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Insights into audio-visual temporal perception in bipolar disorder and schizophrenia

Monica Gori [a,1], Maria Bianca Amadeo [a,1], Andrea Escelsior [b,c,*], Davide Esposito [a], Alberto Inuggi [c], Riccardo Guglielmo [b,c], Luis Polena [c], Juxhin Bode [c], Beatriz Pereira da Silva [c], Mario Amore [c], Gianluca Serafini [b,c]

[a] U-VIP Unit for Visually Impaired People, Fondazione Istituto Italiano di Tecnologia, Genoa, Italy
[b] IRCCS Ospedale Policlinico San Martino, Genoa, Italy
[c] Department of Neuroscience, Rehabilitation, Ophthalmology, Genetics, Maternal and Child Health (DINOGMI), Section of Psychiatry, University of Genoa, Italy

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ABSTRACT

Our perception of the world and sense of self are deeply influenced by our perception of time. Research in psychiatric disorders has shown altered temporal perception across a variety of tasks, though the mechanisms behind these changes remain unclear. This study aims to explore temporal processing in patients with bipolar disorder (BD) and schizophrenia (SZ) by examining auditory, visual, and audio-visual temporal perception. The results revealed impaired temporal performance across all sensory modalities and the absence of auditory dominance in both patient groups. Specifically, in SZ patients, multisensory processing was associated with visual precision, while in BD patients, there was no such relationship with either visual or auditory precision. Notably, in SZ, visual precision was significantly linked to negative symptoms. Moreover, despite the lack of auditory dominance and similar deficits in unisensory performance, neither patient group benefited from redundant multisensory information in the temporal task. These findings highlight distinct patterns of temporal processing in BD and SZ compared to healthy controls, suggesting potential pathways for targeted interventions, such as integrating sensory training into clinical rehabilitative frameworks.

1. Introduction

A growing body of literature underscores the critical role of sensory processing in psychiatric disorders (van den Boogert et al., 2022). Various alterations have been documented across multiple domains, with particular emphasis on temporal perception (Arrouet et al., 2022; Arstila and Lloyd, 2014; Bolbecker et al., 2011, 2014; Bschor et al., 2004; Casassus et al., 2019; Ciullo et al., 2022; Fuchs, 2013; Liu et al., 2022; Mahlberg et al., 2008; Northoff, 2013; Oyanadel and Buela-Casal, 2014; Ryu et al., 2015; Stanghellini et al., 2017; Tewes and Stanghellini, 2020; Thones and Oberfeld, 2015; Tysk, 1984; Vogel et al., 2018). It has been proposed that the human sense of being, self-awareness, and the experience of time are profoundly interconnected (Kent and Wittmann, 2021). Findings in temporal perception in psychiatric disorders raise the question of whether temporal disturbances could act as clinically meaningful predictors of the disorders or serve as markers for early intervention (Kent et al., 2023).

In schizophrenia (SZ), widespread alterations in temporal perception are observed across both short and long temporal intervals (for a review see Amadeo et al., 2022; Ciullo et al., 2016; Thoenes and Oberfeld, 2017). In contrast, studies on bipolar disorder (BD) report few findings, with short temporal intervals showing no significant differences but longer temporal spans revealing a tendency toward overestimation during manic states and underestimation during depressive states (for a review see Escelsior et al., 2025). Interestingly, recent studies on temporal processing in these disorders consistently identify an expanded temporal binding window, indicating a broader timeframe for integrating sensory stimuli and perceiving them as simultaneous. Specifically, individuals with SZ (Di Cosmo et al., 2021; Foucher et al., 2007; Martin et al., 2013; Noel et al., 2018; Stevenson et al., 2017) and schizotypal traits (Ferri et al., 2016, 2017, 2018), as well as those with BD (Amadeo et al., 2024), exhibit a higher tendency for multisensory

* Corresponding author.
E-mail address: andrea.escelsior@unige.it (A. Escelsior).
[1] These authors contributed equally.

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binding of temporally separated sensory inputs. This points to a deficit in the microstructure of temporality. This temporal alteration is associated not only with diagnostic conditions but also with active psychopathological states such as disorganization and hallucinations (Amadeo et al., 2024; Foucher et al., 2007; Stevenson et al., 2017).

Despite evidence of temporal processing impairments in both SZ and BD, the underlying sensory mechanisms remain poorly understood. Typical individuals display auditory dominance in temporal perception (Aschersleben and Bertelson, 2003; Fendrich and Corballis, 2001), with the auditory system thought to calibrate the sense of time of other sensory modalities during development (Gori, 2015). However, it is unclear if this auditory dominance and calibration holds true for patients with SZ and BD. In typical individuals, auditory inputs are weighted more heavily (Burr et al., 2009; Chen and Yeh, 2009; McGovern et al., 2016; Murai and Yotsumoto, 2016; Recanzone, 2003; Repp and Penel, 2002), and multisensory integration in audio-visual tasks is not observed for some temporal tasks (Gori et al., 2020, 2012). Multisensory integration, which provides a gain through the combination of multiple sensory signals (Gori et al., 2020, 2012), is typically achieved through a statistically optimal Bayesian process (Alais and Burr, 2004; Ernst and Banks, 2002). According to this approach, sensory inputs are combined by weighting unisensory signals for reliability, resulting in improved precision compared to unisensory estimations (Gori, 2015; Gori et al., 2008, 2012). However, during tasks such as temporal bisection, which requires comparison of temporal intervals in a sequence of three stimuli, typical individuals show auditory dominance rather than optimal multisensory integration.

This study investigates auditory, visual, and audio-visual temporal perception to identify mechanisms underlying temporal processing impairments in BD and SZ. These clinical populations show significant overlap in genetic vulnerability and in structural and functional brain alterations, as well as in psychotic symptoms, which are core features of SZ and episodic in BD (Laursen et al., 2009; Pearlson et al., 2016; Yamada et al., 2020). However, they also differ significantly as SZ is characterized by chronic negative symptoms and persistent cognitive impairments, whereas BD is marked by episodic mood dysregulation (manic or depressive states) with psychotic symptoms typically occurring during these episodes. These distinctions highlight shared pathways and unique mechanisms, making their comparison valuable for understanding the interplay between temporal perception and psychotic processes. Our first hypothesis, supported by the results, suggests that both BD and SZ patients exhibit distinct patterns compared to controls, including poorer temporal precision in both auditory, visual, and audio-visual modalities and a lack of auditory dominance. The absence of auditory dominance may underlie the overall temporal deficits, possibly due to disrupted auditory calibration during development. Surprisingly, multisensory performance of SZ patients seems to be associated with the visual performance, which is related to their negative symptoms. Moreover, given that greater multisensory gain is typically observed when unisensory signals have lower reliability (Gori et al., 2017, 2020), we hypothesized that patients would show a better multisensory performance compared to the unisensory ones. Although previous findings suggest this is often true for other populations which show lack of auditory dominance and have similar reliability of auditory and visual modalities (Gori et al., 2020, 2017), this was not the case here. Instead, patients exhibited poor multisensory precision, inconsistent with Bayesian predictions, despite no auditory dominance and similar reliability of auditory and visual precision. These findings suggest that patients experience not only lack of auditory dominance and deficits in unisensory temporal perception but also plausible alterations in temporal multisensory processing per se.

2. Methods

2.1. Participants

To conduct the study, we recruited 19 healthy controls (HC), 16 patients with Bipolar Disorder (BD) and 19 patients with Schizophrenia (SZ). All patients were hospitalized and received a diagnosis of BD or SZ according to the Diagnostic and Statistical Manual of Mental Disorders V criteria (DSM-5, American Psychiatric Association, 2013). Exclusion criteria included the following: psychiatric disorders other than SZ or BP, history of drug and alcohol addiction, neurological disorders, and severe somatic diseases. Patients' details are provided in Table 1.

All healthy individuals had no history of psychiatric, neurological, or cognitive disorders. All participants were Italian native speakers. The research protocol was approved by the ethics committee of the local health service (Comitato Etico, ASL3 Genovese, Italy) and conducted in line with the Declaration of Helsinki. Individuals provided written informed consent prior to testing. Sample size was decided based on previously published studies using the same experimental paradigm in children and adults (Gori et al., 2020, 2012). A power analysis (two--tailed paired *t*-test, Cohen's $d = 0.9$, $\alpha = 0.05$; (Gori et al., 2020)) indicated a minimum of 13 participants to reach a power of 0.85.

Two HC individuals, one patient with BD and two patients with SZ have been excluded from the analyses because they were identified as outliers (Interquartile Range method has been used to address outliers in temporal precision within each group and task). Thus, the remaining sample comprised 17 HC (mean age ± standard deviation = 37 ± 11.7 years old, female = 5), 15 BD patients (47.9 ± 16 years old, female = 3), and 17 SZ patients (43.5 ± 14.1 years old, female = 5). Age was not significantly different across groups ($\chi^2 = 4$, df = 2, $p > 0.05$). Among the participants in the BD group, 7 individuals were experiencing a depressive episode, 6 individuals exhibited a manic state, and 2 individuals displayed a mixed episode at the time of testing.

2.2. Experimental procedure

Participants were sitting in front of a light- and sound-emitting rectangular device placed at a distance of 57 cm from the eyes. Visual stimuli consisted of 1° diameter LEDs displayed for 50 ms; auditory

Table 1
Participants' demographic and clinical characteristics. HC: healthy controls; BD: patients with Bipolar disorder; SZ: patients with Schizophrenia; HAM-D: Hamilton Depression Rating Scale; YMRS: Young Mania Rating Scale; PANSS: Positive and Negative Syndrome Scale. * : Information about disease duration is missing for one participant; # : Information is missing for three participants.

	HC	BD	SZ
Sample size	17	15	17
Age (mean ± SD)	37 ± 11.7	47.9 ± 16	43.5 ± 14.1
Male/Female	5/12	3/12	5/12
Years of disease duration (mean ± SD)	–	19.8 ± 13.4 *	16.4 ± 12
HAM-D total score (mean ± SD)			
YMRS total score (mean ± SD)	–	11.3 ± 8.8	9 ± 9.9
PANSS Negative Scale total score (mean ± SD)	–	14.8 ± 10.3	17.8 ± 9.4
PANSS Positive Scale total score (mean ± SD)	–	13.7 ± 6.6	15 ± 6.9
PANSS General Psychopathology Scale (mean ± SD)		39.3 ± 9	35.5 ± 8.3
Antipsychotic treatment equivalent mg/day (mean ± SD)	–	560.7 ± 1106.4 #	306.6 ± 275.2
Mood stabilizer treatment equivalent mg/day (mean ± SD)	–	969.5 ± 541.5 #	651.4 ± 516
Benzodiazepine treatment equivalent mg/day (mean ± SD)	–	6 ± 6.4 #	6.2 ± 7.5
Antidepressant treatment equivalent mg/day (mean ± SD)	–	44 ± 111.6 #	25.3 ± 02.2

stimuli consisted of 500 Hz tones played for 50 ms. Participants performed three temporal bisection tasks: one involving auditory stimuli (auditory temporal bisection), one involving visual stimuli (visual temporal bisection), and one involving synchronous audio-visual stimuli (audio-visual temporal bisection). The order of the tasks was counterbalanced across subjects in order to take into account possible confounds. During each task (i.e., auditory/visual/audio-visual), a sequence of three consecutive stimuli was delivered for a trial duration of 1000 ms (Fig. 1). Participants judged verbally whether the second stimulus was temporally closer to the first stimulus (−500 ms, considering 0 ms the halfway point of the trial duration) or to the third stimulus (+500 ms). The second stimulus could occur randomly at an intermediate time point between −500 ms (corresponding to the trial start time) and + 500 ms in time (corresponding to the trial end time), determined through the QUEST adaptive algorithm (Watson and Pelli, 1983). Number of trials was set to 30 for each task. Responses were given orally in order to minimize the involvement of motor planning and action, and to maintain consistency with previous works using the same experimental paradigm (Gori et al., 2020, 2012). Before testing, participants were warned to maintain a stable head position straight ahead. A short training session with feedback was conducted to make participants familiar with the task and to be sure they understood it correctly. No feedback were given during experimental sessions.

2.3. Psychopathological assessment

To explore symptomatology of patients at the moment of testing, clinicians administered different psychopathological scales: the Hamilton Depression Rating Scale (HAM-D) (Hamilton, 1960), the Young Mania Rating Scale (YMRS) (Young et al., 1978), and the Positive and Negative Syndrome Scale (PANSS, (Kay et al., 1987). The HAM-D is a clinician-administered assessment tool widely used to measure the severity of depressive symptoms. It consists of 21 items covering a range of symptoms such as mood, guilt, sleep disturbances, and suicidal thoughts. Clinicians rate each item on a scale of 0 to 4 or 0 to 2 based on the patient's reported experiences during the evaluation. Higher scores reflect more severe depressive symptoms. The YMRS is a diagnostic scale designed to evaluate the severity of manic symptoms. It consists of 11 items that assess various aspects of mania, including elevated mood, increased energy, irritability, and disruptive behavior. Each item is scored on a scale ranging from 0 to 4 or 0 to 8, with higher scores indicating more severe manic symptoms. The PANSS is a standardized assessment tool typically used in psychiatry to evaluate the severity of symptoms in individuals with schizophrenia. It comprises 30 items that assess various aspects of psychotic disorders. These items are divided into three subscales: positive subscale (including positive symptoms such as hallucinations and delusions), negative subscale (including negative symptoms such as blunted affect and social withdrawal), and general psychopathology (including anxiety, depression, and disorientation). Each item is rated on a scale from 1 to 7, with higher scores indicating more severe symptomatology.

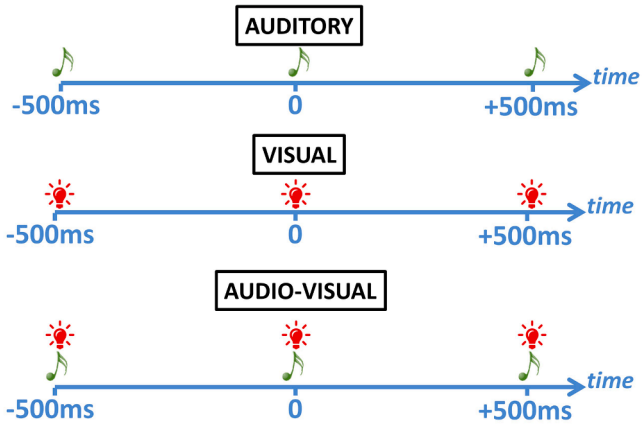

Fig. 1. Graphical representation of the experimental tasks. During each task (auditory, visual and audio-visual temporal bisection), participants listened to a sequence of three stimuli (auditory, visual, or audio-visual) and judged whether the second one was closer in time to the first one (−500 ms) or the third one (+500 ms). The second stimulus could occurred randomly an intermediate time point between −500 ms and + 500 ms in time, determined through the QUEST adaptive algorithm (Watson and Pelli, 1983). 0 ms corresponded to the halfway point of the trial duration (1 s).

2.4. Statistical analyses

All analyses were conducted using R (R Core Team, 2013). For each task, we calculated the proportion of trials where the second stimulus was perceived as closer to the third stimulus and data were fitted by cumulative Gaussian functions. Following standard psychophysical procedures (Kingdom, 2012), point of subjective equality (PSE) and just noticeable difference (JND) estimates were obtained from the mean and standard deviation of the best fitting function, and standard errors for the bisection PSE and JND estimates were calculated by bootstrapping (Efron and Tibshirani, 1994). The PSE represented a participant's perceptual bias in perceiving the halfway point of the trial duration (bisection point); it reflects the accuracy in judgments. The JND represented the discrimination threshold; it reflects the precision in judgments.

Normality distribution for the main variable of interest (i.e., JND) was checked with Shapiro-Wilk normality tests for each group and task. Since normality assumption was not respected, we employed Kruskal Wallis tests and one-sided/two-sided Wilcoxon tests for post-hoc comparisons, correcting data for multiple comparisons using the Bonferroni method. First of all, statistical analyses were performed to explore differences between groups (HC, BD, SZ) in temporal precision (JND) and accuracy (PSE) at each bisection task (Auditory, Visual, Audio-visual). Subsequently, similar analyses were conducted to compare precision (JND) across tasks within each group. Furthermore, to explore the possibility of a dominant attraction of either auditory or visual modality, for each group, linear regressions were conducted to explore the association between the precision of audio-visual temporal bisection and the precision of unisensory auditory and visual temporal bisection.

2.4.1. Association between precision and clinical parameters

Linear regression analyses were conducted to investigate the association between temporal precision in unisensory and multisensory tasks and psychopathological dimensions among patients with BD and SZ. Specifically, we examined whether auditory, visual, and audio-visual precision could be predicted by total scores on the HAM-D, YMRS, and the positive and negative subscales of PANSS. Considering the inclusion of multiple variables, the results pertaining to the association between temporal performance and psychopathological parameters were corrected for multiple comparisons using the Bonferroni method.

To address potential confounding effects associated with medications, Kendall's tau-b correlations were performed between temporal precision (i.e., mean JND value) in unisensory and multisensory tasks and treatment equivalents (mean mg/day) for antipsychotics, mood stabilizers, and benzodiazepines. Antidepressants were not included in correlational analyses as only three out of 15 patients with BD, and two out of 17 patients with SZ, were under this pharmacological treatment. Since both score at the PANSS negative subscale and antipsychotic medication were found to be significantly associated with the visual precision of patients with SZ, we tested a multiple linear regression model with both variables as predictors and visual precision as dependent variable. The multiple linear regression model was then compared with the linear regression model with only score at the PANSS negative subscale as predictor using the Akaike Information Criterion (AIC).

2.4.2. Bayesian predictions

To investigate multisensory integration we applied the Bayesian approach (Alais and Burr, 2004; Ernst and Banks, 2002). The maximum likelihood estimate (MLE) prediction for the audio-visual precision (σ_{AV}) is given by:

$$\sigma_{AV}{}^2 = \frac{\sigma_A{}^2\sigma_V{}^2}{\sigma_A{}^2 + \sigma_V{}^2} \leq \min(\sigma_A{}^2,\ \sigma_V{}^2)$$

where σ_V and σ_A are the visual and auditory unimodal precision. The improvement is greatest ($\sqrt{2}$) when $\sigma_V = \sigma_A$. To test whether the relative contributions of vision and audition can be explained by optimal cue-combination, we compared the observed audio-visual precision with the estimate of the model prediction (σ_{AV}) with one-sided Wilcoxon tests for each group.

2.5. Data availability

Data analyzed during the current study are available from the corresponding author on reasonable request.

3. Results

Precision and accuracy in unisensory and multisensory bisection tasks

First, we demonstrated that both groups of patients compared to healthy controls show an impairment in temporal bisection regardless of the sensory modality involved (Fig. 2). Indeed, for all bisection tasks, the analysis on precision comparing groups revealed a significant difference across them (for auditory: $H = 19.1$, df $= 2$, $p < 0.001$; for visual: $H = 12.1$, df $= 2$, $p = 0.002$; for audio-visual: $H = 13.5$, df $= 2$, $p = 0.001$). Post-hoc comparisons showed that SZ patients have worse precision (i.e., higher JNDs) compared to HC (for auditory: $W = 260$, $p < 0.001$; for visual: $W = 238$, $p = 0.002$; for audio-visual: $W = 244$, $p < 0.001$), and BD patients have worse precision compared to HC (for auditory: $W = 220$, $p < 0.01$; for visual: $W = 199$, $p = 0.01$; for audio-visual: $W = 202$, $p = 0.008$). The precision of BD and SZ patients is instead statistically similar (for auditory: $W = 124$, $p = 0.9$; for visual: $W = 141$, $p = 0.6$; for audio-visual: $W = 133$, $p = 0.9$).

Secondly, we proved temporal precision varies solely within the HC group between the visual and auditory tasks (Fig. 3). In fact, the comparisons across tasks within each group yielded a significant difference in HC ($H = 6.4$, df $= 2$, $p = 0.04$) but not in BD ($H = 0.2$, df $= 2$, $p = 0.9$) and SZ patients ($H = 0.9$, df $= 2$, $p = 0.7$). Post-hoc analysis in HC revealed that temporal precision in the auditory bisection task is better (i.e., lower JNDs) compared to the one in the visual bisection task ($W = 77$, $p = 0.02$), while it is similar between the auditory and audio-visual tasks ($W = 112$, $p = 0.3$), and between the visual and audio-visual tasks ($W = 194$, $p = 0.1$). This suggests auditory dominance only for HC, which is further highlighted in Fig. 4 reporting individual and mean auditory JNDs against visual JND for HC, BD and SZ. Most patients show higher JNDs than the HC group. Moreover, audio and visual JNDs of both patients with BD and SZ fall around the equality line, indicating that their unisensory performance for the two unisensory tasks was similar. In contrast, HC individuals show unisensory JNDs falling mostly below the equality line, indicating better performance in the auditory than in the visual bisection task and auditory dominance.

Despite this difference in precision at the tasks between patients and HC, accuracy does not change across groups (for auditory: $H = 1.4$, df $= 2$, $p = 0.5$; for visual: $H = 0.9$, df $= 2$, $p = 0.6$; for audio-visual: $H = 3.1$, df $= 2$, $p = 0.2$).

Relationship between unisensory and multisensory precision

While an auditory dominance can explain the bimodal performance of HC (in line with previous literature (Gori et al., 2017, 2020, 2012)), this is not the case for BD and SZ groups. Indeed, the linear regression to predict audio-visual precision from unisensory auditory and visual precision is significant for HC ($F_{2,14} = 16.2$, $p < 0.001$, $R^2 = 0.7$) and SZ ($F_{2,14} = 14.8$, $p < 0.001$, $R^2 = 0.7$) but not BD ($F_{2,12} = 1.4$, $p = 0.3$, $R^2 = 0.2$). However, the significant predictor is auditory precision ($p < 0.001$) and not visual one ($p = 0.8$) for HC, and the opposite for SZ (auditory precision: $p = 0.1$; visual precision: $p < 0.001$). Fig. 5 shows the association between auditory/visual precision and audio-visual precision for each group, reporting the results of post-hoc linear regressions considering unisensory modality separately.

Temporal precision and clinical parameters

Linear regressions were carried out to investigate whether temporal precision in unisensory and multisensory tasks was related to psychopathological dimensions for patients with BD and SZ. All linear regressions with auditory/visual/audio-visual precision as dependent variable and scores at HAM-D, YMRS and the positive and negative subscales of the PANSS as regressors failed to find significant associations ($p > 0.05$) except for visual precision of SZ patients and the score at the negative subscale of the PANSS. Specifically, score at the negative subscale of the PANSS explains a portion of the variance of visual precision of patients with SZ ($F_{1,15} = 9.2$, $p = 0.03$, $R^2 = 0.4$; Fig. 6).

Furthermore, Kendall's tau-b correlational analyses revealed a lack of significant association between medication dosage and unisensory and multisensory tasks for both BD and SZ groups, except for antipsychotic medication dosage medications and visual precision in patients with SZ (see Table 2). To better understand the association between PANSS negative subscale scores, antipsychotics, and visual precision in SZ, subsequent linear regression analyses were conducted with visual

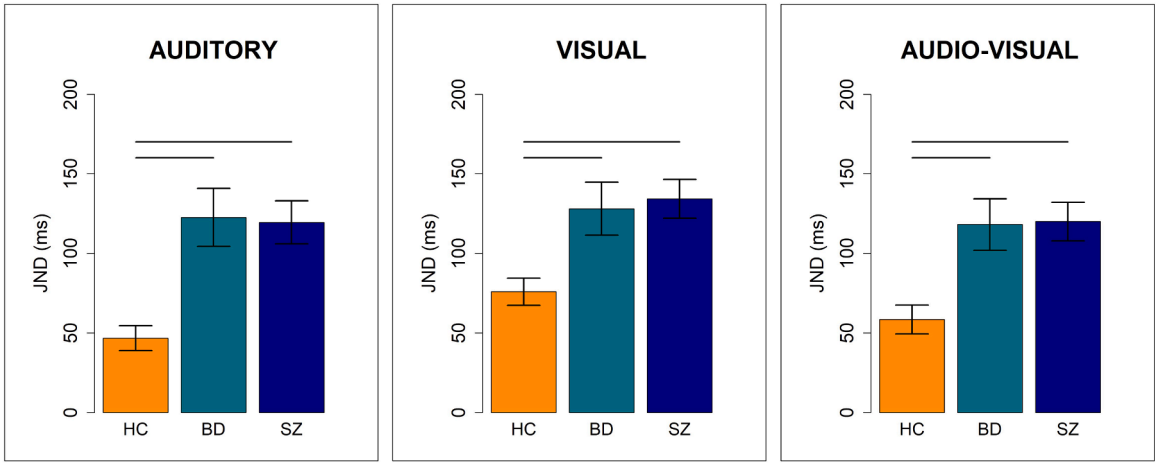

Fig. 2. Precision at auditory, visual, and audio-visual bisection tasks for healthy controls (HC), patients with bipolar disorder (BD) and patients with schizophrenia (SZ). Mean JND ± standard mean error (SEM) is represented for each group and task. Horizontal lines represent significant comparisons.

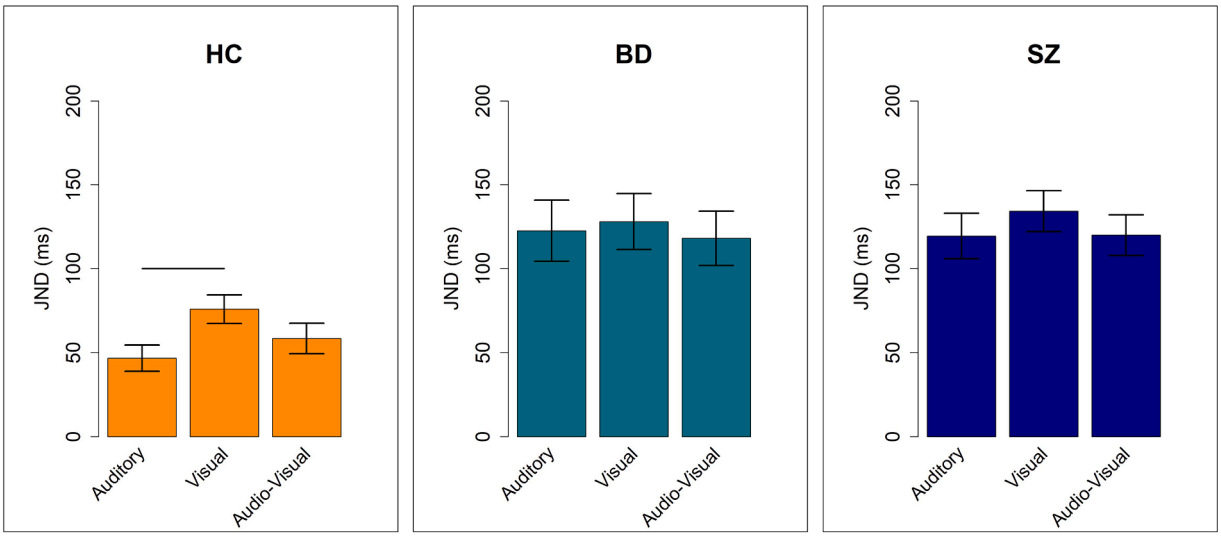

Fig. 3. Precision of healthy controls (HC), patients with bipolar disorder (BD) and patients with schizophrenia (SZ) in auditory, visual and audio-visual bisection tasks. Mean JND ± standard mean error (SEM) is represented for each task and group. Horizontal lines represent significant comparisons.

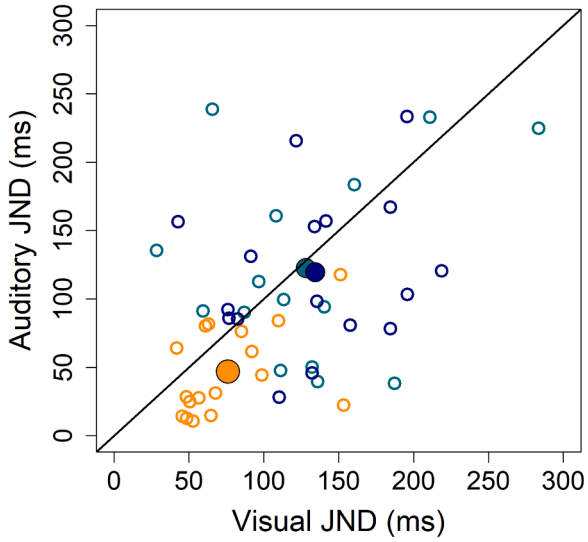

Fig. 4. Auditory precision (JNDs) against visual precision (JNDs) for the healthy controls (in orange), patients with bipolar disorder (in dark cyan) and patients with schizophrenia (in blue). Empty dots represent individual data, filled dots represent mean JND values for each group.

precision as the dependent variable. The linear regression model presented above with PANSS negative subscale scores as the predictor was compared with a multiple linear regression model that combined both predictors (i.e., PANSS negative subscale and antipsychotics). Interestingly, this combined model explained a significant proportion of the variance in visual precision ($F_{2,14} = 7.9$, $p = 0.005$, $R^2 = 0.5$) and exhibited a lower AIC (175.7) compared to the model with only PANSS negative subscale score as the predictor (AIC = 178.3). This suggests that the multiple regression model provides a better balance between model fit and complexity, indicating that considering both PANSS negative score and antipsychotic medication dosage enhances the model's explanatory capacity for visual precision. However, while score at PANSS negative demonstrated a statistically significant role ($p = 0.006$), antipsychotic medication dosage only approached significance ($p = 0.05$), suggesting that the variance in visual precision is predominantly explained by scores on the PANSS negative subscale rather than antipsychotic dosage.

Multisensory processing and Bayesian predictions

Multisensory integration was investigated by comparing precision at the audio-visual temporal bisection task with the bimodal precision predicted by the Bayesian model (Fig. 7). As shown in Fig. 5, a significant difference emerged from each group (HC: $W = 202$, $p = 0.02$; BD: $W = 167$, $p = 0.01$; SZ: $W = 213$, $p = 0.009$), suggesting lack of Bayesian integration for the audio-visual bisection task. Indeed, for all groups, audio-visual JNDs are higher than the Bayesian prediction.

4. Discussion

In this study we investigated auditory, visual, and audio-visual temporal perception in HC, patients with BD and patients with SZ in order to explore temporal representation in these psychiatric disorders. Results demonstrated that: i) patients have worse temporal performance independently of the sensory modality involved; ii) patients show a lack of auditory dominance in temporal perception, with multisensory precision linked either to visual performance (SZ) or none of the unisensory auditory or visual performances (BD); iii) visual precision of SZ patients was significantly associated with negative symptoms as measured by the PANSS negative subscale; and iv) patients do not benefit from redundant multisensory information in building temporal representations despite lack of auditory dominance and similarly less reliable unisensory performance.

i) Lower performance of patients with bipolar disorder and schizophrenia during temporal bisection tasks

Typical individuals and patients were assessed using a temporal bisection task involving auditory, visual, and audio-visual stimuli. They were required to judge whether the second stimulus of a sequence of three consecutive stimuli was closer in time to the first or third one. Across both unisensory and multisensory tasks, patients with BD and SZ exhibited less precision compared to HC. For SZ group, this aligns with previous literature indicating altered time processing at both phenomenological and perceptual levels (Amadeo et al., 2022; Ciullo et al., 2016; Martin et al., 2014; Thoenes and Oberfeld, 2017). For BD patients, the decreased temporal performance falls within a less clear context as temporal skills seem to vary based on interval span and task type (for a review, see Escelsior et al., 2025). Utilizing a different version of the bisection task, two studies reported similar skills between BD patients and HC when evaluating the length of a given temporal interval (Ciullo et al., 2022; Liu et al., 2022), while one study (Bolbecker et al., 2014)

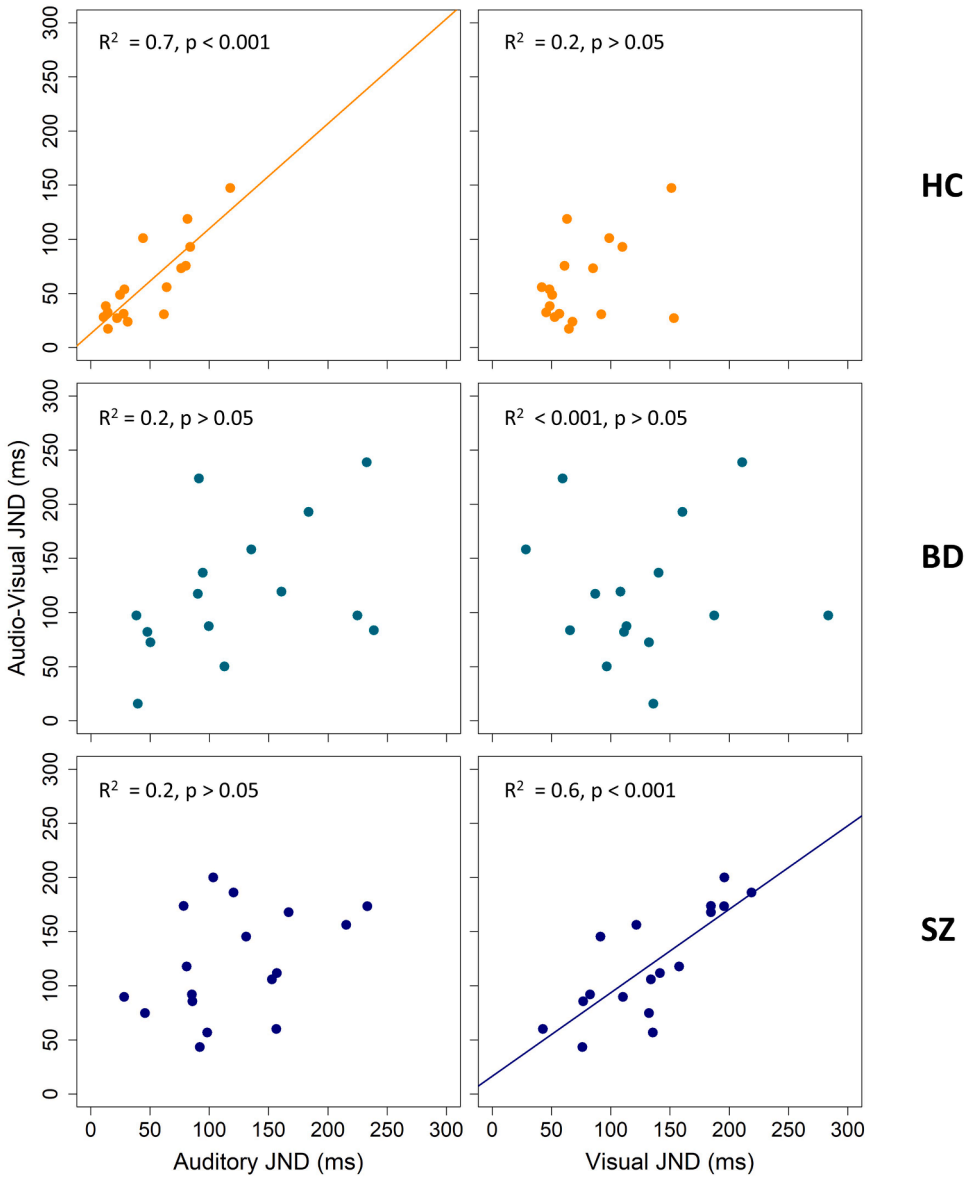

Fig. 5. Individual audio-visual precision plotted against individual auditory precision (left) and visual precision (right) for healthy controls (HC, top), patients with bipolar disorder (BD, middle) and patients with schizophrenia (SZ, bottom). Linear regression results are reported (i.e., R^2 and p-values); straight lines represent significant regressions.

documented increased timing variability (similar accuracy but reduced precision). Notably, the first two studies used near-second stimuli, whereas the latter one involved a time range within 300 ms-600 ms. Since the present study included a maximum temporal interval of 1 second (i.e., the temporal delay between the first and the third stimuli), the results suggest that temporal skills of BD patients could be impaired when dealing with sub-second temporal spans.

Importantly, accuracy was not varying between HC and patients in either unisensory and multisensory bisections, suggesting that all participants understood the instructions and were able to perform the tasks.

ii) Lack of auditory dominance for temporal perception in patients with bipolar disorder and schizophrenia

When comparing temporal precision in unisensory tasks, a significant difference between auditory and visual performance is observed only for HC. Specifically, HC demonstrated higher precision in the auditory task, as evidenced by lower JND. This finding aligns with previous studies demonstrating clear auditory dominance in typical children and adults during temporal bisection (Gori et al., 2017, 2020, 2012). Audition is generally considered the most accurate sense for representing temporal information and prevails in various multisensory temporal tasks (e.g. (Barakat et al., 2015; Bresciani and Ernst, 2007; Burr et al., 2009; Guttman et al., 2005). As such, it has been argued that auditory calibrates the other sensory modality for temporal perception during development (Gori, 2015; Gori et al., 2008, 2012). However, the difference in precision between auditory and visual tasks is absent for patients with BD and SZ. This suggests a lack of auditory dominance and an overall deficit in temporal processing during sub-second intervals, independent of the sensory modality involved. Even in the case of audition, typically considered the most accurate for temporal perception, there is no behavioral advantage observed in the presence of psychiatric disorders such as BD or SZ. The lack of discrepancy between visual and auditory precision may be attributed to an elevated baseline sensory noise present in both patient groups, affecting both modalities albeit to varying degrees among individuals. This can be observed in Fig. 4 showing individual data. While data from HC tend to fall below the equality line, indicating superior auditory precision, individuals

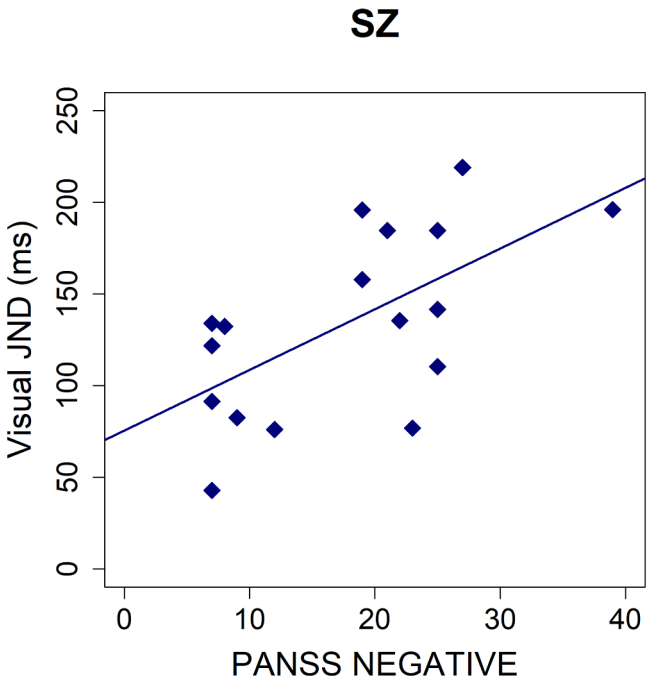

Fig. 6. Association between visual precision of patients with schizophrenia (SZ) and scores at the negative subscale of the PANSS. Individual data are plotted; straight line represents linear regression line.

Table 2
Results of Kendall's tau-b correlational analyses between precision at unisensory and multisensory temporal bisection and treatment-equivalent dosage (mg/day) for antipsychotics, mood stabilizers, and benzodiazepines. Tau coefficient and p-value are reported for each correlation. For each medication dosage, the number of BD and SZ patients who received that specific treatment is reported.

	Antipsychotics (BD: $n = 11$; SZ : $n = 17$)	Mood stabilizers (BD: $n = 11$; SZ : $n = 13$)	Benzodiazepines (BD: $n = 6$; SZ : $n = 11$)
Auditory bisection	BD: 0.04, $p = 0.8$	BD: −0.2, $p = 0.4$	BD: −0.3, $p = 0.3$
	SZ: 0.1, $p = 0.6$	SZ: 0.2, $p = 0.2$	SZ: −0.2, $p = 0.3$
Visual bisection	BD: 0.3, $p = 0.2$	BD: 0.3, $p = 0.1$	BD: −0.03, $p = 0.9$
	SZ: 0.4, $p = 0.02$ *	SZ: −0.1, $p = 0.5$	SZ: 0.07, $p = 0.7$
Audio-Visual bisection	BD: −0.2, $p = 0.2$	BD: −0.09, $p = 0.7$	BD: 0.1, $p = 0.6$
	SZ: 0.3, $p = 0.05$	SZ: 0.07, $p = 0.7$	SZ: −0.07, $p = 0.7$

with BD and SZ exhibit significant dispersion, with roughly equal proportions of participants lying above and below the equality line. We speculate that the absence of auditory dominance may contribute to the overall deficit in temporal perception observed in clinical samples, potentially due to the lack of auditory calibration of other senses during development: without auditory calibration, temporal precision of the other senses may have not properly developed.

The auditory dominance in HC is underscored also by the significant correlation between bimodal precision and auditory precision. Conversely, this association is absent in patients with SZ and BD, where bimodal precision aligns with visual precision or neither auditory nor visual precision, respectively. These findings indicate that audio-visual performance in HC is primarily influenced by auditory precision (in line with previous results), is independent of unisensory performance in BD and is driven by visual precision in SZ. This suggests that different mechanisms of multisensory processing are occurring for the three groups (more auditory-oriented in HC, more visual-oriented in SZ and non-oriented in BD), unveiling intriguing perspectives and prompting further investigations. The independence of bimodal performance from unisensory performance in BD suggests a lack of communication between unisensory and multisensory processing. In contrast, a plausible explanation for the bimodal performance of SZ patients involves visual attraction and a switch from auditory to visual dominance. Notably, existing literature has already suggested a specific link between SZ and vision, with congenital blindness likely acting as a protective factor against the development of the disorder (Morgan et al., 2018). While our data necessitate further scrutiny for comprehensive understanding, it introduces the possibility that visual training could enhance the temporal perception of SZ, and this enhancement may hypothetically transfer to multisensory and auditory conditions (McGovern et al., 2016). On the one hand, we hypothesize that auditory training could improve the overall temporal perception thanks to cross-calibration mechanisms. On the other hand, we speculate that vision could be exploit as calibrating sense for temporal perception in light of lack of auditory dominance for SZ patients.

iii) Clinical assessment in patients with bipolar disorder and schizophrenia

To explore the intricate relationship between temporal perception and psychopathology, we investigated two distinct diagnostic categories (BD and SZ) while considering scores from various clinical scales. Initially, no discernible differences emerged between BD and SZ, indicating that compromised skills and deficits in temporal bisection tasks are shared features in both psychiatric disorders. Upon delving into psychopathological dimensions, we noted that the performance of BD patients showed no significant correlations with depressive symptoms (as assessed by HAM-D), manic symptoms (measured by YMRS), or positive and negative symptomatology (investigated by PANSS). This could imply that alterations in temporal processing represent a trait of the disease rather than a state of it. Intriguingly, in SZ patients, we found no relationships with HAM-D, YMRS, and the positive subscale of PANSS. However, a noteworthy trend emerged, suggesting that visual precision was associated with scores on the negative subscale of PANSS (i.e., better precision associated with reduced symptomatology). This is in line with previous data indicating that poorer visual processing, particularly visuospatial working memory, velocity discrimination and contour integration, is associated with greater negative symptoms in SZ patients (Turkozer et al., 2019). Recently, lower middle temporal (MT) thickness was associated with greater negative symptoms (Adhan et al., 2020). MT is a cortical region involved in velocity discrimination (Zeki, 2015), perhaps serving as a connecting hub between negative symptoms and visual precision in schizophrenic individuals. The link between vision and negative symptoms is even more interestingly if we consider our results indicating an association between multisensory and visual performance in SZ, and with previous research highlighting blindness as a protective factor against SZ (Morgan et al., 2018). Indeed, lower negative symptoms and better visual performance appear to be linked, potentially underlying improved multisensory performance. Nevertheless, further exploration is warranted to better understand the nature of this association. While our study identified a link between poorer visual precision and the severity of negative symptoms, we did not observe a direct corresponding link between multisensory performance and negative symptoms. Further investigations are needed to deepen our understanding of the intricate relationship between visual processing and psychopathological dimensions. This entails exploring the direction of influence and the interconnectedness between sensory deficits and clinical aspects.

As regards potential confounding effects associated with medications, we excluded an influence of dosage of mood stabilizers and benzodiazepines on unisensory and multisensory precision. Nonetheless, dosage of antipsychotics significantly correlates with visual precision of patients with SZ and the latter is better predicated when considering

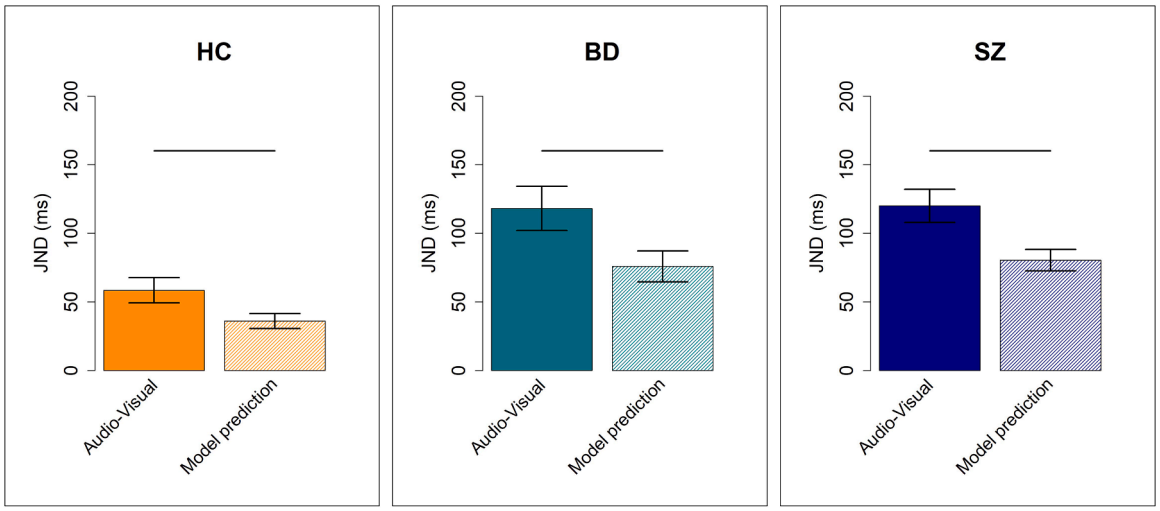

Fig. 7. Precision at audio-visual bisection task and bimodal precision predicted by the Bayesian model for healthy controls (HC), patients with bipolar disorder (BD), and patients with schizophrenia (SZ). Mean JND ± standard mean error (SEM) is represented. Horizontal lines represent significant comparisons.

dosage of antipsychotics together with negative symptomatology. Yet, when evaluating the impact of antipsychotics while considering the negative symptoms as addressed by the negative subscale of the PANSS, we observed that variance in visual precision is predominantly explained by the negative symptomatology rather than the medication dosage. This suggests that it is mainly the psychopathological dimension which is associated with visual performance.

iv) Lack of multisensory gain in patients with bipolar disorder and schizophrenia

The investigation of multisensory processing has garnered considerable attention in psychiatry, particularly in relation to the study of SZ (Grohn et al., 2022; Hornix et al., 2019; Tseng et al., 2015). However, research has revealed varying patterns, showcasing altered integration of sensory information in different directions. On the one hand, reduced multisensory integration has been reported for speech processing (de Gelder et al., 2003; Pearl et al., 2009) and processing of emotional faces and voices (de Jong et al., 2009), as well as lack of multisensory facilitation of reaction times for bimodal targets (Williams et al., 2010). On the other hand, heightened facilitation effects, suggesting higher integration, have been also observed for audio-visual stimuli during a detection task (Stone et al., 2011). Furthermore, while the above studies noted distinct alterations (de Jong et al., 2009; Ross et al., 2007; Williams et al., 2010), others found no disparities in multisensory integration between SZ and non-clinical individuals (de Boer-Schellekens et al., 2014; de Gelder et al., 2003).

To shed light on multisensory processing, we employed the Bayesian approach, which posits that different sensory inputs are combined after weighting for reliability. This framework predicts that the presence of multiple sensory signals, such as visual and auditory stimuli, should result in a gain in the precision of multimodal estimation. Previous studies have demonstrated the efficacy of the Bayesian approach in predicting multisensory gain across various tasks (Alais and Burr, 2004; Ernst and Banks, 2002; Landy et al., 2011). However, for audio-visual temporal bisection, both healthy children and adults have displayed auditory dominance rather than optimal integration due to the higher reliability of the auditory system in temporal perception (Burr et al., 2009; Gori et al., 2012). In our study, we replicated these results in HC by revealing that auditory precision surpasses visual precision and the Bayesian model prediction significantly differed from the observed precision in the audio-visual task. Interestingly, the discrepancy between bimodal precision and model prediction was also observed in both patients with BD and patients with SZ. In other populations, such as dyslexic children (Gori et al., 2020) and children with restored audition (Gori et al., 2017), research has demonstrated that reduced precision in the auditory modality and similar reliability between audition and vision leads to optimal multisensory integration as predicted by the Bayesian model. Hence, the absence of multisensory gain, combined with the lack of auditory dominance in patients with BD and SZ, may suggest an alteration in multisensory processing that adds to the deficits observed in unisensory processing. However, future studies, involving tasks which require multisensory integration also in HC, could be designed and texted to explore multisensory integration using the Bayesian approach in patients.

5. Limitations

This study has certain limitations that should be considered when interpreting the findings. First, the sample size is relatively small, which limits the generalizability of the results and the interpretation of the regression analyses. Secondly, although patients and HC show a similar accuracy in the temporal bisection task, we cannot completely rule out an impact of cognitive functions on the performance. Moreover, while this study has accounted for the impact of pharmacological treatments on the participants, it is important to acknowledge the potential influence such treatments may have on the measured performances. The absence of drug-naive patients in our sample represents a limitation, as it precludes the examination of baseline psychophysical performance without the effects of medication.

6. Conclusion

In this study, we explored auditory, visual, and audio-visual temporal perception in individuals with BD, SZ, and HC. Our findings revealed shared deficits in temporal performance across unisensory and multisensory modalities for both BD and SZ groups. Notably, auditory dominance in temporal perception, observed in HC, was absent in patients with BD and SZ, highlighting a plausible mechanism underlying the deficit in temporal processing observed in clinical samples. Furthermore, multisensory precision in SZ patients was associated with visual performance, which, in turn, was associated with their negative symptoms. These results underscore the presence of distinct patterns of temporal perception in clinical samples, emphasizing the need for future research to investigate the mechanisms underlying temporal deficits reported in the literature. Finally, despite reduced unisensory precision and the absence of auditory dominance, SZ and BD patients did not exhibit multisensory gain in the audio-visual task. These findings reveal

potential critical aspects of sensory processing abnormalities. The ability to integrate sensory information in time has been previously linked to the emergence of a sense of self and disruptions in self-awareness. Exploring this connection further and understanding the intricate relationships between sensory deficits and clinical psychopathology could pave the way for innovative, targeted interventions. Incorporating sensory training into clinical rehabilitative frameworks may offer new avenues for treatment.

CRediT authorship contribution statement

Monica Gori: Conceptualization, Methodology, Writing – original draft, Validation. **Maria Bianca Amadeo:** Conceptualization, Formal analysis, Writing – original draft. **Andrea Escelsior:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **Davide Esposito:** Formal analysis, Writing – review & editing. **Alberto Inuggi:** Data curation, Writing – review & editing. **Riccardo Guglielmo:** Writing – review & editing. **Luis Polena:** Investigation. **Juxhin Bode:** Investigation. **Beatriz Pereira da Silva:** Resources, Funding acquisition. **Mario Amore:** Funding acquisition, Validation, Supervision. **Gianluca Serafini:** Funding acquisition, Validation, Supervision.

Declaration of competing interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Data availability

Data will be made available on request.

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