. Decision threshold modulation in the human brain. J. Neurosci. 30, 14305–14317. https://doi.org/10.1523/JNEUROSCI.2371-10.2010.

Dondé, C., Luck, D., Grot, S., Leitman, D.I., Brunelin, J., Haesebaert, F., 2017. Tone-matching ability in patients with schizophrenia: a systematic review and meta-analysis. Schizophr. Res. 181, 94–99. https://doi.org/10.1016/j.schres.2016.10.009.

Dondé, C., Avissar, M., Weber, M.M., Javitt, D.C., 2019a. A century of sensory processing dysfunction in schizophrenia. Eur. psychiatr. 59, 77–79. https://doi.org/10.1016/j.eurpsy.2019.04.006.

Dondé, C., Martínez, A., Kantrowitz, J.T., Silipo, G., Dias, E.C., Patel, G.H., Sanchez-Peña, J., Corcoran, C.M., Medalia, A., Saperstein, A., Vail, B., Javitt, D.C., 2019b. Bimodal distribution of tone-matching deficits indicates discrete pathophysiological entities within the syndrome of schizophrenia. Transl. Psychiatry 9, 221. https://doi.org/10.1038/s41398-019-0557-8.

Dondé, C., Martinez, A., Sehatpour, P., Patel, G.H., Kraut, R., Kantrowitz, J.T., Javitt, D. C., 2019c. Neural and functional correlates of impaired reading ability in schizophrenia. Sci. Rep. 9, 16022. https://doi.org/10.1038/s41598-019-52669-6.

Dondé, C., Mondino, M., Leitman, D.I., Javitt, D.C., Suaud-Chagny, M.-F., D'Amato, T., Brunelin, J., Haesebaert, F., 2019d. Are basic auditory processes involved in source-monitoring deficits in patients with schizophrenia? Schizophr. Res. 210, 135–142. https://doi.org/10.1016/j.schres.2019.05.034.

Dondé, C., Silipo, G., Dias, E.C., Javitt, D.C., 2019e. Hierarchical deficits in auditory information processing in schizophrenia. Schizophr. Res. 206, 135–141. https://doi.org/10.1016/j.schres.2018.12.001.

Dondé, C., Brunelin, J., Haesebaert, F., 2020. Duration, pitch and intensity features reveal different magnitudes of tone-matching deficit in schizophrenia. Schizophr. Res. 215, 460–462. https://doi.org/10.1016/j.schres.2019.10.003.

Dondé, C., Kantrowitz, J.T., Medalia, A., Saperstein, A.M., Balla, A., Sehatpour, P., Martinez, A., O'Connell, M.N., Javitt, D.C., 2023. Early auditory processing dysfunction in schizophrenia: mechanisms and implications. Neurosci. Biobehav. Rev. 148, 105098. https://doi.org/10.1016/j.neubiorev.2023.105098.

Dunn, W., Rassovsky, Y., Wynn, J.K., Wu, A.D., Iacoboni, M., Hellemann, G., Green, M.F., 2016. Modulation of neurophysiological auditory processing measures by bilateral transcranial direct current stimulation in schizophrenia. Schizophr. Res. 174, 189–191. https://doi.org/10.1016/j.schres.2016.04.021.

Faivre, N., Roger, M., Pereira, M., De Gardelle, V., Vergnaud, J.-C., Passerieux, C., Roux, P., 2021. Confidence in visual motion discrimination is preserved in individuals with schizophrenia. jpn, 46, E65–E73. https://doi.org/10.1503/jpn.200022.

Fett, A.-K.J., Viechtbauer, W., Dominguez, M.-G., Penn, D.L., Van Os, J., Krabbendam, L., 2011. The relationship between neurocognition and social cognition with functional outcomes in schizophrenia: a meta-analysis. Neurosci. Biobehav. Rev. 35, 573–588. https://doi.org/10.1016/j.neubiorev.2010.07.001.

Fioravanti, M., Bianchi, V., Cinti, M.E., 2012. Cognitive deficits in schizophrenia: an updated metanalysis of the scientific evidence. BMC Psychiatry 12, 64. https://doi.org/10.1186/1471-244X-12-64.

Fish, S., Toumaian, M., Pappa, E., Davies, T.J., Tanti, R., Saville, C.W.N., Theleritis, C., Economou, M., Klein, C., Smyrnis, N., 2018. Modelling reaction time distribution of fast decision tasks in schizophrenia: evidence for novel candidate endophenotypes. Psychiatry Res. 269, 212–220. https://doi.org/10.1016/j.psychres.2018.08.067.

Fleming, S.M., Huijgen, J., Dolan, R.J., 2012. Prefrontal contributions to metacognition in perceptual decision making. J. Neurosci. 32, 6117–6125. https://doi.org/10.1523/JNEUROSCI.6489-11.2012.

Friedman, T., Sehatpour, P., Dias, E., Perrin, M., Javitt, D.C., 2012. Differential relationships of mismatch negativity and visual P1 deficits to premorbid characteristics and functional outcome in schizophrenia. Biol. Psychiatry 71, 521–529. https://doi.org/10.1016/j.biopsych.2011.10.037.

Gale, H.J., Holzman, P.S., 2000. A new look at reaction time in schizophrenia. Schizophr. Res. 46, 149–165. https://doi.org/10.1016/S0920-9964(00)00006-2.

Gold, J.I., Shadlen, M.N., 2001. Neural computations that underlie decisions about sensory stimuli. Trends Cogn. Sci. 5, 10–16. https://doi.org/10.1016/S1364-6613(00)01567-9.

Hamilton, H.K., Mathalon, D.H., Ford, J.M., 2024. P300 in schizophrenia: then and now. Biol. Psychol. 187, 108757. https://doi.org/10.1016/j.biopsycho.2024.108757.

Hanks, T.D., Summerfield, C., 2017. Perceptual decision making in rodents, monkeys, and humans. Neuron 93, 15–31. https://doi.org/10.1016/j.neuron.2016.12.003.

Heekeren, H.R., Marrett, S., Bandettini, P.A., Ungerleider, L.G., 2004. A general mechanism for perceptual decision-making in the human brain. Nature 431, 859–862. https://doi.org/10.1038/nature02966.

Heekeren, H.R., Marrett, S., Ungerleider, L.G., 2008. The neural systems that mediate human perceptual decision making. Nat. Rev. Neurosci. 9, 467–479. https://doi.org/10.1038/nrn2374.

Jauhar, S., Johnstone, M., McKenna, P.J., 2022. Schizophrenia. Lancet 399, 473–486. https://doi.org/10.1016/S0140-6736(21)01730-X.

Javitt, D.C., Sweet, R.A., 2015. Auditory dysfunction in schizophrenia: integrating clinical and basic features. Nat. Rev. Neurosci. 16, 535–550. https://doi.org/10.1038/nrn4002.

Javitt, D.C., Shelley, A.-M., Ritter, W., 2000. Associated deficits in mismatch negativity generation and tone matching in schizophrenia. Clin. Neurophysiol. 111, 1733–1737. https://doi.org/10.1016/S1388-2457(00)00377-1.

Kantrowitz, J.T., Leitman, D.I., Lehrfeld, J.M., Laukka, P., Juslin, P.N., Butler, P.D., Silipo, G., Javitt, D.C., 2013. Reduction in tonal discriminations predicts receptive emotion processing deficits in schizophrenia and schizoaffective disorder. Schizophr. Bull. 39, 86–93. https://doi.org/10.1093/schbul/sbr060.

Kantrowitz, J.T., Hoptman, M.J., Leitman, D.I., Silipo, G., Javitt, D.C., 2014. The 5% difference: early sensory processing predicts sarcasm perception in schizophrenia and schizo-affective disorder. Psychol. Med. 44, 25–36. https://doi.org/10.1017/S0033291713000834.

Kantrowitz, J.T., Sehatpour, P., Avissar, M., Horga, G., Gwak, A., Hoptman, M.J., Beggel, O., Girgis, R.R., Vail, B., Silipo, G., Carlson, M., Javitt, D.C., 2019. Significant improvement in treatment resistant auditory verbal hallucinations after 5 days of double-blind, randomized, sham controlled, fronto-temporal, transcranial direct current stimulation (tDCS): a replication/extension study. Brain Stimul. 12, 981–991. https://doi.org/10.1016/j.brs.2019.03.003.

Kelly, S.P., O'Connell, R.G., 2013. Internal and external influences on the rate of sensory evidence accumulation in the human brain. J. Neurosci. 33, 19434–19441. https://doi.org/10.1523/JNEUROSCI.3355-13.2013.

Kirino, E., Hayakawa, Y., Inami, R., Inoue, R., Aoki, S., 2019. Simultaneous fMRI-EEG-DTI recording of MMN in patients with schizophrenia. PLoS One 14, e0215023. https://doi.org/10.1371/journal.pone.0215023.

Koshiyama, D., Miyakoshi, M., Joshi, Y.B., Molina, J.L., Tanaka-Koshiyama, K., Sprock, J., Braff, D.L., Swerdlow, N.R., Light, G.A., 2020. Abnormal effective connectivity underlying auditory mismatch negativity impairments in schizophrenia. Biological Psychiatry: Cognitive Neuroscience and Neuroimaging 5, 1028–1039. https://doi.org/10.1016/j.bpsc.2020.05.011.

Koshiyama, D., Miyakoshi, M., Thomas, M.L., Joshi, Y.B., Molina, J.L., Tanaka-Koshiyama, K., Sprock, J., Braff, D.L., Swerdlow, N.R., Light, G.A., 2021. Unique contributions of sensory discrimination and gamma synchronization deficits to cognitive, clinical, and psychosocial functional impairments in schizophrenia. Schizophr. Res. 228, 280–287. https://doi.org/10.1016/j.schres.2020.12.042.

Lakatos, P., O'Connell, M.N., Barczak, A., McGinnis, T., Neymotin, S., Schroeder, C.E., Smiley, J.F., Javitt, D.C., 2020. The thalamocortical circuit of auditory mismatch negativity. Biol. Psychiatry 87, 770–780. https://doi.org/10.1016/j.biopsych.2019.10.029.

Lasagna, C.A., Tso, I.F., Blain, S.D., Pleskac, T.J., 2024. Cognitive mechanisms of aberrant self-referential social perception in psychosis and bipolar disorder: insights from computational modeling. Schizophr. Bull. https://doi.org/10.1093/schbul/sbae147 sbae147.

Makowski, D., Ben-Shachar, M., Lüdecke, D., 2019. BayestestR: describing effects and their uncertainty, existence and significance within the Bayesian framework. JOSS 4 (40), 1541. https://doi.org/10.21105/joss.01541.

Martin, L.F., Freedman, R., 2007. Schizophrenia and the α7 nicotinic acetylcholine receptor. In: International Review of Neurobiology. Elsevier, pp. 225–246. https://doi.org/10.1016/S0074-7742(06)78008-4.

Mazor, M., Moran, R., Press, C., 2025. Beliefs about perception shape perceptual inference: an ideal observer model of detection. Psychol. Rev. https://doi.org/10.1037/rev0000552.

Medalia, A., Saperstein, A.M., Qian, M., Javitt, D.C., 2019. Impact of baseline early auditory processing on response to cognitive remediation for schizophrenia. Schizophr. Res. 208, 397–405. https://doi.org/10.1016/j.schres.2019.01.012.

Micheyl, C., Delhommeau, K., Perrot, X., Oxenham, A.J., 2006. Influence of musical and psychoacoustical training on pitch discrimination. Hear. Res. 219, 36–47. https://doi.org/10.1016/j.heares.2006.05.004.

Midorikawa, A., Hashimoto, R., Noguchi, H., Saitoh, O., Kunugi, H., Nakamura, K., 2008. Impairment of motor dexterity in schizophrenia assessed by a novel finger movement test. Psychiatry Res. 159, 281–289. https://doi.org/10.1016/j.psychres.2007.04.004.

Mori, Y., Hoshino, H., Osakabe, Y., Wada, T., Kanno, K., Shiga, T., Itagaki, S., Miura, I., Yabe, H., 2021. Omission mismatch negativity of speech sounds reveals a functionally impaired temporal window of integration in schizophrenia. Clin. Neurophysiol. 132, 1144–1150. https://doi.org/10.1016/j.clinph.2021.01.028.

Moustafa, A.A., Kéri, S., Somlai, Z., Balsdon, T., Frydecka, D., Misiak, B., White, C., 2015. Drift diffusion model of reward and punishment learning in schizophrenia: modeling and experimental data. Behav. Brain Res. 291, 147–154. https://doi.org/10.1016/j.bbr.2015.05.024.

Mulder, M.J., Keuken, M.C., Van Maanen, L., Boekel, W., Forstmann, B.U., Wagenmakers, E.-J., 2013. The speed and accuracy of perceptual decisions in a random-tone pitch task. Atten. Percept. Psychophysiol. 75, 1048–1058. https://doi.org/10.3758/s13414-013-0447-8.

Mulder, M.J., Van Maanen, L., Forstmann, B.U., 2014. Perceptual decision neurosciences – a model-based review. Neuroscience 277, 872–884. https://doi.org/10.1016/j.neuroscience.2014.07.031.

Patel, P.K., Green, M.F., Barch, D., Wynn, J.K., 2025. Mechanisms and correlates of incentivized response inhibition in schizophrenia and bipolar disorder. J. Psychiatr. Res. 183, 282–288. https://doi.org/10.1016/j.jpsychires.2025.02.027.

Pereira, M., Megevand, P., Tan, M.X., Chang, W., Wang, S., Rezai, A., Seeck, M., Corniola, M., Momjian, S., Bernasconi, F., Blanke, O., Faivre, N., 2021. Evidence accumulation relates to perceptual consciousness and monitoring. Nat. Commun. 12, 3261. https://doi.org/10.1038/s41467-021-23540-y.

Philiastides, M.G., Auksztulewicz, R., Heekeren, H.R., Blankenburg, F., 2011. Causal role of dorsolateral prefrontal cortex in human perceptual decision making. Curr. Biol. 21, 980–983. https://doi.org/10.1016/j.cub.2011.04.034.

Rabinowicz, E.F., Silipo, G., Goldman, R., Javitt, D.C., 2000. Auditory sensory dysfunction in schizophrenia: imprecision or distractibility? Arch. Gen. Psychiatry 57, 1149. https://doi.org/10.1001/archpsyc.57.12.1149.

Ratcliff, R., Rouder, J.N., 1998. Modeling response times for two-choice decisions. Psychol. Sci. 9, 347–356. https://doi.org/10.1111/1467-9280.00067.

Ratcliff, R., Smith, P.L., 2004. A comparison of sequential sampling models for two-choice reaction time. Psychol. Rev. 111, 333–367. https://doi.org/10.1037/0033-295X.111.2.333.

Revheim, N., Corcoran, C.M., Dias, E., Hellmann, E., Martinez, A., Butler, P.D., Lehrfeld, J.M., DiCostanzo, J., Albert, J., Javitt, D.C., 2014. Reading deficits in schizophrenia and individuals at high clinical risk: relationship to sensory function, course of illness, and psychosocial outcome. AJP 171, 949–959. https://doi.org/10.1176/appi.ajp.2014.13091196.

Saperstein, A.M., Brennan, R., Qian, M., Javitt, D.C., Medalia, A., 2025. Impact of early auditory processing on negative symptom response to cognitive remediation for schizophrenia. Schizophr. Bull. https://doi.org/10.1093/schbul/sbaf017 sbaf017.

Schall, J.D., 2003. Neural correlates of decision processes: neural and mental chronometry. Curr. Opin. Neurobiol. 13, 182–186. https://doi.org/10.1016/S0959-4388(03)00039-4.

Schönwiesner, M., Novitski, N., Pakarinen, S., Carlson, S., Tervaniemi, M., Näätänen, R., 2007. Heschl's gyrus, posterior superior temporal gyrus, and mid-ventrolateral prefrontal cortex have different roles in the detection of acoustic changes. J. Neurophysiol. 97, 2075–2082. https://doi.org/10.1152/jn.01083.2006.

Sehatpour, P., Kreither, J., Lopez-Calderon, J., Shastry, A.M., De Baun, H.M., Martinez, A., Javitt, D.C., 2023. Network-level mechanisms underlying effects of transcranial direct current stimulation (tDCS) on visuomotor learning in schizophrenia. Transl. Psychiatry 13, 360. https://doi.org/10.1038/s41398-023-02656-3.

Smith, P.L., Ratcliff, R., 2004. Psychology and neurobiology of simple decisions. Trends Neurosci. 27, 161–168. https://doi.org/10.1016/j.tins.2004.01.006.

Strous, R., Cowan, N., Ritter, W., Javitt, D., 1995. Auditory sensory ("echoic") memory dysfunction in schizophrenia. AJP 152, 1517–1519. https://doi.org/10.1176/ajp.152.10.1517.

Sui, J., Pearlson, G.D., Du, Y., Yu, Q., Jones, T.R., Chen, J., Jiang, T., Bustillo, J., Calhoun, V.D., 2015. In search of multimodal neuroimaging biomarkers of cognitive deficits in schizophrenia. Biol. Psychiatry 78, 794–804. https://doi.org/10.1016/j.biopsych.2015.02.017.

Takahashi, H., Rissling, A.J., Pascual-Marqui, R., Kirihara, K., Pela, M., Sprock, J., Braff, D.L., Light, G.A., 2013. Neural substrates of normal and impaired preattentive sensory discrimination in large cohorts of nonpsychiatric subjects and schizophrenia patients as indexed by MMN and P3a change detection responses. NeuroImage 66, 594–603. https://doi.org/10.1016/j.neuroimage.2012.09.074.

Thuné, H., Recasens, M., Uhlhaas, P.J., 2016. The 40-Hz auditory steady-state response in patients with schizophrenia: a meta-analysis. JAMA Psychiatry 73, 1145. https://doi.org/10.1001/jamapsychiatry.2016.2619.

Twomey, D.M., Murphy, P.R., Kelly, S.P., O'Connell, R.G., 2015. The classic P300 encodes a build-to-threshold decision variable. Eur. J. Neurosci. 42, 1636–1643. https://doi.org/10.1111/ejn.12936.

Vehtari, A., Gelman, A., Simpson, D., Carpenter, B., Bürkner, P.-C., 2021. Rank-normalization, folding, and localization: an improved $\hat{R}$ for assessing convergence of MCMC (with discussion). Bayesian Anal. 16. https://doi.org/10.1214/20-BA1221.

Vinogradov, S., Poole, J.H., Willis-Shore, J., Ober, B.A., Shenaut, G.K., 1998. Slower and more variable reaction times in schizophrenia: what do they signify? Schizophr. Res. 32, 183–190. https://doi.org/10.1016/S0920-9964(98)00043-7.

Weindel, G., Anders, R., Alario, F.-X., Burle, B., 2021. Assessing model-based inferences in decision making with single-trial response time decomposition. J. Exp. Psychol. Gen. 150, 1528–1555. https://doi.org/10.1037/xge0001010.