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Body-environment integration: Temporal processing of tactile and auditory inputs along the schizophrenia continuum

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ABSTRACT

According to the dimensional approach to psychosis, there is a continuum from low schizotypy to schizophrenia patients. The temporal aspect of sensory processing seems to be compromised across such continuum, as suggested by different studies separately investigating unisensory or multisensory domains. Most of these studies have so far focused primarily on the temporal processing of visual and auditory stimuli, either in schizotypy or schizophrenia, while leaving the tactile domain and the integration of touch with other senses mostly unexplored. Given the relevance of body-related perceptual abnormalities for psychosis proneness, we aimed at filling this gap in the literature across two studies. We asked participants with increasing levels of schizotypy (study 1) and schizophrenia patients (study 2) to perform three simultaneity judgement tasks: a unimodal tactile task, a unimodal auditory task and a bimodal audio-tactile task. Each task allowed estimating a simultaneity range (SR), as a proxy of the individual tolerance to asynchronies in the tactile, auditory and audio-tactile domains, respectively. Results showed larger SRs as the level of schizotypy increases. Specifically, the linear effect of schizotypy levels on the audio-tactile task was stronger than on the auditory task, which in turn was greater than the effect on the tactile task (study 1). Differently, schizophrenia patients showed larger SRs than controls in all the three tasks (study 2). The current study is the first empirical investigation across the continuum from low schizotypy to schizophrenia of the tolerance to asynchronies in the processing of external (auditory) and body-related (tactile) inputs.

1. Introduction

How events are perceived in time is crucial for experiencing them coherently and producing adaptive behavior. Stimuli that occur in the same moment, or very close to each other, are more likely to be bound together and to be perceived as a unique and single event. However, distinct inputs do not have to occur exactly in the same moment, as there is a limited tolerance to asynchronies. Individuals can perceive two stimuli as simultaneous, and bound them together, as far as they occur within their temporal window of integration or temporal binding window (TBW). The width of TBW largely varies across individuals, especially along the continuum ranging from normal to clinical conditions. In particular, the TBW has been shown to be abnormally wide in those conditions characterized by misperception of the time flow of events, such as schizophrenia (Giersch et al., 2015). Schizophrenia is generally held to involve abnormal perceptual integration (Postmes et al., 2014), in addition to cognitive and affective integration (Tseng et al., 2015).

Abnormalities in the temporal aspect of sensory processing in schizophrenia have been proved using both explicit and implicit tasks, especially in the audio-visual domain. Using a simultaneity judgement task, in which participants had to explicitly judge if an auditory stimulus

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and a visual stimulus presented at different delays were simultaneous or not, Stevenson et al. (2017) showed that schizophrenia patients have a wider audio-visual TBW, as compared to healthy controls. Consistent results were obtained by Foucher et al. (2007) using the same task and sensory modalities. Interestingly, there is evidence suggesting that increased tolerance to audio-visual asynchronies in schizophrenia may be coupled with an exaggerated proneness to some audio-visual illusions, such as the streaming-bouncing illusion (Zvyagintsev et al., 2017) the double-flash illusion (Haβ et al., 2017), but not the McGurk illusion (Martin et al., 2013; Romero et al., 2016; White et al., 2014). Such generally increased proneness to perceptual illusions is likely due to abnormalities in the temporal constraints between the senses, which normally provide a contextual framework for interpreting ambiguous or otherwise incoherent stimuli. Patients' difficulty to discriminate simultaneous from asynchronous stimuli, as well as their requirement of longer intervals to detect asynchronies, seem to be not confined to the multisensory (audio-visual) domain though. Several studies using different tasks have shown low temporal resolution also in the unisensory visual domain (Capa et al., 2014; Foucher et al., 2007; Giersch et al., 2009; Martin et al., 2013; Schmidt et al., 2011). Hence, larger TBWs in schizophrenia, reflecting exaggerated tolerance to asynchronies, might arise from impairments in temporal aspects of sensory processing that extend across unisensory and multisensory domains.

Anomalies in the sensory/perceptual processing have been proposed to represent a core deficit in schizophrenia (Butler and Javitt, 2005; Uhlhaas and Mishara, 2007). As such, they may characterize also the prodromal phase of the illness, as well as individuals at relatively higher risk, such as those with high schizotypal trait levels. In the last years, schizotypy has played a crucial role in the understanding of the psychosis development. According to a dimensional approach, there is a continuum with low schizotypy at one end and the schizophrenia at the other end, associated to increasing psychosis-pronesses (Kwapil and Barrantes-Vidal, 2015; Nelson et al., 2013). In fact, schizotypy is thought to reflect the subclinical expression of the symptoms of schizophrenia in the general population (Debbané and Mohr, 2015; Lenzenweger, 2006; Raine, 2006). Even if most individuals with high schizotypal trait levels are not expected to develop psychosis, schizotypy is associated with increased risk for the development of psychotic disorders (Kwapil et al., 2013). Schizotypal traits are commonly assessed using the Schizotypal Personality Questionnaire (SPQ; Raine, 1991). Interestingly, according to the continuum hypothesis of schizophrenia (Kwapil and Barrantes-Vidal, 2015; Nelson et al., 2013), individuals with high SPQ scores exhibit sensory/perceptual alterations that, although less severe, are similar to those observed in schizophrenia (Bergman et al., 2000). Specifically, using a simultaneity judgement task Ferri et al. (2017) showed that individuals with higher SPQ scores have larger audio-tactile TBW, i.e. extended simultaneity threshold, as compared to individuals with lower SPQ scores. Consistent results have been obtained also in the unisensory tactile domain using another explicit task, the Temporal Order Judgement task (Ferri et al., 2016). In this task participants were required to judge which tactile stimulus came first, if the one on their right or left hand, delivered at different temporal delays. High-SPQ individuals showed weaker temporal sensitivity, that is higher tolerance to asynchronies, than low-SPQ individuals, especially when keeping their hands crossed, rather than uncrossed. As in schizophrenia patients, also in individuals with high-schizotypy abnormalities in the temporal aspect of sensory processing have been proved not only asking them for explicit judgements, but also using implicit tasks. For example, the audio-visual double-flash illusion, which occurs when a single flash that is presented alongside two rapidly repeating tones is perceived as two flashes, revealed that the temporal range within which the illusion is maximally perceived, is significantly wider in participants with high, as compared to low, schizotypal personality traits (Ferri et al., 2018).

Although from this evidence we can easily infer that, according to the continuum model of psychosis, a similar impairment of the temporal dimension of sensory integration likely affects both high-schizotypy individuals and schizophrenia patients, a systematic investigation using the same tasks and sensory modalities across the different groups is lacking. Moreover, especially in schizophrenia, most of the studies have so far focused primarily on the visual domain and mainly explored the audio-visual integration, while leaving the tactile domain and the combination of touch with other senses mostly unexplored, despite the relevance of body-related perceptual abnormalities in both schizophrenia (e.g., Ferri et al., 2014, 2012; Gallese and Ferri, 2013, 2014) and schizotypy (e.g., Di Cosmo et al., 2018; Ferri et al., 2016).

The aim of this study is to investigate the temporal processing of tactile and auditory stimuli along the continuum from low schizotypy to schizophrenia. We will use the simultaneity judgement (SJ) task to compute the individual simultaneity range. We will run two studies, each including three SJ tasks, tactile (T-SJ), auditory (A-SJ) and audio-tactile (AT-SJ). The first study will test participants with increasing levels of schizotypy, while the second will compare schizophrenia patients (SCZ) and matched healthy controls (HC). In line with existing evidence in the audio-visual domain, we expect to find wider simultaneity ranges as the levels of schizotypy increase and in schizophrenia. In particular, if the abnormal tolerance to asynchrony in the audio-tactile domain originates as a multisensory deficit, we should find enlarged simultaneity ranges associated to high schizotypy and schizophrenia only in the audio-tactile SJ task. Conversely, if it originates as a general, modality-independent, deficit in the temporal dimension of sensory processing, we should find enlarged simultaneity ranges associated to high schizotypy, in addition to schizophrenia, in all the tasks.

2. Methods and materials

2.1. Study 1

Study 1 aims at investigating whether the temporal processing of auditory and tactile inputs changes as a function of schizotypal personality levels, and to what extent these changes affect the multimodal audio-tactile domain, as compared to the auditory and the tactile unimodal domains.

2.2. Participants

Forty-three right-handed, healthy volunteers (age: 21,9 ± 1,8; female: 16) were recruited. They were undergraduate and postgraduate students at the University of G. d'Annunzio of Chieti-Pescara. No participant had a history of neurologic, general medical or psychiatric condition. All provided written informed consent before taking part in the study, which consisted in three different simultaneity judgement (SJ) tasks. Moreover, participants were asked to fill in the Italian version of the 74-item Schizotypal Personality Questionnaire (SPQ, Raine, 1991).

2.3. Simultaneity judgement tasks

2.3.1. Apparatus and procedure

The audio-tactile apparatus, which was mounted on the table, consisted of (i) two identical loudspeakers, positioned 25 cm to the left and right of the participants' midline, and 30 cm from the participants' body; and (ii) two constant-current electrical stimulators (Digitimer DS7A) controlling two pairs of neurological electrodes attached on the participant's right and left index fingers. Auditory stimuli consisted of a 3.500-Hz pure tone of 30 ms. Tactile stimuli were single, constant voltage, rectangular monophasic pulse of 100 μs (Fig. 1).

During each SJ task, participants were blindfolded and comfortably seated at the table keeping both the middle fingers on two separate keys placed on a response box (Cedrus RB-834). Stimulus intensity was titrated at a threshold of 100% of detection for the both auditory and tactile stimulus.

During each task, two stimuli in a pair were delivered in opposite

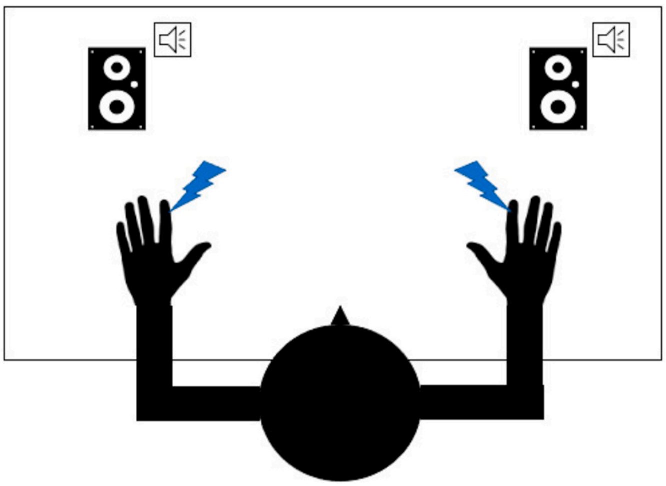

Fig. 1. Scheme of the experimental setting.

hemispaces in each trial. Stimulus pairs were presented in a randomly interleaved fashion at the following stimulus onset asynchronies (SOAs): ±5. ±10. ±15. ±25. ±40. ±70. ±120. ±200 and ± 350 ms. During each task, participants had to indicate whether the two stimuli were presented simultaneously or not.

Unisensory SJ tasks. Each unisensory task, the auditory SJ (A-SJ) and the tactile SJ (T-SJ), consisted of two blocks of 144 trials for a total of 288 trials per task (16 trials per SOA). Stimulus-response association was counterbalanced between blocks.

Audio-tactile SJ task. The audio-tactile SJ (AT-SJ) consisted of four blocks of 144 trials each for a total of 576 trials (32 trials per SOA). The association between side and modality was balanced across trials. Stimulus-response association was counterbalanced between blocks.

2.4. Data analysis

2.4.1. Estimation of individual simultaneity ranges (SR)

The data collected from each SJ task allowed us to measure three individual simultaneity ranges (SRs) for each participant: Auditory (A-SR), tactile (T-SR) and audio-tactile (AT-SR). To calculate each individual SR, we first computed the percentage of simultaneous responses across all SOAs for each participant. Then, we applied an independent channels model (ICM, García-Pérez and Alcalá-Quintana, 2012b; 2012a) to the distribution of responses for each participant's data and obtained measures of model parameters. Additionally, estimates of synchrony ranges (SR) were obtained. This model is a version of the independent-channels model 3 of Stenberg and Knoll (Sternberg et al., 1973). The ICM model used here has been previously described and validated by Garcia-Perez and Alcala-Quintana (2012) and Alcala--Quintana and Garcia-Perez (2013) for use with synchrony judgment and temporal order judgment data. In contrast to psychometric functions commonly used to fit this type of data (e.g. Gaussian and Logistic) this model is generative in that it models the underlying sensory and decisional processes that lead to the pattern of responses consistently across tasks. Importantly, this model also allows for asymmetric distribution of data which are common in these tasks. Routines to fit the model are available on Matlab (Alcalá-Quintana and García-Pérez, 2013). The model fitting procedure was conducted separately for each participant and stimulus combination. Individuals' data that did not significantly fit the ICM model ($p < 0.05$) were discarded from the analyses. Then, we used Pearson correlations to test the association between SPQ scores and SR values. The alpha level was Bonferroni corrected.

Finally, we performed a General Linear Model (GLM) analysis on participants' SR values with *modality (AT, T, A)*, as a within-subjects factor, and *schizotypy* (SPQ scores), as a continuous predictor, also including the interaction term. To explain main effects and interactions, we conducted pairwise planned comparisons.

3. Results

3.1. Individual SR values

The average A-SR value across participants was 85 ± 53 ms. The average T-SR value across participants was 119 ± 52, while the average AT-SR value across participants was 265 ± 106 ms. A-SR was correctly estimated on 28 participants. T-SR was correctly estimated on 38 participants, while AT-SR was correctly estimated on 40 participants.

3.2. Correlations between SR values and SPQ dimensions

Results from the Pearson correlation analyses, with Bonferroni corrected alpha level, showed significant associations between the SR values and the SPQ total scores in all the three tasks. AT-SR: $r = 0.42$, $p = 0.007$; A-SR: $r = 0.61$, $p < 0.001$; T-SR: $r = 0.40$, $p = 0.01$. The results are represented in Fig. 2.

3.3. General Linear Model (GLM)

Given the main aim of the GLM analysis, that is to test the continuous effect of SPQ on SR values in both the unimodal and crossmodal tasks, in this analysis we included only participants for which the ICM model correctly estimated the SR values in all the three tasks. Hence, 24 participants were included.

The GLM analysis revealed the main effect of *modality* ($F(2,44) = 24.25$, $p < 0.001$, $\eta^2_p = 0.524$). Pairwise planned comparisons revealed wider SR for AT ($M = 270$ ms, $SD = 108$ ms) as compared to both T ($M = 120$ ms, $SD = 51$ ms; $p < 0.001$) and A ($M = 87$ ms, $SD = 57$ ms; $p < 0.001$), which in turn differed from each other ($p = 0.002$).

The main effect of *schizotypy* was also significant ($F(1,22) = 13.66$, $p = 0.001$, $\eta^2_p = 0.383$), with a positive linear relation between SPQ score and SR ($b = 3.009$, $SE = 0.814$): on average, participants' with higher SPQ scores tended to have wider SR. Importantly, this effect was significantly different across the tasks (*schizotypy* by *modality* interaction: $F(2,44) = 11.08$, $p < 0.001$, $\eta^2_p = 0.335$). This result was explained by the fact that the linear effect of SPQ scores on participants' performance on AT ($b = 5.224$, $SE = 1.293$) was significantly stronger than that observed in both A ($b = 2.656$, $SE = 0.697$; $t(22) = 4.41$, $p < 0.001$) and T ($b = 1.148$, $SE = 0.772$; $t(22) = 2.53$, $p = 0.019$). Moreover, the linear effects of SPQ on participants' performance in A was significantly stronger than that observed in T ($t(22) = 2.33$, $p = 0.030$) (see Fig. 3).

4. Study 2

Study 2 aims at investigating how the temporal processing of audio-tactile, tactile and auditory information further changes in schizophrenia patients, that is, if it becomes pervasive severely affecting also the unisensory domains.

5. Methods and materials

5.1. Participants

Eighteen out-patients with schizophrenia (SCZ) were recruited for this study. Six of them did not provide reliable data and will not be considered further. Hence, twelve matched healthy control participants (HC) were recruited. Both SCZ (see Table 1) and HC participants were right-handed. All SCZ participants received a diagnosis of schizophrenia according to Diagnostic and Statistical Manual of Mental Disorders (DSM-V) and were rated for symptom severity with the Positive And Negative Symptom Scale (PANSS; Positive symptoms: 11.5 ± 5.38, Negative symptoms: 13.5 ± 6.55) (Kay et al., 1987). All patients

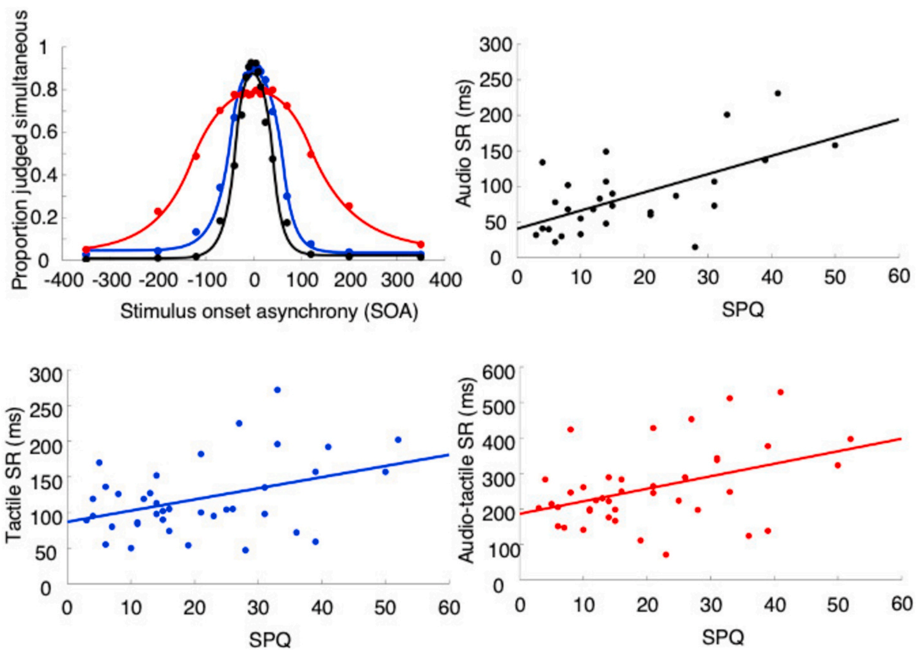

Fig. 2. Upper left: Across-participants average probability of judging the stimuli as simultaneous plotted as a function of the delay. The curve represents the ICM fit determining the simultaneity range. The points represent across-participants average raw data. Black indicates audio SR, blue indicates tactile SR, red indicates audio-tactile SR. The scatter plots represent the positive correlation between the audio SR value and the SPQ score (Upper right), tactile SR value and the SPQ score (Lower left), audio-tactile SR value and the SPQ score (lower right). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

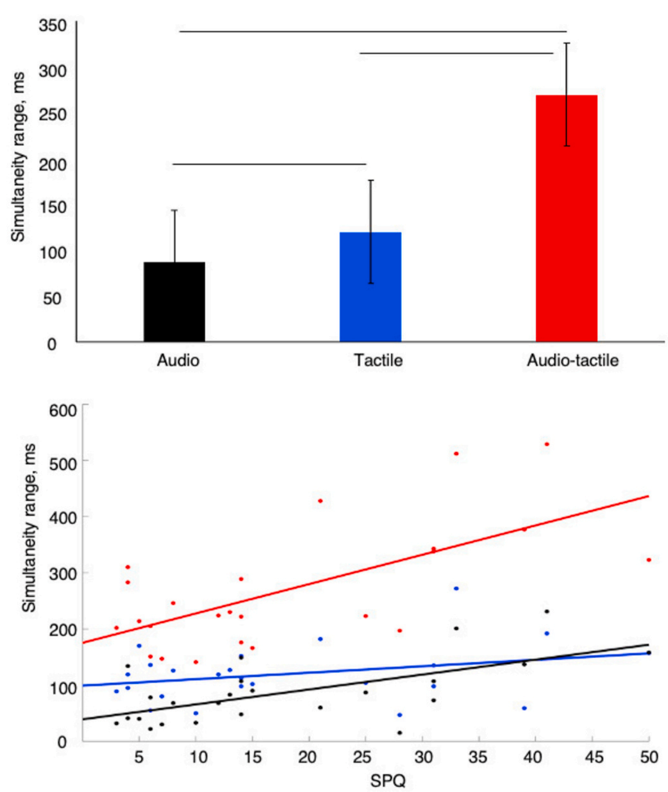

Fig. 3. The histogram (upper panel) shows the SR values in the audio (black), tactile (blue) and audio-tactile (red) tasks. Error bars represent standard errors. Horizontal lines indicate significant differences. The scatter plot (lower panel) represents the positive correlation between the three tasks and the SPQ scores. Colour codes are the same as in the upper panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Demographic information about Schizophrenia patients (N = 12).

Age	31 (±6.5)
Duration of illness (years)	8,5 (±6,10)
Education	13,9 (±2,9)
Male/female	11/1
Diagnosis	Schizophrenia
PANSS Positive scale	11.5 (±5.38)
PANSS Negative scale	13.5 (±6.55)
Medication	1 Risperidone, 2 Paliperidone, 5 Aripiprazole, 2 Clozapine, 1 Risperidone, 1 Clopixol*

*Clorpromazine equivalent mean dose = 318.24 mg/die SD = 228.

received atypical antipsychotic therapy; the chlorpromazine equivalents were calculated for each participant (M±SD: 318,24 ± 228,05) (Danivas and Venkatasubramanian, 2013). The study was approved by the local Ethics Committee. Written informed consent was obtained from all participants after full explanation of the procedure of the study, in line with the Declaration of Helsinki.

5.2. Simultaneity judgement tasks

The tasks, procedure and curve fitting method were the same as in Study 1.

5.3. ANOVA

We performed a mixed ANOVA with *group* (HC, SCZ) as the between-subjects factor and *modality* (SJ-A, SJ-T, SJ-AT) as the within-subjects factor, followed by pairwise planned comparisons among sample means.

6. Results

6.1. Individual SR values

The average A-SR value across SCZ participants was 148 ± 71 ms, while it was 72 ± 61 across HC. The average T-SR value across SCZ participants was 162 ± 52 ms, while it was 117 ± 47 across HC. The average AT-SR value across SCZ participants was 444 ± 279 ms, while it was 247 ± 98 across HC participants (Fig. 4). No significant correlation

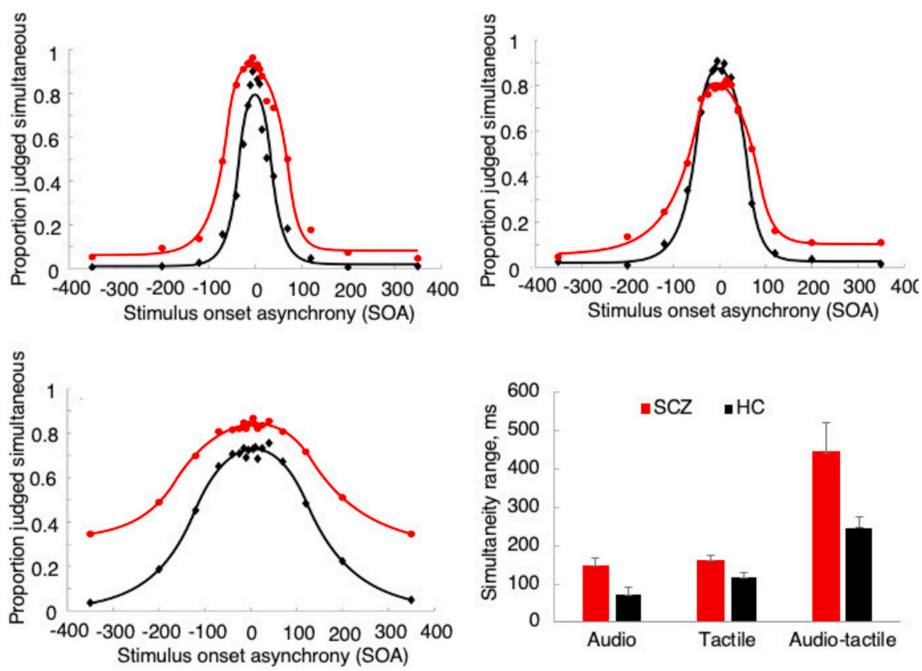

Fig. 4. Across-participants average probability of judging the stimuli as simultaneous plotted as a function of the delay. The curve represents the ICM fit determining the simultaneity range. The points represent across-participants average raw data. Black indicates Healthy controls; red indicates schizophrenic patients. Upper left: Audio SR, upper right: tactile SR, lower left: audio-tactile SR. The histogram in the lower right panel shows the SR values in the audio, tactile and audio-tactile tasks in healthy controls (black) and schizophrenic patients (red). Error bars represent standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was found between chlorpromazine equivalents and patients' SRs (all ps > 0.05).

7. ANOVA

ANOVA results (Fig. 4, lower right panel) showed a significant main effect of group ($F_{1,22} = 14.0$, $p < 0.001$, $\eta_p^2 = 0.39$), with SCZ group showing wider SRs than HC group (252 ± 209 vs. 145 ± 101). The main effect of modality was also significant ($F_{2,44} = 24.5$, $p < 0.001$, $\eta_p^2 = 0.53$), with AT-SR larger than T-SR (346 ± 220 vs. 140 ± 53; $p < 0.001$) and A-SR (346 ± 220 vs. 110 ± 76; $p < 0.001$), which in turn differed from each other (140 ± 53 vs. 110 ± 76; $p = 0.01$). The interaction group by modality was not significant. Accordingly, T-test analyses revealed that the SRs were always wider in the SCZ group than the HC group (AT-SR: SCZ 444 ± 267, HC 247 ± 93, $p < 0.05$; T-SR: SCZ 162 ± 50, HC 117 ± 47, $p < 0.05$; A-SR: SCZ 148 ± 72, HC 73 ± 61, $p = 0.01$).

8. Discussion

In this study we investigated the tolerance to asynchronies of tactile and auditory inputs, as indexed by the simultaneity ranges (SRs), along the continuum from low schizotypy to schizophrenia. While previous research on those populations mostly focused on the audio-visual domain, here we explored the audio-tactile function for the first time. To better understand the origin and the specificity of the expected temporal dysfunction in the audio-tactile domain, we asked each participant to perform simultaneity judgement tasks with unimodal tactile and unimodal auditory pairs, in addition to audio-tactile pairs. Our results showed that SRs become larger as the level of schizotypy increases. Specifically, the linear effect of schizotypy levels on the audio-tactile task is stronger than on the auditory task, which in turn is greater than the effect on the tactile task (study 1). In agreement with the schizophrenia continuum hypothesis, this effect is even more severe in patients, as they generally show exaggerated tolerance to audio-tactile, auditory and tactile asynchronies, as compared to healthy controls, with no significant difference between multisensory and unisensory domains (study 2).

Overall, our results are consistent with prior evidence showing reduced multisensory temporal acuity in schizophrenia and extend it to other sensory domains. In fact, they demonstrate that the deficit does not only affect the integration of external inputs, such as auditory and visual information from the environment (Giersch et al., 2015; Postmes et al., 2014; Tseng et al., 2015); rather, the alteration of multisensory temporal acuity along the schizophrenia continuum pertains also to body-related somatosensory stimuli and the perception of their synchrony with external stimuli (i.e., auditory inputs).

Abnormal audio-tactile processing along the continuum from low schizotypy to schizophrenia has been previously shown in relation to the spatial, rather than the temporal dimension of multisensory perception. In fact, multisensory interactions are subject to both temporal and spatial constraints and, according to the latter, facilitative effects on RTs are observed only in conditions of spatial proximity between multisensory inputs. Di Cosmo and colleagues (2017) showed that in high-schizotypy individuals looming sounds facilitated the detection of tactile stimuli delivered on their hand only when the auditory object was perceived very close to their body, as compared to low-schizotypy individuals. The perceived distance of the sound objects facilitating the tactile detection was even closer to the body for schizophrenia patients, as compared to healthy controls. Taken together, these results suggest that spatio-temporal abnormalities of the audio-tactile processing could be early markers of schizophrenia risk. However, in line with previous studies in the audio-visual domain (Foucher et al., 2007), our results also suggest that such abnormalities are not confined to multisensory processing.

We found, indeed, also the temporal processing of unisensory pairs, both somatosensory and auditory, to be affected by increasing levels of schizotypy and schizophrenia. Lengthened simultaneity ranges for auditory stimuli had been already shown in schizophrenia (Foucher et al., 2007), but not in high-level schizotypy individuals. Most importantly, for the first time here, we demonstrate larger simultaneity ranges also for temporal processing of tactile stimuli, along the schizophrenia continuum. That dysfunctions of auditory processing are associated to schizophrenia risk is well documented by empirical data (e.g., Francisco et al., 2020; Koh et al., 2011; Shin et al., 2012), while evidence of a similar role for dysfunctions of somatosensory processing is still scant. In agreement with the present findings, in a previous study we showed reduced tactile temporal acuity and tactile remapping abilities in high-schizotypy individuals, as compared to moderate and low schizotypes (Ferri et al., 2016). In that study, however, we asked participants to perform a temporal order judgement task (TOJ), rather than a simultaneity judgement task, with crossed and uncrossed hands. Regardless the debate on the fact that perceptual judgments on simultaneity and temporal order might be based on different information about the incoming sensory inputs (e.g., Hirsh and Sherrick, 1961; Stelmach and Herdman, 1991), either temporal or spatial, (Axelrod et al., 1968; Hirsh, 1959; Mitrani et al., 1986; Schneider and Bavelier, 2003; Shore et al., 2005; Shore et al., 2002), instead of tapping on the same timing processes (García-Pérez and Alcalá-Quintana, 2015; Parise and Ernst, 2016), overall this evidence supports the idea that critical changes of temporal processing of somatosensory inputs may occur pretty early along the schizophrenia continuum.

Reduced temporal sensitivity of sensory processing and higher tolerance to asynchronies may reflect abnormal temporal dynamics of the neural activity, in both high schizotypy (Ferri et al., 2017) and schizophrenia (Nikulin et al., 2012). In general, there is plenty of evidence that neural oscillations orchestrate multisensory processing in normal conditions and that their abnormalities may lead to multisensory processing deficits in schizophrenia (for a review, see Keil and Senkowski, 2018). For example, in the specific context of the audio-visual double-flash illusion, Balz et al. (2016) found that aberrant beta- and gamma-band oscillations may play a crucial role in this sense. Further supporting the fully dimensional approach to the relationship between schizotypal personality traits and schizophrenia, abnormal resting-state oscillatory brain dynamics have been found also in high-schizotypy individuals (Fuggetta et al., 2014). Most importantly, in the specific context of multisensory integration Fotia and colleagues (*under revision*) demonstrated that the reduced temporal sensitivity to visuo-tactile events in high schizotypy, as revealed by the tactile-induced Double--Flash-Illusion, reflects a slowing down of the oscillatory beta activity. Hence, abnormal oscillatory patterns associated to multisensory deficits may represent a neurobehavioral marker of psychosis risk. However, a systematic investigation of the potential contribution of any frequency band oscillations to the temporal aspect of multisensory and unisensory processing, especially in the somatosensory domain, is still lacking.

The current study is not without limitations. In particular, the sample size of the schizophrenia patient group was small and, given the heterogeneity of schizophrenia symptoms, it is somewhat risky to make a general conclusion based on the present study. Further investigation is definitely warranted to confirm the relation between symptoms and tolerance to asynchronies in schizophrenia. This limitation notwithstanding, our results are in line with the above discussed evidence of multisensory and unisensory temporal deficits in schizophrenia. Moreover, the current study is the first empirical investigation across the continuum from low schizotypy to schizophrenia of the tolerance to asynchronies in the processing of external (auditory) and body-related (tactile) inputs. Besides the novelty, another advantage of this approach is that it reveals that data from the schizophrenia group are consistent with, hence also supported by, that obtained from the high-schizotypy group.

Author statement

Giulio Di Cosmo: Methodology, Software, Data curation, **Marcello Costantini:** Conceptualization, Methodology, Writing- Original draft preparation, Writing- Reviewing and Editing, Data curation, **Ettore Ambrosini:** Data curation; **Anatolia Salone:** Data curation; **Giovanni Martinotti:** Data curation; **Mariangela Corbo:** Data curation; **Massimo Di Giannantonio:** Data curation; **Francesca Ferri:** Conceptualization, Methodology, Writing- Original draft preparation, Writing- Reviewing and Editing, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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