

Autistic and schizotypal traits influence audiovisual temporal binding window malleability following alpha-band entrainment

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ARTICLE INFO

Keywords:

Neural Entrainment
Alpha Oscillations
Audiovisual Temporal Acuity
Autism
Schizophrenia
Interindividual Differences

ABSTRACT

The likelihood of integrating audiovisual (AV) information is reflected in the construct of temporal binding window (TBW), which accounts for the differing processing times across sensory regions. Wider TBWs within the autistic and schizotypal spectrums predict the degree of cognitive-perceptual and socio-communicative atypicalities. Alpha oscillations (8–13 Hz) represent an important neural mechanism for AV binding, and consequently alpha-band entrainment can shrink or expand TBWs. However, whether interindividual differences in autistic and schizotypal traits influence TBW modulations under entrainment is unexplored. Here, we used alpha-band sensory AV entrainment to explore how individual traits affect TBW malleability in neurotypical individuals ($n = 113$), administering rhythmic stimulations at slower (~ 8.5 Hz) and faster alpha (~ 12 Hz) frequencies before an AV simultaneity judgement task. Participants self-reported autistic and schizotypal traits, and a cluster analysis stratified individuals into three groups: high Cognitive-Perceptual Traits (CPT), high Socio-Affective Traits (SAT), Low Traits (LT). Results revealed that, across groups, upper alpha entrainment narrowed TBWs, enhancing AV temporal acuity. However, following lower alpha stimulation, only the CPT group exhibited wider TBWs, indicating a heightened responsiveness to entrainment stimulation, reflecting bottom-up atypical integration of sensory information into coherent models. Additionally, the typical leading sense asymmetry determining narrower TBWs for auditory-leading sequences was observed only in the LT group, suggesting that even sub-clinical cognitive-perceptual and socio-communicative atypicalities may disrupt basic aspects of cross-modal interactions. These findings suggest that socio-communicative and cognitive-perceptual anomalies associated with autistic and schizotypal traits influence low-level aspects of temporal binding across sensory modalities, including their malleability following alpha-band stimulation.

1. Introduction

In daily life, our brain integrates sensory input from multiple modalities, conveying information to sensory areas at different propagation speeds (Recanzone, 2009).

A certain degree of temporal tolerance for audiovisual (AV) asynchrony is functionally valuable for constructing a coherent sensory perception (Vatakis & Spence, 2007; Ampollini et al., 2024). This temporal tolerance is reflected in the construct of temporal binding window (TBW), the time frame within which auditory and visual inputs are perceived as simultaneous, even when presented asynchronously (Noel et al., 2016; Stevenson et al., 2017). The width of TBWs serves as a proxy

measure for AV temporal acuity, where narrower TBWs indicate higher temporal precision and are linked to enhanced cognitive-perceptual and socio-communicative abilities (Lovelace et al., 2003; Powers et al., 2009). In contrast, broader TBWs reflect lower temporal acuity, leading to ambiguous perceptual experiences and sensory overload (Ferri et al., 2017; Marsicano et al., 2022). Notably, this latter scenario is evident in clinical populations, such as in Autism Spectrum Disorder (ASD), and Schizophrenia Spectrum Disorder (SSD), where wider TBWs are frequently associated with the underlying socio-communicative and cognitive-perceptual atypicalities (Tseng et al., 2015; Balz et al., 2016; Haß et al., 2017). Even among neurotypical individuals, substantial variability exists in AV temporal resolution (Ampollini et al., 2024).

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<https://doi.org/10.1016/j.biopsycho.2025.109082>

Received 18 December 2024; Received in revised form 17 June 2025; Accepted 7 July 2025

Available online 12 July 2025

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Interestingly, higher levels of ASD- and SSD-like traits are often linked to broader TBWs and reduced AV temporal acuity (Fenner et al., 2020; Zhou et al., 2021). Thus, examining sub-clinical ASD and SSD traits within the neurotypical population can provide a valuable framework for understanding core features of these conditions, offering insights into their etiology and neurocognitive dynamics (Zhou et al., 2019, 2021).

A key neural mechanism underlying this perceptual variability is hypothesized to depend on the speed of neural oscillations within the alpha frequencies (8–13 Hz), which are thought to orchestrate AV binding mechanisms, with a faster individual alpha frequency (IAF) predicting higher AV acuity (Samaha & Postle, 2015; Ronconi et al., 2018, 2023). Interestingly, ASD and SSD populations have been associated with a slowed IAF (Ippolito et al., 2022), potentially explaining their larger TBWs. Furthermore, subclinical ASD- and SSD-like traits in the neurotypical population are associated with similar atypical perceptual and oscillatory patterns (Muller et al., 2021; Zhou et al., 2021).

Recent research has demonstrated that AV temporal perception can be modulated using rhythmic neuromodulation techniques. By synchronizing alpha oscillations to either the lower or upper boundaries of the alpha-band, these approaches have been shown to respectively expand or shrink TBW widths (Cecere et al., 2015; Venskus et al., 2021; Marsicano, Bertini, et al., 2024). While neuromodulatory techniques effectively entrain neural oscillations and modulate AV TBWs, their neural and perceptual outcomes can vary substantially between individuals (Bachtar & Stagg, 2014; Stern et al., 2017). This variability is frequently influenced by different behavioural phenotypes linked to subclinical ASD- and SSD-like traits, which affect both AV temporal resolution and the ability to entrain to rhythmic sequences. Indeed, individuals with higher ASD and SSD traits often show difficulties in synchronizing with external rhythms, resulting in impaired temporal predictions from rhythmic sensory streams (Ghuman et al., 2017; Beker et al., 2021).

In this study, we used alpha-band sensory entrainment to investigate how ASD- and SSD-like traits influence the malleability of TBWs in neurotypical individuals. We employed a web-based paradigm, administering brief audiovisual rhythmic stimulations at slower (~8.5 Hz) and faster alpha (~12 Hz) frequencies before participants performed an AV simultaneity judgement (SJ) task (Marsicano et al., 2022, 2024). Importantly, participants self-reported their cognitive, socio-affective, and communicative styles using the Autism Quotient (AQ; Baron-Cohen et al., 2001) and Schizotypal Personality Questionnaire (SPQ; Raine, 1991). By clustering individuals based on their ASD- and SSD-like traits, we aimed to uncover how interindividual differences influence AV temporal acuity and the modulation of TBWs.

Unlike classical methods correlating ASD and SSD questionnaire scores with AV temporal acuity, clustering analysis can uncover multiple distinct profiles of AV temporal processing, differentiated by various dimensions of ASD and SSD traits (Zhou et al., 2020). We hypothesized that interindividual differences in ASD- and SSD-like traits across cognitive-perceptual and socio-communicative domains may reveal variations in AV temporal acuity and in the malleability of TBW width following alpha-band entrainment.

2. Methods

2.1. Participants

A total of 113 volunteers were recruited among university students (a subset of the data was part of a previously published study in Marsicano, Bertini, et al., 2024). Participants did not receive compensation and presented normal or corrected-to-normal vision and hearing. Exclusion criteria were self-reported neurological and attention disorders, epilepsy, and photosensitivity. All subjects performed the Simultaneity Judgment (SJ) task and completed the Autism Quotient (AQ; Baron-Cohen et al., 2001) and Schizotypal Personality Questionnaire

(SPQ; Raine, 1991). During data collection, the refresh rate of the monitor/display was recorded for each participant, ensuring a correct timing of AV stimulation at the desired refresh rate (60 Hz). Eight participants were excluded from subsequent analyses since they performed the SJ task using a monitor with different refresh rate. The final sample included 105 participants (67 females, mean age=23.4 years, SD=4.49). Given the subsequent data-driven stratification of the total sample into different subgroups, the reliability of the sample size was estimated based on a post-hoc power analysis to evaluate the effect size of our results (see below). We emphasised the critical importance of sitting in a dimly lit and quiet room, using headphones/earbuds at a comfortable volume, and keeping a viewing distance of ~50 cm from the screen. The research project was approved by the Ethical Committee of the University of Bologna (Prot. n. 0159726), and all participants gave their informed consent.

2.2. Apparatus and stimuli

The task was created with PsychoPy3 (Peirce, 2007) and administered in Pavlovia (<https://pavlovia.org/>), a web-based platform for the presentation of psychophysics experiments via common web browsers. Audio and visual stimuli were created using Psychtoolbox on MATLAB 2019a (MathWorks, Inc), generating videos of AV stimuli at different stimulus-onset asynchronies (SOAs). The AV stimuli used for the entrainment were created in a similar way. We collected directly from Pavlovia information about the type of operative system used (Windows=74 participants, MacOS=39 participants). The visual stimulus used for the entrainment was a white square with a diameter of 6° of visual angle presented at the centre of the screen. The auditory stimuli used for the entrainment were sinusoidal 500 Hz sounds presented binaurally through headphones/earbuds at a comfortable volume. The AV target stimuli of the SJ task were a white circle sized 6° of visual angle presented at the center of the screen and a sinusoidal 750 Hz sounds presented binaurally through headphones/earbuds at a comfortable volume.

2.3. Experimental design

We employed a web-based AV Simultaneity Judgment (SJ) task, preceded trial by trial by a rhythmic sensory stimulation (entrainment) at two different frequencies in the lower (~8.5 Hz) or upper (~12 Hz) alpha-band, and by a non-rhythmic control stimulation condition, to investigate the possible modulations of AV TBWs following sensory entrainment (Fig. 1). All trials started with the onset of one of the two types of entrainment or with the onset of the control pre-stimulus condition. These conditions lasted for ~2000 ms, and the duration of each AV stimulus was set to three refresh cycles (49.98 ms). In the ~8.5 Hz condition (lower alpha), the AV stimuli were presented repeatedly for three refresh cycles, separated by four cycles of a blank screen, resulting in a SOA of 116.62 ms. In the ~12 Hz condition (upper alpha), the AV stimuli were presented again repeatedly for three refresh cycles, separated by two cycles of a blank screen, resulting in a SOA of 83.3 ms. Regarding the control condition, the AV stimulus was presented in the first 3 refresh cycles and in the last three cycles of the 2000-ms time window preceding the SJ task. The presentation of these experimental pre-stimulus conditions was randomized and counterbalanced.

2.4. Autistic traits

Autistic traits were computed using the Autism spectrum Quotient (AQ; Baron-Cohen et al., 2001). In this self-report questionnaire, participants were asked to report their answers regarding different aspects of cognitive style, behavioural and socio-communicative patterns, and sensory experiences. AQ includes 50 items divided into 5 different subscales (10 items for each subscale), investigating different features of the individual profile: i) attention to detail, ii) attention switching, iii)

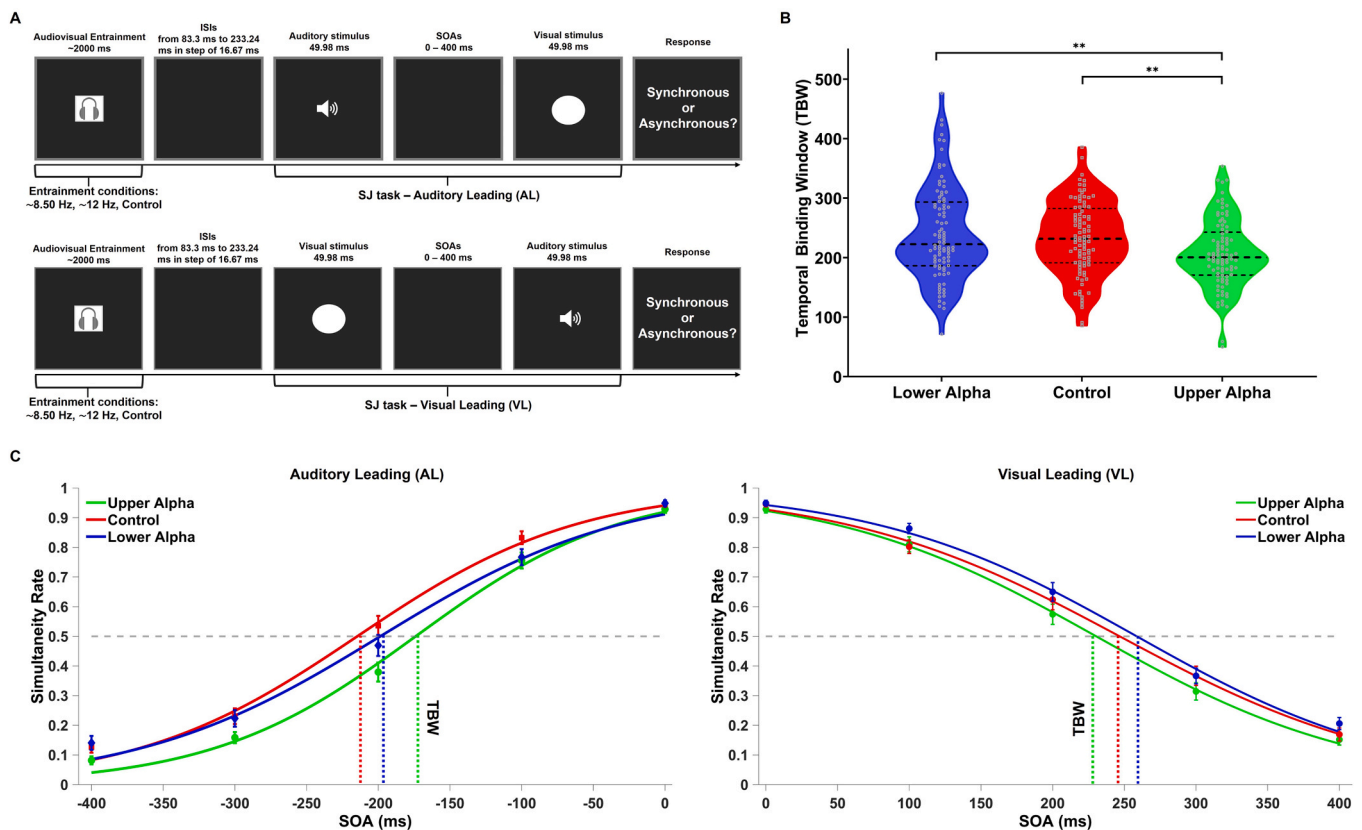


Fig. 1. Experimental paradigm and overall results. **A)** Schematic representation of the experimental paradigm, adapted from Marsicano, Bertini, et al., 2024. In the upper panel are represented the Auditory Leading (AL) trials, in which the auditory stimulus was followed by the visual stimulus. In the lower panel are represented the Visual Leading (VL) trials, in which the visual stimulus was followed by the auditory stimulus. Each trial began with the audiovisual entrainment (lower alpha or upper alpha stimulation) or control condition (no stimulation). After a variable time (ISIs) between 83.3 ms and 233.23 ms (in steps of 16.67 ms) the audiovisual target of the Simultaneity Judgment task appears at the centre of the screen. A fixed array of SOAs between the first and second stimulus was used across trials (± 400 , ± 300 , ± 200 , ± 100 , 0). Trials were counterbalanced between conditions. **B)** Violin plot displaying TBWs modulations as a function of stimulation conditions, showing a narrower TBW following upper alpha entrainment with respect to lower alpha and control conditions, while in contrast no differences emerged between lower alpha and control conditions. Black dotted lines indicate median and quartiles. Grey circles and squares show the individual values. * $p < .05$; ** $p < .01$; *** $p < .00$. **C)** Logistic curves obtained across participants in different entrainment conditions (Upper Alpha, Control, Lower Alpha), separately for Auditory Leading (AL) and Visual Leading (VL) conditions (Left panel: AL; Right panel: VL). Each individual TBW was derived at a 50 % criterion (horizontal grey dotted line). Vertical dotted lines show the TBW value following each stimulation condition. Circles show simultaneity rates as a function of the SOA in the three stimulation conditions, where different types of pre-target entrainment were employed (Green Curve = Upper Alpha; Red Curve = Control; Blue Curve = Lower alpha). The error bars indicate the standard error of the mean (SEM).

imagination, iv) communication, v) social skills. For each item, participants were required to indicate the degree to which they express approval or endorsement on a 4-point Likert scale ranging from “definitely agree” to “definitely disagree”. We followed the original scoring methods (Baron-Cohen et al., 2001), and the total sum of the scores obtained in each subscale provided a global score, with higher values indexing higher levels of autistic traits.

2.5. Schizotypal traits

Schizotypal traits were measured using the Schizotypal Personality Questionnaire (SPQ; Raine, 1991). This self-report questionnaire is composed of 74 items divided into 9 subscales (ideas of reference, magical thinking, social anxiety, unusual perceptual experiences, constricted affect, no close friends, odd behaviour, odd speech and suspiciousness), further organised into 3 main factors (cognitive-perceptual, interpersonal and disorganisation), in which participants are asked to answer questions regarding different aspects of their personality, sensorial experiences and beliefs, with “Yes” or “No” statements to each item. We used the original scoring methods (Raine, 1991) and assigned the response to a binary code (no = 0; yes = 1).

3. Data analysis

3.1. Entrainment modulations of AV temporal acuity: logistic fitting

We indexed AV TBW performing a logistic fitting of SJ task performance for each participant, with the aim to investigate whether AV temporal acuity is modulated by the different sensory entrainment sequences and to disentangle potential asymmetries in the modulations of the AV temporal acuity for AL and VL trials. Importantly, this procedure allowed us to address the core question of the current study, which was to investigate potential interindividual differences (i.e., ASD and SSD traits) in the modulation of AV temporal acuity following different entrainment conditions.

Adjusted R^2 was evaluated separately for each experimental condition and for each leading sense. We performed the fitting of the psychometric logistic curve for each participant, separately for the AL and the VL condition, and for each stimulation condition (lower alpha, upper alpha, and control). Thus, we obtained the individual 50 % threshold values from the fitting of the psychometric logistic curve, reflecting the width of the AV TBW. We decided to use the individual 50 % threshold values as they more sensitively represent the simultaneity rate distribution obtained in our experiment. We used a logistic equation and a

non-linear least squares method to fit the proportion of simultaneity rate reported to the SJ task as a function of SOAs. The formula used was the following: $y = 1/(1 + \exp(b \times (t - x)))$. In this equation, x represents the SOA between audio and visual stimuli and y represents the proportion of simultaneity responses to the SJ task. The lower y bound was set at 0 and the higher y bound was set at 1. The only free parameters of the function were b (the function slope) and t (the 50 % threshold), which were restricted to assuming positive values above zero. Both AL and VL curves were also fitted using the data point corresponding to SOA = 0 ms.

3.2. Interindividual differences: cluster analysis

To characterize the multiple phenotypes observable within the ASD-SSD spectrum, previous studies implemented factorial (e.g., Principal Component Analysis; Tarasi et al., 2022) and cluster analysis (e.g., k-mean/k-median; Choteau et al., 2016; Abu-Akel et al., 2017; Marsicano & Melcher, 2025) approaches on the measures deriving from the AQ and SPQ questionnaires. In the current study, we decided to implement a data-driven cluster analysis technique rather than a factorial approach, as the latter grounds on a variable-centered approach which tends to underestimate the interindividual variability of individuals in a sample (Choteau et al., 2016). On the contrary, cluster analysis is a person-centered approach, unveiling commonalities between individuals, thus identifying group-specific relationships between variables that are typically masked in a globalizing factorial approach. Crucially, no a priori assumptions were made regarding the number, size, or nature of the resulting clusters. Instead, the optimal cluster solution was determined empirically from the data, by jointly evaluating the clustering solutions with the highest silhouette scores, optimal Bayesian Information Criterion (BIC), and proportion of explained variance (i.e., highest R^2). A bootstrapped cluster stability analysis (Hennig, 2007) was then conducted as an additional validation of the reliability and robustness of our clustering solution. Accordingly, our sample was stratified using a data-driven, k-median cluster analysis (Hartigan-Wong method with squared Euclidean distance, maximum number of iterations for finding the optimal clustering solution set to 25) based on participants' z-scored ratings on the 5 subscales of AQ (*social skills, attentional switching, attentional to detail, communication, imagination*) and the 9 subscales of the SPQ (*ideas of reference, social anxiety, odd beliefs/magical thinking, unusual perceptual experiences, eccentric/odd behaviour, no close friends, odd speech, constricted affect, suspiciousness*) questionnaires.

3.3. Power analysis

Given the subsequent data-driven stratification of the total sample into different clusters, we performed a post-hoc power analysis to evaluate the effect size of our results. This analysis focused on the within-between interaction effect in a repeated measures ANOVA (see Results).

3.4. Entrainment AV temporal acuity modulations as a function of cluster profile

Finally, we performed a $3 \times 2 \times 3$ repeated-measure analysis of variance (rmANOVA) on the AV TBW with the aim of testing whether performance was influenced by the stimulation condition (within-subjects factor with three levels: lower alpha, upper alpha, control condition), leading sense (within-subjects factor with two levels: AL and VL), and cluster (between-subjects factor with three levels). The Greenhouse-Geisser correction was applied as appropriate where the sphericity assumption was violated. We performed planned comparisons to investigate AV temporal acuity modulations (i.e., narrowing or broadening of the size of AV TBW) following different entrainment conditions (i.e., lower alpha, upper alpha, control condition) as a function of the clusters (i.e., SAT, CPT, LT) and leading sense (AL and VL).

4. Results

4.1. Logistic Fitting

Following previous literature (Hillock-Dunn et al., 2016), participants with poor logistic fitting (adjusted $R^2 < 0.3$), were excluded from the statistical analysis ($N = 13$), thus obtaining a final sample of 92 participants. The average values were: AL lower alpha adjusted $R^2 = 0.927$; AL upper alpha adjusted $R^2 = 0.931$; AL control adjusted $R^2 = 0.935$; VL lower alpha adjusted $R^2 = 0.901$; VL upper alpha adjusted $R^2 = 0.928$; VL control adjusted $R^2 = 0.917$.

4.2. Interindividual differences: AQ and SPQ traits and cluster analysis

To assess the diversity of trait expression, we computed descriptive statistics across all AQ and SPQ scales. Scores demonstrated a wide range, with AQ Total scores spanning from 4 to 37 ($M = 17.87$, $SD = 6.89$) and SPQ Total scores from 1 to 58 ($M = 21.50$, $SD = 13.21$). Full summary statistics, including means, standard deviations, and score ranges for each subscale, are presented in Table 1. These results highlight the heterogeneity of the sample, which included individuals with both low and elevated levels of atypical traits across cognitive-perceptual, socio-communicative and affective domains of the AQ (Baron-Cohen et al., 2001) and the SPQ (Raine, 1991). This distribution supports the validity of the subsequent data-driven, trait-based stratification into different groups (see below for cluster analysis results and Table 1 for group-level subscale profiles).

Regarding cluster analysis, silhouette scores, Bayesian Information Criterion (BIC), and the proportion of explained variance (R^2) were calculated for clustering solutions with K ranging from 1 to 10, in order to determine the optimal number of clusters (K). The 3-cluster solution was selected as the optimal model based on the convergence of these three criteria: it exhibited the highest silhouette score (0.23), the optimal BIC value (996.76), and the highest R^2 (0.346; see Table 2 for a summary of clustering solutions), supporting a reasonable 3-cluster structure (Kaufman & Rousseeuw, 2009). As an additional validation step, cluster stability was further evaluated via a bootstrapped resampling analysis (1000 resamples), using the *clusterboot* function in R (Hennig, 2007), which computes Jaccard similarity indices to assess the consistency of cluster assignments across bootstrap samples. To ensure that the bootstrapped cluster stability results were not dependent on a specific random seed, we repeated the analysis across multiple seeds. Results indicated high stability for Cluster 2 (Jaccard $> .93$) and good stability for Clusters 1 and 3 (Jaccard $> .79$), further supporting the robustness of the 3-cluster structure.

In line with previous evidence describing the ASD-SSD continuum using similar methods (Choteau et al., 2016; Abu-Akel et al., 2017; Gong et al., 2017; Zhou et al., 2019; Tarasi et al., 2022; Marsicano & Melcher, 2025), the 3-cluster structure obtained in our analyses (Fig. 2) comprised: 1) a first cluster ($n = 22$, 23.9 % of participants), named "Socio-affective Traits (SAT)", composed with individuals displaying high scores on the socio-affective dimension (SPQ subscales: *no close friends, social anxiety, restricted affect*; AQ subscales: *social skills, communication, attentional switching*), and low scores in the cognitive-perceptual domain (SPQ: *ideas of reference, odd beliefs/magical thinking, unusual perceptual experiences, suspiciousness*; AQ subscales: *attentional to detail, imagination*); 2) a second cluster ($n = 28$, 30.4 % of participants), called "Cognitive-perceptual Traits (CPT)", was characterized by individuals showing high scores on the cognitive-perceptual dimension (SPQ subscales: *ideas of reference, odd beliefs/magical thinking, unusual perceptual experiences, suspiciousness*; AQ subscales: *attentional to detail, imagination*), and low scores in the socio-affective dimension (SPQ subscales: *no close friends, social anxiety, restricted affect*; AQ subscales: *social skills, communication, attentional switching*); a third cluster ($n = 42$, 45.6 % of participants), called "Low Traits" (LT), composed of individuals with low scores in both AQ and SPQ subscales.

Table 1

Descriptive statistics for AQ and SPQ total and subscale scores across the full sample and stratified by trait-defined cluster groups (SAT, CPT, LOW). The overall sample statistics include the mean, standard deviation, minimum, and maximum for each trait measure. The cluster-wise columns reflect group-level trait profiles identified through cluster analysis, with values representing summary statistics (mean and standard deviation) for each group.

Scales	All Subjects Mean (SD)	Min Score	Max Score	SAT Mean (SD)	CPT Mean (SD)	LOW Mean (SD)
AQ Total	17.87 (6.89)	4.0	37.0	25.55 (4.52)	19.75 (4.57)	12.60 (4.33)
AQ Attention to Detail	5.05 (2.3)	1.0	10.0	5.41 (1.82)	6.79 (1.89)	3.71 (1.93)
AQ Attention Switching	5.15 (2.21)	0.0	10.0	7.41 (1.26)	5.18 (1.49)	3.95 (2.09)
AQ Imagination	2.77 (1.6)	0.0	8.0	3.36 (1.40)	3.46 (1.67)	2.00 (1.31)
AQ Communication	2.29 (1.83)	0.0	9.0	4.18 (1.76)	2.21 (1.37)	1.36 (1.34)
AQ Social Skills	2.6 (2.05)	0.0	9.0	5.18 (2.20)	2.11 (1.20)	1.57 (1.04)
SPQ Total	21.5 (13.21)	1.0	58.0	29.77 (10.81)	32.00 (8.98)	10.17 (5.56)
SPQ Ideas of Reference	2.83 (2.79)	0.0	9.0	2.64 (2.46)	5.43 (2.66)	1.19 (1.47)
SPQ Magical Thinking	1.2 (1.82)	0.0	7.0	0.73 (1.42)	2.71 (2.23)	0.43 (0.89)
SPQ Anxiety	4.18 (2.57)	0.0	8.0	6.45 (1.92)	4.71 (2.31)	2.64 (1.97)
SPQ Perceptual Experience	1.84 (2.04)	0.0	9.0	1.91 (1.72)	3.68 (2.18)	0.57 (0.80)
SPQ Constricted Affect	2.01 (2.02)	0.0	7.0	4.36 (1.89)	1.93 (1.56)	0.83 (1.10)
SPQ No Close Friends	1.82 (2.06)	0.0	8.0	4.55 (1.92)	1.75 (1.24)	0.43 (0.74)
SPQ Odd Behaviour	1.37 (1.86)	0.0	7.0	1.82 (1.82)	2.25 (2.22)	0.55 (1.19)
SPQ Odd Speech	3.17 (2.39)	0.0	9.0	4.05 (2.75)	3.82 (2.36)	2.29 (1.92)
SPQ Suspiciousness	3.09 (3.17)	0.0	23.0	3.27 (2.41)	5.71 (3.86)	1.24 (1.14)

Table 2

Cluster solutions derived from the clustering analysis. The table presents R^2 , Bayesian Information Criterion (BIC), and Silhouette scores for the cluster solutions obtained. The analysis revealed a higher Silhouette score and a lower Bayesian Information Criterion (BIC) for the 3-cluster structure.

N Clusters	R^2	BIC	Silhouette
2	0.243	1081	0.21
3	0.346	996.76	0.23
4	0.307	1003.16	0.19
5	0.331	1044.39	0.09

The subscales *imagination* (AQ) and *odd speech* (SPQ) showed comparable moderate scores in SAT and CPT clusters, and lower scores in LT cluster. Overall, these results align with previous findings, highlighting a diametral pattern among individuals exhibiting atypicalities in cognitive-perceptual and socio-communicative dimensions (Tarasi et al., 2022; Marsicano & Melcher, 2025).

4.3. Power analysis

Based on the selected clustering solution, the input parameters for the interaction effect between condition and stimulation were as follows: effect size = 0.25, significance level = 0.05, total sample size = 92, number of groups = 3, and number of measurements = 3. The output parameters indicated a critical F-value of 2.42, which was lower than the

observed F-value for the interaction of interest ($F = 3.07$; see Results).

4.4. Entrainment AV temporal acuity modulations as a function of cluster profile

First, we indexed participants' TBW from the logistic fitted curves separately for each cluster, stimulation condition, and leading sense (Fig. 3).

In line with our recent study (Marsicano, Bertini, et al., 2024), different entrainment conditions modulated AV temporal acuity during the SJ task. The ANOVA revealed a statistically significant main effect of stimulation ($F(1.63, 145.52) = 16.08, p < .001, \eta^2p = 0.15$; Fig. 1B) and leading sense ($F(1, 89) = 4.04, p = .047, \eta^2p = 0.04$). On the contrary, clusters did not show a statistically significant main effect ($F(2, 89) = 1.9, p = .15, \eta^2p = 0.04$). Post-hoc comparisons revealed that the upper alpha (~ 12 Hz) condition resulted in a significantly narrower TBW (i.e., higher temporal acuity), compared to the lower alpha condition (~ 8.5 Hz; $M = 207.56, SD = 60.19$ vs. $M = 240.84, SD = 79.91$; $t(178) = -5.46, p = .003$) and non-rhythmic control stimulation condition ($M = 233.17, SD = 62.41$; $t(178) = -4.03, p = .003$).

In addition, such analysis revealed a statistically significant interaction between stimulation and leading sense ($F(1.74, 155.23) = 3.99, p = .02, \eta^2p = 0.043$; Fig. 1C). In the AL condition, participants showed a narrower TBW following upper alpha entrainment ($M = 181.24, SD = 75.89$) as compared to the lower alpha entrainment condition ($M = 220.10, SD = 136.23$; $t(320.41) = -5.24, p < .001$) and to the control

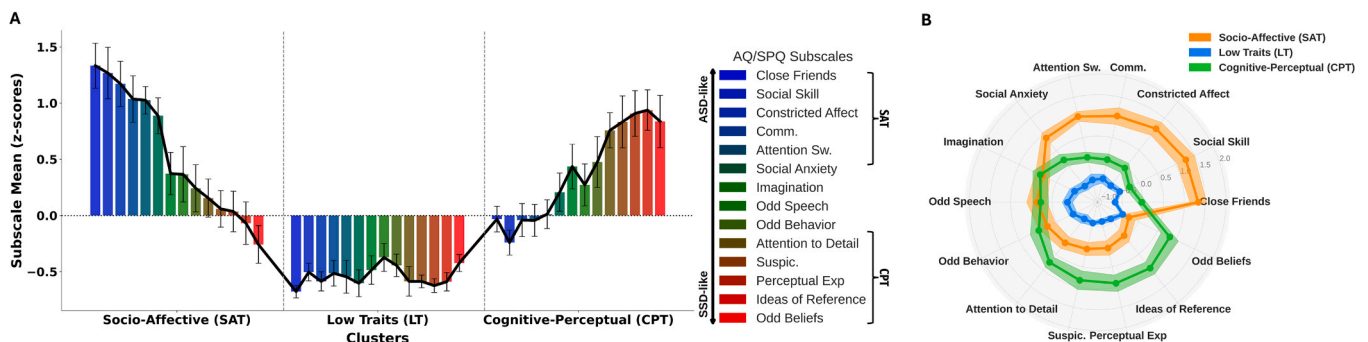


Fig. 2. Barplots (Panel A) and Radar Plot (Panel B) depicting mean value z-scores for each subscale of the SPQ and AQ questionnaires in relation to the 3 different clusters. For each cluster, the graph highlights the contribution of the subscales of the cognitive-perceptual domain (AQ: attentional switching, communication; SPQ: ideas of reference, odd beliefs/magical thinking, unusual perceptual experiences, eccentric/odd behaviour, suspiciousness) and socio-affective domain (AQ: social skills, attention to detail; SPQ: social anxiety, no close friends, restricted affect) in clustering structure. Odd speech and imagination subscales showed comparable moderate mean values both in SAT and CPT clusters. 1st cluster: Socio-affective Traits (SAT); 2nd cluster: Low Traits (LT); 3rd cluster: Cognitive-perceptual Traits (CPT). The error bars indicate the standard error of the mean (SEM).

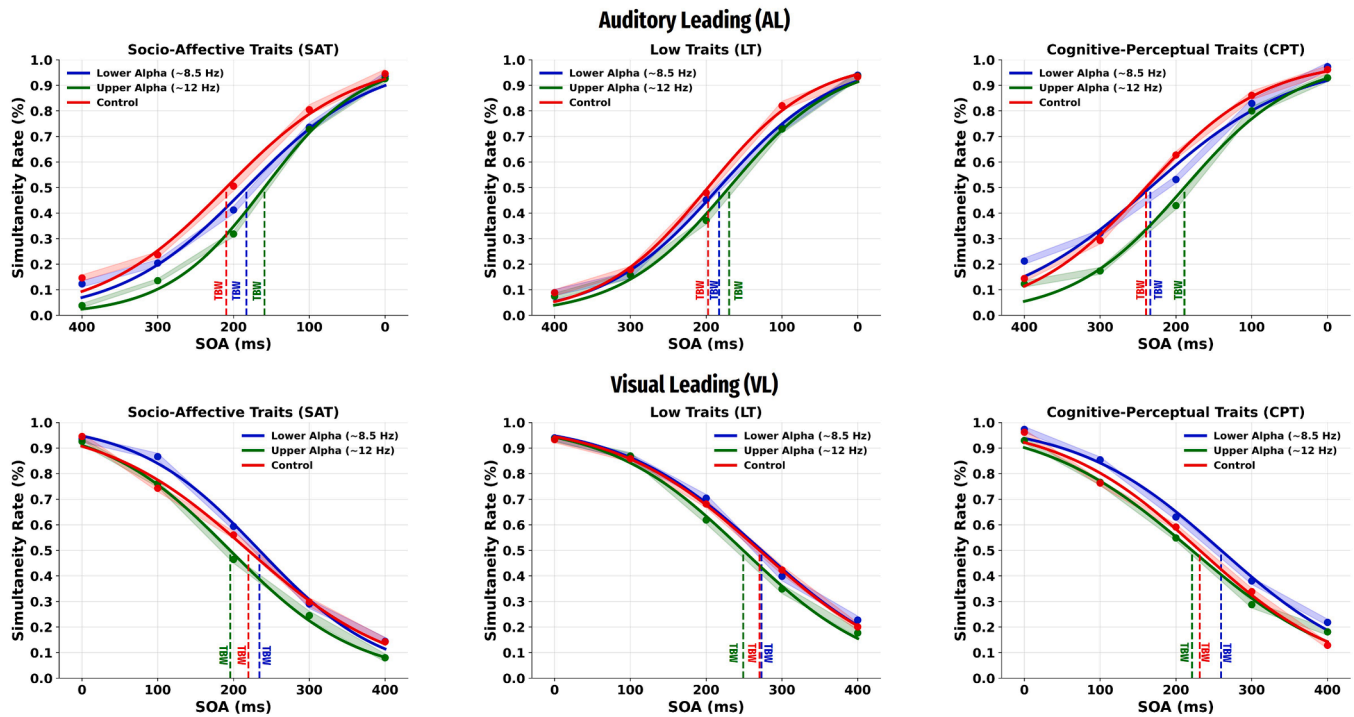


Fig. 3. Logistic curves obtained across participants for each cluster (Socio-affective Traits – SAT -, Low Traits – LT -, Cognitive-perceptual Traits – CPT -) in different entrainment conditions (Upper Alpha, Control, Lower Alpha), separately for Auditory Leading (AL) and Visual Leading (VL) condition (Upper panel: AL; Lower panel: VL). Each individual TBW was derived at a 50 % criterion (horizontal grey dotted line). Vertical dotted lines show the TBW value following each stimulation condition. Circles show simultaneity rates as a function of SOAs in the three different stimulation conditions, where diverse types of pre-target entrainment were employed (Green Curve = Upper Alpha; Red Curve = Control; Blue Curve = Lower Alpha). The error bars indicate the standard error of the mean (SEM).

condition ($M = 219.20$, $SD = 93.11$; $t(320.41) = -4.92$, $p < .001$), whereas following lower alpha entrainment participants did not show a broader AV TBW with respect to the control condition ($t(320.41) =$

0.31 , $p = .75$). In the VL condition, participants displayed a narrower TBW in the upper alpha entrainment ($M = 233.88$, $SD = 110.25$) compared to the lower alpha entrainment ($M = 261.58$, $SD = 98.66$; t

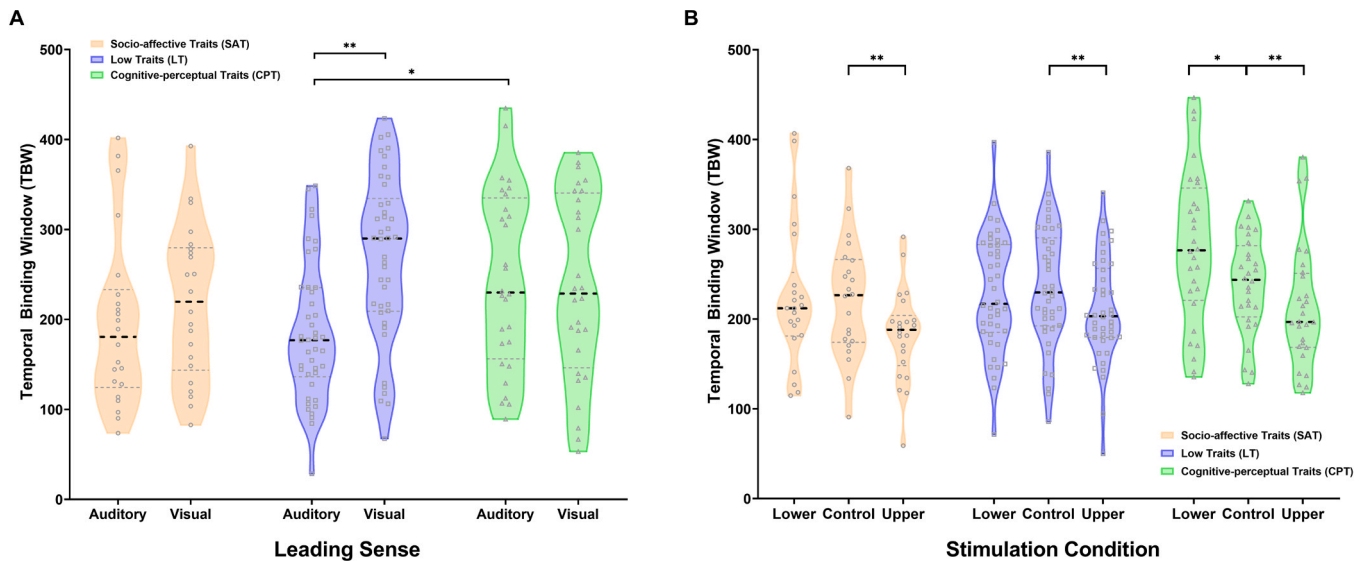


Fig. 4. Violin plots showing TBWs modulations as a function of stimulation condition, cluster and leading sense. **A)** Violin plots highlighting the interaction between cluster and leading sense, showing in the Visual Leading condition an enlarged AV TBW in Low Traits (LT) cluster with respect to Auditory Leading condition, whereas Socio-affective Traits (SAT) and Cognitive-perceptual (CPT) clusters did not show statistically significant differences between leading sense. Furthermore, the CPT cluster showed a narrower TBW in the AL condition with respect to the LT group. Black dotted lines indicate the median, while grey dotted lines indicate the quartiles. Grey circles, squares and triangles show the individual values. $*=p < .05$; $**=p < .01$; $***=p < .001$. **B)** Violin plots highlighting the interaction between stimulation condition and cluster, revealing an increased AV temporal acuity following upper alpha condition when compared to the control condition in each cluster (SAT, LT, CPT). On the contrary, lower alpha entrainment broadened AV TBW with respect to the control condition in the CPT cluster, but not in SAT and LT clusters. Black dotted lines indicate the median, while grey dotted lines indicate the quartiles. Grey circles, squares and triangles show the individual values. $*=p < .05$; $**=p < .01$; $***=p < .001$.

(320.41) = -3.68, $p < .001$), but not compared to the control condition ($M = 247.14$, $SD = 109.39$; $t(320.41) = -1.66$, $p = .09$), whereas following lower alpha entrainment participants showed an enlarged AV TBW as compared to the control condition ($t(320.41) = 2.02$, $p = .04$). In line with previous findings (Cecere et al., 2015; Marsicano, Bertini, et al., 2024), these results revealed an overall improvement of AV temporal acuity following upper alpha entrainment as compared to the lower alpha condition.

Importantly, such analysis revealed statistically significant interactions between leading sense and cluster ($F(2, 89) = 3.66$, $p = .03$, $\eta^2p = 0.076$; Fig. 4A), and stimulation and cluster ($F(3.27, 145.52) = 3.07$, $p = .02$, $\eta^2p = 0.06$; Fig. 4B).

The interaction between leading sense and cluster factors revealed a broader AV TBW in LT cluster in the VL condition ($M = 269.25$, $SD = 91.87$) as compared to AL condition ($M = 185.09$, $SD = 75.89$; $t(89) = -3.67$, $p < .001$), whereas SAT (VL: $M = 221.59$, $SD = 91.85$; AL: $M = 197.86$, $SD = 98.66$; $t(89) = 0.75$, $p = .45$) and CPT (VL: $M = 235.35$, $SD = 102.61$; AL: $M = 246.54$, $SD = 104.26$; $t(89) = -0.39$, $p = .69$) clusters did not show statistically significant differences between leading senses. The statistical comparison between groups as a function of leading sense revealed in the AL condition a lower AV temporal precision in CPT cluster ($M = 246.54$, $SD = 104.26$) with respect to LT group ($M = 185.09$, $SD = 75.89$; $t(165.87) = -2.7$, $p = .036$). No other statistically significant effects emerged when comparing the AV TBW between AL and VL conditions in the different clusters (all p -values $> .068$).

On the other hand, the stimulation condition and cluster interaction revealed narrower AV TBWs following upper alpha entrainment (~ 12 Hz) when compared to the control non-rhythmic condition across clusters (SAT upper alpha: $M = 0.182.43$, $SD = 51.45$; SAT control condition: $M = 221.69$, $SD = 65.19$; $t(178) = -2.89$, $p = .004$. CPT upper alpha: $M = 212.85$, $SD = 69.05$; CPT control condition: $M = 238.29$, $SD = 54.12$; $t(178) = -2.11$, $p = .036$. LT upper alpha: $M = 210.39$, $SD = 48.61$; LT control condition: $M = 235.77$, $SD = 57.04$; $t(178) = -3.25$, $p < .001$). On the contrary, lower alpha entrainment (~ 8.5 Hz) was effective in broadening AV TBWs as compared to the control non-rhythmic condition in CPT cluster (CPT lower alpha: $M = 271.69$, $SD = 92.58$; $t(178) = 2.77$, $p = .006$), but not in SAT (SAT lower alpha: $M = 225.05$, $SD = 80.05$; $t(178) = 0.24$, $p = .85$) and LT clusters (LT lower alpha: $M = 228.54$, $SD = 65.63$; $t(178) = -.73$, $p = .46$). The statistical comparison between groups in the size of TBW following different stimulation conditions revealed, in the lower alpha condition (~ 8.5 Hz), an enlarged AV TBW in CPT cluster ($M = 271.69$, $SD = 92.58$) as compared to SAT ($M = 225.05$, $SD = 80.05$; $t(166.17) = -2.43$, $p = .016$) and LT clusters ($M = 228.54$, $SD = 65.63$; $t(166.17) = -2.63$, $p = .009$).

This analysis did not reveal a statistically significant interaction between stimulation condition, leading sense and cluster factors ($F(3.48, 155.23) = 1.53$, $p = .20$, $\eta^2p = 0.03$).

5. Discussion

5.1. Audiovisual TBW modulations following alpha-band sensory entrainment

The main purpose of the current study was to investigate how the individual's perceptual, cognitive, and socio-affective profile may impact audiovisual (AV) temporal acuity, and the malleability of the AV temporal resolution following alpha-band sensory entrainment.

The overall pattern of results aligns with previous research on alpha-band tACS and AV entrainment (Cecere et al., 2015; Marsicano, Bertini, et al., 2024) showing that alpha oscillatory speed affects AV temporal resolution (Cooke et al., 2019). By applying AV alpha-band sensory entrainment for a brief period during the prestimulus interval of an AV Simultaneity Judgment (SJ) task, we found that upper alpha sensory stimulation (~ 12 Hz) enhanced AV temporal perception, similarly for both AL and VL conditions, by shrinking TBWs width and reducing

perceived simultaneity, compared to the non-rhythmic control and lower alpha (~ 8.5 Hz) conditions. We hypothesize that the entrainment of neural oscillations may have enhanced the temporal sampling capacity of AV perception by aligning endogenous oscillatory activity with the external stimulation frequency. However, in the absence of direct electrophysiological measurements (e.g., M/EEG), our behavioural data do not permit definitive conclusions regarding this hypothesis. As such, our findings do not constitute mechanistic evidence, and future studies employing M/EEG are required to investigate the potential role of neural entrainment in the observed effects.

5.2. Interindividual variability: cognitive-perceptual, low, and socio-affective trait profiles

A central question of this study was whether trait-dependent individual profiles could affect AV temporal resolution and its malleability following alpha-band stimulation. To capture interindividual differences, a cluster analysis based on the Autism Quotient (Baron-Cohen et al., 2001) and Schizotypal Personality Questionnaire (Raine, 1991) identified three groups sharing common features: Cognitive-Perceptual Traits (CPT), Socio-Affective Traits (SAT), and Low Traits (LT). This cluster structure aligns with prior research showing a diametric relationship between ASD- and SSD-like traits in the general population, showing that individuals with anomalies in socio-communicative traits often exhibit intact cognitive-perceptual abilities and vice versa (Zhou et al., 2019; Tarasi et al., 2022).

Importantly, these distinct personological profiles have been associated with distinct sensory processing signatures and different AV temporal abilities, where cognitive-perceptual and socio-communicative atypicalities can reliably predict AV temporal acuity (Van Laarhoven et al., 2019; Yaguchi & Hidaka, 2018). In this regard, individuals in the CPT group, characterized by heightened cognitive-perceptual anomalies such as magical thinking, unusual perceptual experiences, and suspiciousness, are often associated with generalized sensory processing deficits. These include reduced filtering of irrelevant sensory input, increased neural noise, and diminished sensory prediction accuracy (Uhlhaas & Singer, 2015; Ferri et al., 2018; Sterzer et al., 2019). Prominent features within this domain, such as delusional ideation, ideas of reference, and perceptual aberrations (van Os & Kapur, 2009; Corlett et al., 2007), have consistently been linked to an excessive reliance on internal models (Zhou et al., 2019, 2021), which may contribute to distortions in the processing of incoming sensory information. Collectively, these anomalies point to broader dysfunctions in multisensory integration mechanisms and a reduced capacity for the effective binding of sensory inputs over time. These anomalies are likely influenced by atypical alpha oscillatory dynamics (Uhlhaas & Singer, 2010), altered excitation/inhibition (E/I) balance (Gao et al., 2017), and disrupted cross-modal phase synchrony (Donoghue et al., 2020). In contrast, individuals primarily characterized by socio-affective atypicalities, such as social anxiety, limited social interaction, and flattened affect, may not display the same generalized sensory anomalies. This trait profile, frequently associated with ASD, is typically marked by a wide range of socio-communicative and affective difficulties, together with a heightened reliance on bottom-up sensory input and a reduced influence of top-down priors (Pellicano & Burr, 2012; Lawson et al., 2014; Van de Cruys et al., 2014; Palmer et al., 2017; Noel et al., 2022; Marsicano, Bertini, et al., 2024). Accordingly, these individuals are more likely to exhibit selective high-order anomalies in processing socially relevant stimuli, such as speech or facial expressions, rather than broad impairments in basic sensory binding. This pattern may suggest a more domain-specific alteration in information processing, potentially rooted in differences in attentional modulation or predictive coding mechanisms involved in social cognition (Zhou et al., 2020; Seymour et al., 2020). Finally, individuals exhibiting low levels of both cognitive-perceptual and socio-affective atypicalities likely demonstrate a more neurotypical sensory processing profile,

characterized by balanced temporal binding and typical patterns of sensory responsiveness.

Collectively, this stratification sheds light on how interindividual differences in neurocognitive trait profiles may manifest as distinct sensory processing phenotypes, allowing us to examine how specific ASD- and SSD-like traits influence AV temporal processing and reveal potential differences in the modulation of AV TBWs, depending on the nature of cross-modal interactions (i.e., leading sense) and the different rhythmicity embedded in the sensory stream (i.e., sensory entrainment).

5.3. Interindividual differences and TBW leading sense asymmetry

Our findings highlighted a significant asymmetry in the width of AV TBW between auditory-leading (AL) and visual-leading (VL) trials in the LT group, but not in the SAT or CPT groups. Specifically, the LT group exhibited a broader TBW in the VL condition, aligning with previous findings showing larger TBWs for VL sequences compared to AL (Van Wassenhove et al., 2007; Marsicano et al., 2022, 2024). The auditory system's higher temporal resolution compared to the visual system may explain this leading sense asymmetry (van Wassenhove, 2013; Cecere et al., 2016), possibly grounded in different neural mechanisms orchestrating the cross-modal phase reset of neural oscillations (Lakatos et al., 2009; Cecere et al., 2017).

Contrary to this typical pattern, both the SAT and CPT groups did not exhibit the leading sense asymmetry, with the typical auditory-leading higher temporal acuity being reduced in high-trait individuals. The absence of differences in TBW size between AL and VL sequences may reflect a tendency of individuals with marked cognitive-perceptual and socio-affective anomalies to perceive AL pairs as more simultaneous. This may be linked to less efficient auditory temporal sampling mechanisms (Donohue et al., 2012; Zhou et al., 2020), which would reduce the typical auditory-leading temporal precision observed in audiovisual cross-modal interactions.

Regarding the CPT group, previous evidence indicates an association between anomalous perceptual experiences and a slowdown in sampling sensory information in auditory brain areas (Foucher et al., 2007; Muller et al., 2020). Notably, cognitive-perceptual anomalies are often associated with atypical AV temporal binding (Ferri et al., 2018; Muller et al., 2021; Dalal et al., 2021; Marsicano et al., 2022), consistent with the CPT group's features and its atypicality in AV temporal processing observed in our findings. Similarly, individuals with atypical socio-communicative abilities tend to prioritize visual information processing while exhibiting slower auditory encoding (Donohue et al., 2012; Zhou et al., 2020; Aykan et al., 2020; Seymour et al., 2020). A recent study observed that in individuals with ASD, AV binding processes were predominantly driven by the auditory input, indicating that excessive encoding of auditory information may contribute to their atypical AV temporal processing (Ronconi et al., 2023).

Interestingly, another potential mechanism underlying this atypical tendency to treat AL and VL interactions more equivalently may lie in how cross-modal signals are anticipated and integrated into stable sensory representations in individuals within the CPT and SAT groups (Noel et al., 2018; 2022). In individuals with elevated cognitive-perceptual anomalies resembling SSD profiles, this could stem from a stronger reliance on inflexible internal models or overly precise priors, which might lead to anticipating AL and VL signals as equally synchronous, regardless of their actual temporal structure (Sterzer et al., 2019). Conversely, individuals with high ASD traits have often been associated with a reduced reliance on prior models (Lawson et al., 2014; Noel et al., 2018) and a greater dependence on current sensory input (Lieder et al., 2019; Marsicano, Bertini, et al., 2024). Such atypicalities in predictive processing could weaken the internal expectation that auditory signals typically precede visual ones in naturalistic contexts, leading to a more uniform perception of audiovisual asynchrony and increased difficulty in parsing temporally complex AV information, such as speech stimuli (Van Wassenhove et al., 2007; Zhou et al., 2020; 2021). Thus, despite

the similarity in behavioral outcomes, namely the absence of the typical auditory-leading advantage, the underlying mechanisms contributing to the patterns observed in the CPT and SAT profiles may differ.

Additionally, when comparing TBW widths across groups in AL and VL trials, the CPT group showed lower temporal acuity in AL trials compared to the LT group, while no significant differences were found between LT and SAT groups. While these findings align with the idea that perceptual atypicalities may stem from a lower auditory temporal resolution (Foucher et al., 2007; Muller et al., 2020), they also support previous evidence highlighting a general multisensory deficit (Zhou et al., 2021). Indeed, ASD-like traits are typically linked to selective AV temporal processing anomalies for stimuli with socio-communicative value (e.g., speech), while SSD-like traits are frequently associated with generalized sensory processing anomalies, resulting in AV temporal binding atypicalities affecting both speech and nonspeech stimuli (Zhou et al., 2020; 2021). These generalized deficits in AV binding mechanisms may help account for the CPT group's more marked AV temporal processing anomalies observed in response to our flash-beep SJ task, where AV stimuli lacked socio-communicative features.

Overall, our results suggest that interindividual differences within cognitive-perceptual and socio-communicative domains can impact cross-modal audiovisual interaction mechanisms, contrasting the natural asymmetry between AL and VL sequences typically observed in the general population.

5.4. Interindividual differences drive TBWs modulation following alpha-band sensory entrainment

Finally, we examined whether interindividual differences influenced the modulation of TBWs under different entrainment conditions. First, after non-rhythmic control condition, no differences were found in TBWs width among groups, suggesting that AV temporal acuity was comparable across participants in their natural AV temporal sampling. This finding contrasts with previous literature linking broader AV TBWs to SSD- and ASD-like traits in the general population (Noel et al., 2018; Zhou et al., 2019, 2020; Weiland et al., 2023), as our data-driven stratification of individuals based on their cognitive-perceptual and socio-communicative profiles revealed no differences in natural AV temporal acuity.

Despite the lack of between-group differences in the control condition, our findings suggest that interindividual differences influenced the modulation of AV TBWs following alpha-band neural entrainment. Across all groups, upper alpha stimulation (~12 Hz) resulted in narrower TBWs compared to the non-rhythmic control condition, suggesting that the faster alpha stimulation (~12 Hz) enhanced AV temporal acuity, consistent with prior evidence (Marsicano, Bertini, et al., 2024). However, following lower alpha stimulation (~8.5 Hz), only the CPT group exhibited a significant widening of TBWs, while the LT and SAT groups showed no modulation. These behavioural differences across groups following alpha-band entrainment align with previous reports showing significant interindividual variability in adapting to rhythmic sensory sequences (Ghuman et al., 2017; Northoff, 2018; Beker et al., 2021; Black et al., 2024). Indeed, while entrainment is an adaptive neural feature allowing the synchronization of endogenous and external rhythms, ensuring that sensory input falls within optimal temporal phases of information processing (Gallina et al., 2023), individuals with higher SSD-like traits often display atypicalities in processing rhythmic sensory inputs (Ghuman et al., 2017; Northoff, 2018; Bharathi et al., 2019; Black et al., 2024). These sensory atypicalities may stem from anomalies in bottom-up perceptual processes, resulting in a dysfunctional integration of sensory information into coherent models. Indeed, individuals exhibiting marked atypicalities in structuring their perceptual experience tend to adhere rigidly to prior models of the sensory environment, giving less weight to sensory prediction errors (Sterzer et al., 2019; Liddle & Liddle, 2022; Tarasi et al., 2022; Marsicano & Melcher, 2025). Accordingly, our findings may suggest that difficulties

in organizing incoming sensory information into coherent representations (Sterzer et al., 2019; Tarasi et al., 2022) may lead to an increased rigidity in adhering to probabilistic representations generated from rhythmic sensory sequences, which could have promoted synchronization to entrainment, ultimately affecting AV TBWs.

From a different standpoint, we may speculate that the observed group differences may arise from interindividual variability in oscillatory neural activity (Ippolito et al., 2022), or from differences in the underlying neurophysiological mechanisms that regulate the synchronization of endogenous neural oscillations with alpha frequencies stimulation. In this regard, a potential explanation for the selective widening of AV TBWs in the CPT group may be that participants in the SAT and LT clusters may have received slower alpha stimulation (~8.5 Hz) at a frequency closer to their IAF, thereby diminishing its effectiveness in modulating endogenous oscillatory dynamics (Notbohm et al., 2016; Huang et al., 2021). In this regard, Garakh et al. (2012) observed that within a sample of individuals with SSD, those exhibiting more pronounced cognitive-perceptual atypicalities displayed a faster IAF relative to both healthy controls and individuals mainly characterized by socio-affective anomalies. Thus, it can be speculated that slower alpha stimulation (~8.5 Hz) modulated TBW size in participants with pronounced cognitive-perceptual anomalies, potentially by slowing down an otherwise faster endogenous alpha rhythm, whereas in the SAT and LT groups, the same stimulation frequency may have proven ineffective due to a higher convergence between the stimulation frequency and their intrinsic IAF.

Additionally, individuals with SSD-like traits showing pronounced cognitive-perceptual atypicalities often exhibit more variable neural activity, likely driven by increased intrinsic noise and instability in neural processing (Smyrnis et al., 2009; Vinogradov et al., 1998; Yang et al., 2014). This variability has been linked to flatter aperiodic 1/f spectral slopes, reduced oscillatory synchronization, and imbalances in excitatory/inhibitory mechanisms, which are neurophysiological markers associated with cortical hyperexcitability and impaired top-down feedback control (Donoghue et al., 2020; Foss-Feig et al., 2017; Uhlhaas & Singer, 2015; Ramsay et al., 2021). These factors may underlie the increased sensitivity to alpha band entrainment observed in CPT participants and contribute to the widening of their TBWs, whereas individuals with lower levels of cognitive-perceptual atypicalities, such as those in the LT and SAT groups, may exhibit more stable neural activity patterns and preserved inhibitory function, potentially making them less susceptible to modulations induced by an external rhythmic stimulation (Uhlhaas & Singer, 2015; Ramsay et al., 2021).

Thus, these different neural mechanisms may reflect a complex interaction between trait-related cortical excitability and frequency-specific tuning of endogenous oscillatory systems, suggesting that entrainment outcomes are shaped by the alignment between stimulation frequency and an individual's neurophysiological state. However, without neurophysiological M/EEG measures, these remain speculative, and other factors, such as task and stimuli characteristics, may also contribute to the observed effects (Stevenson & Wallace, 2013).

6. Conclusion, limitations and future perspectives

Our findings suggest that, within the general population, interindividual differences can influence temporal processing abilities and their related malleability following AV entrainment. By stratifying participants into distinct subgroups based on ASD- and SSD-like traits, we revealed behavioural patterns that might remain hidden without considering such individual differences, underscoring the importance of accounting for individual trait profiles when studying AV temporal processing and entrainment mechanisms. Given that an individual's profile is a complex outcome of interactions among multiple cognitive-perceptual, socio-affective, and communicative domains, greater emphasis should be placed on understanding how ASD- and SSD-like features such as incoherent perception, communicative dysfunction,

social and affective cognition interact in characterizing the specific individual profile, as these behavioural manifestations are all rooted in effective multisensory abilities and in the intrinsic capacity to align with sensory streams.

It is important to note that, while examining subclinical ASD-like and SSD-like traits in neurotypical individuals offers a valuable framework for understanding core features of these conditions (Zhou et al., 2019, 2021), and contributes to a more comprehensive understanding of how AV temporal processing varies across individuals in the general population, our findings may not fully generalize to diagnosed ASD or SSD populations. However, the effects observed here align with those reported in clinical studies of ASD and SSD, where atypical AV temporal precision (Foucher et al., 2007; Noel et al., 2018; Regener, Heffer, Love, Petrini, & Pollick, 2024) and disrupted synchronization to rhythmic sensory streams (Northoff, 2018; Bharathi et al., 2019; Black et al., 2024) have also been documented. Thus, our findings suggest that these patterns may have relevance across the broader neurodiversity continuum, both within and beyond the neurotypical population. Nevertheless, future work should directly investigate whether individuals with diagnosed ASD or SSD exhibit similar AV atypicalities and entrainment-induced changes.

While our findings may theoretically reflect group differences in the entrainment of neural oscillations, the absence of direct electrophysiological measures precludes definitive conclusions. Future M/EEG studies are needed to clarify the role of neural entrainment in the observed effects and to determine whether individual trait characteristics modulate neural and behavioral responses to sensory entrainment. Relatedly, a promising direction for future research involves the use of alpha-band sensory entrainment to enhance AV temporal perception in both neurotypical individuals and those with neurodevelopmental conditions. Perceptual training has been shown to improve AV temporal acuity (Stevenson & Wallace, 2013; Cecere et al., 2016; McGovern et al., 2022), and recent work suggests that such improvements may relate to modulations of alpha oscillatory dynamics (Venskus, 2024). By synchronizing endogenous rhythms with external stimuli, alpha entrainment may support AV temporal prediction with minimal participant effort (Gallina et al., 2023; Marsicano, Bertini, et al., 2024). Furthermore, in the current study we stimulated across participants using fixed slow (~8.5 Hz) and fast (~12 Hz) frequencies within the alpha-band, but given the substantial interindividual variability in endogenous alpha frequency (Gallina et al., 2023), tailoring alpha-band sensory entrainment using an individualized approach that aligns the stimulation frequency to each participant's IAF range (i.e., ± 2 Hz; Cecere et al., 2015) could optimize neural synchronization and perceptual outcomes, thereby enhancing the efficacy of alpha-band entrainment for perceptual processing (Lakatos, Gross, & Thut, 2019; Gallina et al., 2023). Such sensory entrainment techniques may therefore hold significant potential for tuning the individual endogenous alpha rhythm and increasing AV temporal acuity in individuals with high autistic or schizotypal traits, who often exhibit reduced AV temporal sensitivity (Ferri et al., 2018; Van Laarhoven et al., 2019; Fenner et al., 2020; Muller et al., 2021; Zhou et al., 2021; Marsicano et al., 2022). This approach may more broadly prove beneficial for neurodevelopmental and neurological populations characterized by atypical alpha oscillatory activity and anomalous sensory processing (Babiloni et al., 2008; Dubovik et al., 2012; Westlake et al., 2012; Pietrelli et al., 2019; Gallina et al., 2022a; 2022b; Amidfar & Kim, 2020; Lense et al., 2021; Ippolito et al., 2022). Future studies could further explore whether individualized alpha entrainment protocols can selectively enhance AV temporal precision in high-trait and clinical populations, potentially informing novel sensory-based interventions.

CRedit authorship contribution statement

Gianluca Marsicano: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caterina Bertini:** Writing –

review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Luca Ronconi**: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Sara Garofalo**: Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

Author contributions

Conceptualization: G.M.; L.R.; C.B. Investigation: G.M. Contributed analytic tools: G.M.; S.G. Analyzed data: G.M.; S.G. Supervision: L.R.; C. B. Resources: C.B. Visualization: G.M. Wrote the paper (original draft preparation): G.M.; S.G.; L.R.; C.B. Wrote the paper (reviewing and editing): G.M.; S.G.; L.R.; C.B.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that they did not employ generative AI or AI-assisted technologies during the writing process.

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.

Acknowledgements and Funding Information

C.B. was supported by Ministero dell'Istruzione, dell'Università e della Ricerca, PRIN 2022 (2022HNYMHR). L.R. was supported by Ministero dell'Istruzione, dell'Università e della Ricerca, PRIN 2022 (2022H4ZRSN). S.G. was supported by European Union's NextGenerationEU and the Italian Ministry of Research (MUR) National Recovery and Resilience Plan (NRRP-PNRR), project titled "Individual variations in resisting temptation: the balance between motivational and inhibitory control" (ES PNRR - M4C2 - I1.3 - Prot. P2022KAZ45_001 – CUP J53D23017240001). The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

Data availability

Data will be made available on request.

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